STUDIES ON PERFORMANCE ASPECTS OF SMART WIRELESS DEVICES AND RELATED NETWORK SERVICES

by

Aziz Ulhaq Noori

A Dissertation Submitted to the Faculty of
the College of Engineering and Computer Science
in Partial Fulfillment of the Requirements for the Degree of
Doctor of Philosophy

Florida Atlantic University
Boca Raton, Florida
May 2015
Copyright 2015 by Aziz Ulhaq Noori
STUDIES ON PERFORMANCE ASPECTS OF SMART WIRELESS DEVICES AND RELATED NETWORK SERVICES

by

Aziz Ulhaq Noori

This dissertation was prepared under the direction of the candidate’s dissertation advisors, Dr. Perambur S. Neelakanta and Dr. Shihong Huang, Department of Computer & Electrical Engineering and Computer Science, and has been approved by the members of his supervisory committee. It was submitted to the faculty of the College of Engineering and Computer Science and was accepted in partial fulfillment of the requirements of the degree of Doctor of Philosophy.

SUPERVISORY COMMITTEE:

Perambur S. Neelakanta, Ph.D.
Dissertation Advisor

Shihong Huang, Ph.D.
Dissertation Co-Advisor

Mohammad Ilyas, Ph.D.

Jonathan Bagby, Ph.D.

Dolores De Groff, Ph.D.

Date
ACKNOWLEDGMENTS

This study would not have been completed without the direction, guidance and motivation from Dr. Perambur S. Neelakanta, the Committee Chairperson and dissertation advisor. I admire his immense knowledge and experience on the research topics. I would like to thank Dr. Neelakanta for providing continuous support during my PhD study and research. Dr. Neelakanta was available on weekends, weekdays, nights and almost at anytime to provide constructive feedback regarding questions related to this research, algorithms and related computations. My sincere thanks to him for his time and editing this dissertation and providing valuable information pertinent to this study.

I wish to thank the Co-advisor Dr. Shihong Huang and other Committee Members, Drs. Mohammad Ilyas, Jonathan Bagby, and Dolores De Groff for their time, advisement and serving as members of the committee. Their inputs and providing of their educated assessments to this dissertation are highly appreciated.

Finally, I am so greatly thankful to my family for their continuous support, constant encouragement and enormous patience while going through this journey.
ABSTRACT

Author: Aziz Ulhaq Noori

Title: Studies on Performance Aspects of Smart Wireless Devices and Related Network Services

Institution: Florida Atlantic University

Dissertation Advisor: Dr. Perambur S. Neelakanta

Degree: Doctor of Philosophy

Year: 2015

This study is a focused effort on elucidating the performance aspects of modern, handheld wireless devices and associated mobile network services. Specifically addressed thereof are: (i) Assessing the performance details on certain hardware sections of smart handheld devices and (ii) determining the performance profile of market penetration considerations vis-à-vis provisioning mobile networks. To meet the scope of this research, the projected efforts are exercised in compiling relevant literature and deciding the said hardware and technoeconomic performance issues. Hence, written in two parts, Part A is devoted to hardware performance details of smart, handheld devices relevant to (a) delay issues in PCB layouts; (b) crosstalk problems at the baseband level (audio/multimedia) using EMI concepts and (c) ascertaining non-catastrophic EMP/EMI effects at the RF-sections so as to implement protection strategies via compensating networks. Part B is concerned with
the technoeconomics of wireless networks in supporting mobile (handheld devices). Correspondingly, two market related considerations versus service performance details are considered. The first one refers to deducing a relative performance index that includes technology (mobile speed) details plus economics profiles of the users in the service area. The second task refers to elucidating a performance index of such services in terms of hedonic pricing heuristics.

The theoretical aspects of the test studies as above are supplemented with experimental and/or simulation details as appropriate. Hence, the efficacy of performance details are discussed in real-world applications.

Lastly, possible research items for future studies are identified as open-questions.
STUDIES ON PERFORMANCE ASPECTS OF SMART WIRELESS DEVICES AND RELATED NETWORK SERVICES

LIST OF TABLES ......................................................................................................................... x

LIST OF FIGURES ...................................................................................................................... xii

1. CHAPTER I ................................................................................................................................. 1
   1.1 General ................................................................................................................................. 1
   1.2 Scope of the Research .......................................................................................................... 2
   1.3 Objective of the Research .................................................................................................. 3
   1.4 Contributions: Outcomes of the Research ....................................................................... 5
   1.5 Motivational Considerations ............................................................................................. 8
   1.6 Organization of the Dissertation and Closing Remarks .................................................. 9

2. CHAPTER II ............................................................................................................................. 12
   2.1 General ............................................................................................................................... 12
   2.2 Introduction ........................................................................................................................ 13
   2.3 Digital Data Format Seen at Baseband in Smartphones or Similar Devices .................. 17
   2.4 Architectural Layouts of Baseband Infrastructures ........................................................ 18
   2.5 Planar Inductors: An Overview ......................................................................................... 18
   2.6 Test Inductance/Delay-line: Description and Measurements .......................................... 22
   2.7 Remarks Inferential .......................................................................................................... 26
   2.8 Closure ............................................................................................................................... 26

3. CHAPTER III ............................................................................................................................ 27
   3.1 General ............................................................................................................................... 27
   3.2 Introduction ........................................................................................................................ 28
   3.3 Digital Signal Transport at Baseband Section of Wireless Handheld Devices ................ 29
   3.4 EMI on the Cluster of PCB Traces: An Overview ............................................................. 32
   3.5 Crosstalk Estimation: Statement of the Problem and Description ................................... 33
3.6 Inter-trace Coupling Factor (F) Estimation via EM Field Considerations .......... 41
3.7 Test PCB Layout for Analysis, Computational and Experimental Study .......... 42
3.8 Analysis .................................................................................................................. 45
3.9 Computed and Measured Results and Inferential Remarks ............................... 55
3.10 Inferential Remarks and Closure .......................................................................... 61

4. CHAPTER IV ................................................................................................................. 64
4.1 General ...................................................................................................................... 64
4.2 Introduction ............................................................................................................... 65
4.3 Theoretical Considerations and Analysis ............................................................... 71
4.4 Simulation Experiments and Results ....................................................................... 79
4.5 Discussions ............................................................................................................... 81
4.6 EMP Protection of the RF-Section in Wireless Devices: The Design Flow .......... 83
4.7 Design of Lossless \( \lambda_c/4 \) Shorted-stub ................................................................. 88
4.8 Design of Lossy \( \lambda_c/4 \) Shorted-stub ................................................................. 88
4.9 Design of Lossy Compensating Inductor .............................................................. 88
4.10 Concluding Remarks and Closure .......................................................................... 90

5. CHAPTER V ................................................................................................................. 93
5.1 Introduction ............................................................................................................... 93
5.2 Background .............................................................................................................. 94
5.3 Performance Aspects of Wireless Networks \( vis-à-vis \) Smartphone Technology ............................................................................................................. 98
5.4 Relative Performance of Mobile Networks: : PCMag.com Heuristics on the MSI .......................................................... 100
5.4.1 Service-related Technological Details ................................................................ 100
5.4.1.1 Definitions and Details of Techno-centric Parameters Adopted by PCMag.com [5.25] – [5.30] in Evaluating the MSI ................................................. 101
5.5 Evaluation of the MSI ............................................................................................. 104
5.6 Role of Service-related Economics Parameters of Wireless Networks .......... 112
5.6.1 Mobile Carriers Mobile Growth \( vis-à-vis \) Productivity-related Economics .... 115
5.7 Relative Technoeconomic Performance Index (RTPI) of Mobile Carriers .......... 117
5.7.1 Evaluating RTPI: An outline .............................................................................. 118
5.8 Computed Data ........................................................................................................ 124
5.9 Discussions and Concluding Remarks ................................................................... 128
LIST OF TABLES

Table 2-1: Typical planar geometries (of Figure 2.5) that can be used to emulate inductance and related delay-lines ........................................................................................................... 21

Table 2-2: Dimensional details of the test fractal inductor (Figures 2.2 and 2.3) ............... 24

Table 3-1: Measured and computed data on NEXT and FEXT relevant to the test PCB illustrated in Figure 3.13 ........................................................................................................ 58

Table 4-1: Assumed nominal parameters relevant to a hypothetical test PCB and EMP waveform/spectrum ........................................................................................................ 81

Table 5-1: Test service area: Boston Metro, MA: USA; Service period: 2010 to 2013..... 112

Table 5-2: An example of: Census data on population and PCI: USA and Boston Metro, MA: 2000-2010 ........................................................................................................ 115

Table 5-3: US Smart-phone sales penetration relative to feature phone sales [5.19] ........ 115

Table 5-4: Relative economics productivity parameters vis-à-vis smart-phone deployment in the business suites [5.4] ......................................................................................... 116

Table 5-5: Summary data on the estimated values of the MSI [5.25] - [5.30] and the RTPI at Boston, MA: USA in 2013 ................................................................................................. 131

Table 5-6: Upper and lower percentages of variability of the RTPI values: (Error-bar limits based on Wiener upper- and lower-bounds). Service area BOSTON, MA:USA; Period: 2010-2013 [5.25]-[5.30] ......................................................................................... 132

Table 6-1: Evaluation of MSI: Exemplified with relevant turf data of a mobile network provider in a service area ................................................................................................. 144
Table 6-2: Evaluation of RTPI: Exemplified with relevant turf data of a mobile network provider in the service area................................................................. 145

Table 6-3: Evaluation of hedonic pricing (HPI) examplified with relevant turf data........ 156

Table 6-4: Performance Indices: Summary of compiled MSI, RTPI and HPI value across 2010 to 2013: Summary........................................................................... 157

Table 6-5: Summary -Computed data on HPI of the services versus relevant actual prices enforced by the network operators. (The prices are specified as normalized values with respect to the average pricing enforced in the service area) ........................................................................................................ 159

Table 6-6: Summary of results: Tariff details and pricing structure in practice - A comparison.................................................................................................................. 160
LIST OF FIGURES

Figure 2.1: Example of copper-trace route on a typical printed circuit-board layout........... 14

Figure 2.2: A set of spiral inductors configured as a planar fractal delay-line: (a) With circular- spirals and (b) square-spirals.......................................................... 14

Figure 2.3: Photograph of the distributed delay-line (DDL) on a PCB made based on circular spiral fractal geometry: Test module studied conforming to Figure 2.2(a)........................................................................................................ 16

Figure 2.4: Equivalent circuit representation of a planar inductor conceived with a spiral (L: Inductance, R_s: Inherent series resistance, R_p: Leakage resistance, and C_p: Parasitic capacitance).................................................................................. 19

Figure 2.5: A: Single circular loop; B: multiple circular-loop spiral; C: Multiple square-loop spiral and D: Meanderline............................................................................... 19

Figure 2.6: Measurement setup......................................................................................... 23

Figure 2.7: Measured delay (δ) normalized with respect to the signal period (T), versus signal frequency (f) in MHz, (L_1 to L_{11} etc.: Number of spirals in the fractal geometry cascaded and tested) ........................................................................ 24

Figure 2.8: Waveforms measured at the input and output at 40 MHz for 5 spirals (L_1 through L_5 serially connected in the fractal structure).............................................. 25

Figure 2.9: Waveforms measured at the input and output at 80 MHz for 5 spirals (L_1 through L_{10} serially connected in the fractal structure)................................................. 25

Figure 3.1: Trace clusters fanning out on a PCB: For example, in the baseband infrastructure of a handheld device.................................................................................. 33
Figure 3.2: A parallel set of hypothetical victim traces \( \{ V_T \}_v = 1, 2, \ldots \) and an aggressor trace (\( A_T \)) on a PCB. The terminal nodes of the aggressor and the victim are shown with the associated voltages, \( \{ v_s, u_s \} \) and \( \{ v_L, u_L \} \) respectively corresponding to source and load-ends.

Figure 3.3: Set of possible layouts of aggressor (\( A_T \)) and victim (\( V_T \)) traces showing their relative, non-parallel geometrical dispositions on the PCB with one, more or zero turning-points seen on the victim traces.

Figure 3.4: Randomly-patterned set of victim traces \( \{ V_T \}_v = 1, 2, \ldots \) disposed with respect to an aggressor trace (\( A_T \)) on the PCB. The entities \( X_A \) and \( \{ X_V \} \) denote respectively, the RMS values of random geometrical undulations of the respective traces on the PCB 2D-plane.

Figure 3.5: A matrix \( K: [I \times J] \) meshes conceived on the 2D-plane of the PCB layout infested with victim traces.

Figure 3.6: Victim and aggressor traces: Terminal nodes and turning-points.

Figure 3.7: Set of victim (\( P_1 - P_2 \)) and aggressor (\( Q \)) trace-layouts each with varying number of turning points (\( N \)).

Figure 3.8: A hypothetical PCB layout with aggressor (\( AA' \)) and a set of victim traces, \( \{ V_T \}_v = 1, 2, \ldots \). (No crossing of traces is assumed). The regions \( \Omega_1 \) and \( \Omega_2 \) denote the near-end and far-end domains specified with respect to source and receiving ends.

Figure 3.9: Illustration of bifurcated domains \( \Omega_1 \) and \( \Omega_2 \) with the set of susceptibility indices \( \{ S_i \}_1 \) and \( \{ S_i \}_2 \) respectively; and, \( \alpha \) and \( \beta \) denote NEXT and FEXT levels respectively on the victim trace.

Figure 3.10: Point-by-point representation of the susceptibility indices at nodes specified within each mesh of the matrix drawn on the 2D-plane of victim layout.
Figure 3.11: Illustration of hypothetical sets \( \{m \times v\} \) and \( \{n \times v\} \) meshes prescribed for \( \Omega_1 \) and \( \Omega_2 \) respectively. (The victim traces are denoted by the index \( v \) both in \( \Omega_1 \) and \( \Omega_2 \) as identified in the text). 

Figure 3.12: Geometrical parameters of the traces and the associated distance values of node separation, \( (\ell_v = 1, 2, \ldots)_N \) and \( (\ell_v = 1, 2, \ldots)_F \) pertinent to the set of victims \( \{v = 1, 2, \ldots\} \) experiencing the NEXT and FEXT respectively.

Figure 3.13: Test PCB with the aggressor plus a set of eight (8) victim traces. The traces are terminated with \( R_o = 50 \) ohm impedance. The source impedance \( R_s \) is also 50 ohm. Each trace has sixteen nodes (including the NEXT and FEXT nodes located at near- and far-ends with reference to the source).

Figure 3.14: The PCB used in the experimental studies.

Figure 3.15: Measured and computed values of NEXT and FEXT of the test PCB at 40 MHz. (MV: Measured values and UB and LB denote the upper and lower bounds respectively of the computed data).

Figure 3.16: Measured and computed values of NEXT and FEXT of the test PCB at 80 MHz. (MV: Measured values and UB and LB denote the upper and lower bounds respectively of the computed data).

Figure 4.1: Geometrical details of an arbitrary, hypothetical set of randomly-routed traces laid on the PCB at the RF section (\( \Omega \)) nodes \( \{n = 1, 2, \ldots, N\} \) experiencing the fluence of EMP striking at a vulnerable reference node. The victim site is divided into a set of 2D matrix-grids; and, the nodes of interest namely, \( \{n = 1, 2, \ldots, N\} \) are identified at these grids by the coordinates, \( \{i, j\} \).

Figure 4.2: Spectral representation of the envelope of a typical transient EMP: Amplitude density function \( V_s(\omega) \) in dB versus frequency in Hz [4.11].

Figure 4.3: EMP waveform functions: Amplitude, \( v_s(t) \) versus time, t. (a) Ideal EMP waveform with an impulsive instantaneous, amplitude (corresponding to a
delta-Dirac function); (b) Practical EMP exhibiting a rectangular pulse shape with extremely small, finite pulse-width, \( \tau \). (c) Transient trend of EMP waveform manifesting as a double-exponential curve with a very sharp leading-edge reaching the maximum level in an extremely short duration with a finite rise-time, \( t_r \). (d) EMP waveform seen as a damped sinusoidal function depending on the damping factor, \( \xi \), as decided by lossy and reactive components dispersed in the receptive domain, \( \Omega \).

Figure 4.4: Computed results on \(|K(\cdot)|\) versus the EMP rise-time \( t_r \): Data cluster obtained via Monte Carlo simulations with the algorithmic predictions of the upper- and lower-bounds UB and LB). Computed result obtained using nominal (fixed) values of PCB and EMP parameters as assumed is as presented.

Figure 4.5: Proposed EMP-EMI protection method for the RF-section of the wireless device.

Figure 4.6: A Smith-chart representation of the input VSWR characteristics of the final test structure improvised for EMP-EMI protection: It is assumed in the calculations the unloaded-Q as 2; and, the corresponding bandwidth is: \( \Delta f = 500 \text{ MHz at } f_x = 1000 \text{ MHz} \).

Figure 5.1: Estimated relative performance indicator (RPI) depicting the MSI, the RTPI and the Wiener bounds of the RTPI values versus the service period 2010 through 2013. Service area: BOSTON, MA:USA (a: MSI [25]-[30]; b: RTPI; c: RTPI: W-UB and d: RTPI: W-LB).

Figure 6.1: Performance indices versus the service period (2010-2013) for AT & T in the service area, Boston, MA.

Figure 6.2: Performance indices versus the service period (2010-2013) Verizon in the service area, Boston, MA.
Figure 6.3: Performance indices versus the service period (2010-2013) for T-Mobile
in the service area, Boston, MA................................................................. 162

Figure 6.4: Performance indices versus the service period (2010-2013) for Sprint in
the service area, Boston, MA................................................................. 162
CHAPTER I
INTRODUCTION

1.1 General

This study is conceived to elucidate the performance aspects of modern wireless mobile/fixed units including smart and feature phones. Relevantly, performance issues concerning certain hardware aspects of the devices and service details pertinent to the associated mobile networks are addressed. Appropriate metrics to measure the underlying performances details are defined and applied to practical wireless devices and field data concerning mobile services and network operations. Commensurate with the topic of research proposed and consistent with the scope as above, the efforts exercised are presented in two parts as outlined below:

Part A:

This part is devoted to address certain hardware issues and evaluate performance details specific to smart wireless devices. It covers three major topics:

- Evaluating the performance of smart, handheld devices via time interval error (TIE) observed in high-speed baseband digital transports at the baseband section: Mitigation suggestions using delay compensation with fractal inductors are presented.
- Evaluating the crosstalk performance at printed circuit board (PCB) level of baseband sections in smart handheld devices: The test PCB layout is modeled with a random cluster of traces that facilitate the high-speed digital transport an statistical aspects of inter-trace electromagnetic interference (EMI) are deduced to evaluate the crosstalk performance and relevant mitigation are suggested.


Developing a performance assessment scheme pertinent to RF-sections of modern wireless devices vis-à-vis electromagnetic pulse (EMP) ambient and related EMI considerations: Mitigation via compensating network is indicated.

Part B:
This second part refers to technoeconomic performance details of mobile networks supporting co-diffusion of smart and traditional feature phone devices. Specifically, the following two considerations are addressed:

- Making a comparison of mobile services and networking operations via mobile-speed index (MSI) and deduce a corresponding technoeconomics performance index (RTPI): Practical field data are considered and analyzed in the proposed model
- Comparing the performance of mobile networks on the basis of tariff structure imposed (in terms of pricing leased to subscribers) subject to their “preferences” for such services: This is a hedonic approach (meaning, price-worthiness matching the “subscriber crush” for the product). Again, turf details are considered and analyzed. Available pricing data of mobile operations in the market are compared against computed details.

1.2 Scope of the Research
In view of the focused research efforts indicated above, the scope of the present study is consistent with a gist of topics of interest in the context of modern wireless telecommunication. In the existing and upcoming long term evolution (LTE) prospects of mobile communication, a huge burden of technological and economics necessities are inevitable. For example, since the beginning of the century, considering the growth profile of global telecommunications (wire-line and wireless), there has been an inevitable proliferation of a plethora of wireless devices and services that have surged, thanks to the pressures of demand from the consumer side. Especially, in such wireless communications, the scope of conceiving newer, better and smarter devices is seen due to the aspiration of
users for extensive triple services namely, voice, data and video data. In addition, such services have become heavily data intensive; as a result, enormous versions of Apps have been inculcated into the market *vis-à-vis* subscribers' choice. Correspondingly, the mobile networks that support such smart devices have become highly complex in provisioning the required technological resources that stream the data transparently with no bottlenecks. Such complexity is anticipated inasmuch as, it is a legacy of trend streaming from plain-old-telephone system (POTS) and wireline telecommunications [1.1]. Further, such data intense and App-specific services are accommodated with reliable and larger bandwidths (high-speed) reception by smart devices (handheld and/or fixed) at the subscribers end; and, in such services, mainly the overall Quality-of-Service (QoS) is a major consideration that decides the relative network performance in the service area.

Considering the underlying technological features of the network and devices as well as the associated technoeconomic profile of the service area, it has become a necessity to assess the relative performance both at the device-level as well as at the juncture of networks that enable the services provisioning. Explicitly, it implies looking at the performance issues at the device-level as well as deciding the performance of the network operations in terms of the technology adopted, economics of the subscriber-base and the subscribers' liking for the services rendered. Hence, this research work is deliberated in two parts as outlined below earlier and relevant objectives are indicated in the following sections.

1.3 Objective of the Research

Commensurate with the scope of the research outlined above, the associated tasks performed are deliberated in two parts (Part A and Part B) indicated below. Relevant contents address
the overall performance of modern mobile systems in terms of the following two major considerations:

- Hardware performance aspects of smart, handheld wireless devices (Part A).
- Technoeconomic performance of mobile network services rendered by various operators (Part B).

Hence the research issues studied and presented in this dissertation (via two Parts A and B) are explicitly stated below:

Part A : Device-level Performance Considerations

Typically, the device-level performance of smart handheld wireless units can be assessed by a set of issues related to the following:

- Overall signal (audio/video) displayed without call drop-out performance
- Power consumption and longevity of battery-life as decided by RF-circuit, baseband section and display units
- Digital signal-processing (DSP) capabilities
- Receiver sensitivity of the front-end
- Transmission efficiency of the back-end
- Signal-transport integrity of: (a) Baseband and display sections concerning time-interval error (TIE) and crosstalk issues; and, (b) RF-section EMP-EMI problems
- Software integrity (such as, Avatar system, an open-source operating system (OS) developed to condense desktop and mobile designs in future for scalable website development)
- RF-to-baseband signal transmission: Mixed-signal integrity.

The first part (Part A) of the present study focuses on three considerations on performance details relevant to signal-transport features at: (i) The baseband/peripheral and display sections and (ii) at the RF-section. Hence, three major issues addressed towards relevant hardware performance decisions are as follows:
- Time-interval error (TIE) perceived on PCB traces due to uneven signal transport delays encountered in the baseband section: Remedial pursuit via delay compensation techniques using fractal inductors (on the PCB traces) is suggested
- Crosstalk effects across the crowded and randomly patterned PCB traces at the baseband section: Relevant analysis and mitigation considerations are indicated
- Non-catastrophic EMI-EMP effects at the RF-section of smart handheld devices and related electromagnetic environmental effects (E3). Analysis and mitigation suggestions thereof are presented.

Part B: Network Performance: Technoeconomics of Mobile Services and Operations

This part of study refers to a devoted effort on the technoeconomic performance considerations pertinent to mobile network operations and services rendered. Hence, two performance indicators are proposed and appropriate matrices are derived as indicated below:

- By cohesively considering the mobile-speed technology details and relative technoeconomics of the service area, a comprehensive relative technoeconomics-based performance index (RTPI) is derived using available field data. This RTPI is indicated to supersede the so-called mobile speed index (MSI) due to PCmag.com [1.2-1.7].
- Based on customer-liking (hedonic-feeling), the pricing structure adopted by various network operators is used as another relative hedonic pricing index (HPI). Relevant hedonic concept is explained in terms of turf details and pricing strategies on mobile services adopted across the nation.

1.4 Contributions: Outcomes of the Research

The efforts deliberated in this dissertation indicate the following salient outcomes that can be regarded as essential contributions of this research:

Part A. 1: Time-Interval Error (TIE) in PCB Digital Transports
A major concern in modern smartphones and handheld devices refers to a way of mitigating the so-called *time-interval error* (TIE) perceived at high-speed digital transits along the traces of circuit-boards (rigid and/or flexible) used in baseband infrastructures. Hence, a method of adopting a planar fractal inductor configuration so as to improvise the necessary time-delay in the transits of such digital signal transmissions, the phase-jitter reduction and compensation of the TIE is studied. Experimental results are presented to evaluate the efficacy of the proposal.

Part A. 2: EMI/crosstalk Performance *vis-à-vis* Randomly Patterned Traces on the PCB at Audio/multimedia Baseband Sections of Smart Wireless Devices
In modern devices services, dense PCB traces are inevitable. They go zigzag routed on *ad hoc* basis and they are also very close to each other, proximally placed. The present study is to develop a random PCB trace-line layout model and deduce the associated near- and far-crosstalk coupling effects *via* appropriate EMI analysis. Hence, mitigation suggestions are offered.

Part A. 3: Presence of Electromagnetic Pulse (EMP) Induced Disturbance at the RF-section of Wireless Devices and Evaluating the Resulting Performance in Terms of *pros* and *cons*
Issues
In wireless communication deployment with a comprehensive smart-device portfolio (at mobile/handheld and fixed nodes), there are situations where the presence of EMP disturbances could be significant. Such disturbances are known as EMP-EMI and the ambient is described as the domain infested with electromagnetic environmental effects (E3) ambient. In such situations, suppose the wireless devices are used, where there could be an invasion of EMP-EMI that may cause non-catastrophic effects on the devices/circuit and systems inducing intense logic upsets and degradation of device/system performance.
Mostly, the RF-sections (with antennas exposed to E3) are highly susceptible for EMP-EMI invasion. In this context, the performance aspects of RF-sections in which devices need to be exclusively decided especially in smart, handheld devices and systems considering. Correspondingly, the non-catastrophic EMP-EMI is assayed and protections via lossy distributed compensating network are considered towards electromagnetic compatibility (EMC) in the present study.

Part B. 1: Performance of LTE-specific Mobile Service Profiles: Nationwide Service Deployment and Market Penetration plus Technoeconomic Considerations

Mobile service performance can be specified in terms of following techno-centric parameters (for example, as in the studies due to PCMag.com) [1.2-1.7]:

- Download speed (Mbps)
- Upload speed (Mbps)
- Mean time to first byte (ms)
- Average web download speed (Mbps)
- User datagram protocol (UDP) stream success-factor (%) in supporting voice/music and video wireless transports and accessed at smart device
- Percentage of web page completion by various service providers

Concerning the aforesaid parameters, the research endeavors addressed in this study includes the following queries and the relevant efforts exercised thereof.

What is new proposed in this study? It is opined in this study that the performance of mobile services indicated by PCMag.com (via Mobile Speed Index, MSI) is deduced [1.2-1.7] purely from techno-centric point-of-view; as such, it is not suffice, (inasmuch as no technoeconomic details are explicitly included). A more comprehensive analysis on mobile service performance should therefore, cohesively include the following: (i) Technocentric parameters (as needed); (ii) details on the economics-base of the users (such as user population, percapita income, willingness-to-pay (WP) etc.); and (iii) consequences of
A paradigm shift in users’ economics-base caused by productivity improvement across various businesses situated in the service area as a result of prolific smart-device usage causing explosive mobile traffic due to underlying business transactions. Hence, a new version of relative technoeconomics performance indicator (RTPI) is proposed in this study (in lieu of PCMag’s MSI).

**How is RTPI deduced?** The proposal to deduce RTPI is envisaged here *via* the following considerations: (i) Determining a single parameter based on: (a) technology-centric factors, (b) parameters of economics relevant to user demography, PCI etc. and (c) productivity-based indices of economics that boost the wireless operations in the service area; (ii) hence, a single parameter (RTPI) is deduced based on the logistic regression of (a), (b) and (c) as above; (iii) upper and lower-bounds on RTPI are also obtained to account for the limits of statistical variations and (iv) RTPI *versus* MSI: Comparison is done and relevant operational impacts are discussed with reference to practical available data on mobile networks nationwide and applied to specific metro-areas.

**Part B. 2:** A Dissection Study on the Existing Price Structure of Tariff Extended Commonly to Users of Feature Phones and App-intense Smart-devices

This study is done by evaluating a performance index based on customer preferences or the hedonic concept. It refers to the personal liking of the service product by the subscribers matching their *willingness-to-pay* (WP) and the network operator's *willingness-to-accept* (WA).

1.5 Motivational Considerations

The motivational impetus residing behind this research is as follow: Relevant to Part A, the topics addressed are motivated by the lack of pertinent details, and the research
information available on the crucial performance of modern wireless devices at their PCB level. Mostly, such devices belong to the latest generation of smart handheld/fixed units intensively used with significant App penetration. Hence, relevant circuits are designed at RF and baseband sections involving highly integrated active devices plus passive components. In accommodating, it is obvious the supporting infrastructure of the PCB is clustered with extensive and the randomly placed traces. As such, undo extent of crosstalk and EMI/EMP influences can be anticipated. However, no explicit details (experimental or theoretical) are available in the open literatures. Hence, the study niche as above motivated the task presented under Part A.

Not only that the performance details at device-level on the state-of-the-art wireless smart devices are yet to be comprehensively addressed. the market-related and competitive performance aspects of wireless services also need specific attention. this indicates another avenue for the underlying research, which is addressed here (at least to a limited extent) as a motivated study and presented in Part B are the topics considered.

1.6 Organization of the Dissertation and Closing Remarks
In order to cohesively present the research efforts and elaborate the outcomes, this dissertation is written with an organized set of chapters identified as follows:

Chapter I- Introduction: This (present) chapter provides an introduction to the topic of research pursued with the indication of relevant scope, objectives and motivation. The salient outcomes are also identified and the dissertation format is outlined
Chapter II- Performance Aspects of Baseband Infrastructure of Smart Wireless Devices:
Part A. 1 - Mitigating Time Interval Error in High-speed Digital Transports: This chapter is written on the topic pertinent to Part A. 1. That is, the conceived efforts of evaluating the
hardware performance of smart handheld devices via time interval error (TIE) observed in high-speed baseband digital transports at the baseband level are described along with suggestions and a proposal towards mitigation using delay compensation technique facilitated by fractal inductors.

Chapter III- Performance Aspects of Baseband Infrastructure of Smart Wireless Devices: Part A. 2 - EMI and Crosstalk Adversity Across Randomly-patterned Multiple Traces: It is devoted to present the studies of Part A. 2 on applying EMI concepts to deduce the crosstalk performance at the baseband level of smart handheld devices; that is, considering the highly dense and randomly dispersed cluster of copper traces on the PCB. the mutual EM-coupling manifesting as the crosstalk is analyzed and a corresponding performance metric is deduced. Simulation details and experimental results are presented and discussed. Possible mitigation pursuits are indicated.

Chapter IV- Performance Aspects of RF-section Infrastructure of Smart Wireless Devices: Part A. 3- EMP-EMI effects and protection scheme for devices operation under E3 situations: Relevant to EMP-EMI issues at the RF-sections of smart wireless devices, indicated as Part A. 3 are efforts, furnishing a comprehensive gist of background details; and, the performance of the device under E3 environment is assessed by estimating a performance index via simulation studies. Pertinent to the results obtained, a mitigation strategy using a lossy compensation network is described.

Chapter V- Wireless Networks Supporting Smart Devices and Services: Part B. 1- Evaluation of Technology-based Performance Index (RTPI): Commensurate with the objective indicated as Part B. 1, this chapter is written to address details on the performance of mobile networks supporting a co-diffusion of smart and traditional featured
phones/devices. Hence, a comparison of mobile services and network operations is done in terms of a mobile-speed index and a relative technoeconomics performance index. Practical turf data are considered and analyzed.

Chapter VI- Wireless Networks Supporting Smart Devices and Services: Part B. 2 - Price-worthiness Measure Deduced via Hedonic Heuristics: Pertaining to comparing the performance of mobile networks on the basis of tariff structure posted as Part B. 2, the underlying details elaborating the network performance in terms of pricing leased to subscribers subject to the performance for the services and subscriber-likings. This is a hedonic approach where the price worthiness matches the subscribers' crush for the product. Again, field data are considered and analyzed.

Chapter VII- Results and Discussions: With reference to the topics studied and analyzed in Parts A and B across the previous chapters, the observed details vis-à-vis measured and/or or computed data are compiled and systematically discussed. Conclusions are derived and the efficacy of the analyses pursued are evaluated.

Chapter VIII- Summary of the Research Study and Open-Questions for Future Studies: The gamet of the studies performed and results obtained is summarized in this chapter enumerating essential inferential conclusions. Indicated are also possible research items for future efforts identified as open-questions.

In closure, this introduction chapter (Chapter I) outlines the overall content of the dissertation and highlights the scope of the research and the objectives along with a note on the driving motivation plus the contributions made. Organization of the dissertations is also outlined in terms of the format as adopted in the ensuing chapters.
CHAPTER II

PERFORMANCE ASPECTS OF BASEBAND INFRASTRUCTURE OF SMART WIRELESS DEVICES: PART A.1 - MITIGATING TIME INTERVAL ERROR IN HIGH-SPEED DIGITAL TRANSPORTS

2.1 General

This chapter describes the study Part A.1 exercised to evaluate the performance of the hardware part of the baseband infrastructure in smart wireless devices. The specific topic addressed governs the issues concerning high-speed digital transports in the baseband section and a mitigating pursuit is proposed thereof.

A major concern in modern smartphones and handheld devices is a way of mitigating the time interval error (TIE) perceived at high-speed digital transits along the traces of the circuit-board (rigid and or flexible) used in baseband infrastructures. Indicated here is a way of adopting a planar fractal inductor configuration to improvise the necessary time-delay in the transits of digital signal phase jitter and reduce the TIE. This chapter addresses systematic design considerations on fractal inductor geometry commensurate with practical aspects of its implementation as delay-lines in the high-speed digital transports at the baseband operations of smartphone infrastructures. Experimental results obtained from a test module are presented to illustrate the efficacy of the design and acceptable delay performance of the test structure commensurate with the digital transports of interest.
2.2 Introduction

In the context of the state-of-the-art smartphones and other mobile/handheld devices, the data bit-rates adopted at baseband levels could be significantly high (~ 500Mbps); and, such streams of high-speed bits are often transferred between chips and/or various circuit nodes during baseband signal-processing, for example, between an image-sensor and an image sensor processor (ISP). To negotiate such transfers, numerous copper-traces are envisaged at the board-level formed either on a single surface or in multiple board/flex stacks. Normally, such trace-lines are of different lengths so as to accommodate ad hoc interconnections and digital transits between the pins across any two devices placed at distinct locations on the board. Further, several of these lines may run almost parallel to each other with jagged tracks. An example of such a track is illustrated in Figure 2.1. As a result of varying physical lengths of the traces, the digital bits transported from one end on any given trace will arrive at the pin of signal destination (terminated on the chips in question) with a specific extent of transmission-line dependent delay. However, this delay could be distinctly variable in each of the traces due to varying path-lengths involved and varying bit-rates of information transmitted. That is, the observed delay is specific to each line-length as defined by the associated line-parameters namely, the inductance and the capacitance per unit length and the digital signature of the information communicated. The resulting data dependent jitter (DDJ) [2.1] introduces time interval error (TIE) (also known as phase jitter) perceived invariably on the bits.

Given the spatial features (length etc.) of the high-speed line (transmission topology) and the associated data transceived, the DDJ and the associated TIE can be viewed as a class
of deterministic timing jitter. It is an undesired artifact and may cause flicker in displays (or the camera view finders etc.).

Figure 2.1: Example of copper-trace route on a typical printed circuit-board layout

![Example of copper-trace route on a typical printed circuit-board layout](image)

Figure 2.2: A set of spiral inductors configured as a planar fractal delay-line: (a) With circular- spirals and (b) square-spirals

![A set of spiral inductors configured as a planar fractal delay-line](image)
It would also affect the performance of the digital processors at large. Hence, the data pulses received with varying delays traversing different parallel lines may become unusable for applications and digital-processing efforts at the receiving devices due to the associated randomness of delay variations tied to the TIE. Therefore in practice, delay-lines are introduced in each trace to compensate for the transit-delay so that the digital data supported are displaced in time on \textit{ad hoc} basis and get synchronized at the receiving end as needed minimizing the influence of TIE.

Traditionally, at circuit-board level, physical inductors in solenoidal forms are designed, trimmed and incorporated on transmission-lines so as to offer a desired inductance (especially at RF sections) \cite{2}. However, such a conventional (solenoidal) inductor element on a circuit-board implies a complex component-accommodation task due to the bulky, three-dimensional geometry of the solenoid designed for baseband applications. Therefore, relevant option is not conducive for applications in systems like smartphones and other handheld devices encountering restricted space. Alternative to bulk solenoidal inductors, advocated in practice for space-constrained circuit-board applications is planar geometry of copper-traces (such as spiral traces) designed to emulate the desired inductance values \cite{2.3}\cite{2.4}.

Yet, considering the specific needs of modern smartphones or similar handheld gizmos \textit{vis-à-vis} emulating tailor-made extents of delays compatible for high-density traces (at baseband levels), a novel design is proposed in this chapter toward synthesizing a new class of planar inductors using fractal geometry. Shown in Figure 2.2 is the geometry of a conceivable module of distributed delay-line (DDL) based on spiral circular or square-loop geometry conforming to a fractal structure. Shown in Figure 2.3 is the photograph of the circular-spiral fractal inductance used in the present study.
Figure 2.3: Photograph of the distributed delay-line (DDL) on a PCB made based on circular spiral fractal geometry: Test module studied conforming to Figure 2.2(a)

It is surmised in this study that the fractal planar inductors can be designed to facilitate a desired delay-time in a constrained on-board area. Apart from spiral, other options such as meander line, Hilbert structure, Minkowski curve, Koch’s curve etc. can be adopted in making fractal geometry. Conceived thereof in vogue, are structures to optimize the delay-line performance *versus* space-filling considerations as warranted in baseband, high-speed operations of smartphones and/or similar devices. Associated higher order fractal curves enable design options with good space-filling properties. Most of such fractal structures have been conceived in the contexts of antenna designs and related RF units as reported in [2.3-2.11]. The underlying considerations are however, can be borrowed in conceiving fractal inductance as time-delay lines.

This chapter is organized to describe a test study on a proto-type of fractal inductor geometry illustrated in Figure 2.2(a) and Figure 2.3, which is commensurate with practical aspects of its implementation as a delay-line in high-speed digital transports at baseband
operations at the infrastructure of smartphones (and/or similar handheld devices). Experimental results obtained from the test module are presented to illustrate the efficacy of the module and realizable delay performance vis-à-vis the digital transports of interest. Thus, the scope of this chapter in essence is evolved to provide an overview of general details on digital information transmission/processing at baseband levels of modern smartphones and similar gadgets of different technologies; and, indicated the conceived fractal geometry as a plausible delay-line structure for combating the TIE.

2.3 Digital Data Format Seen at Baseband in Smartphones or Similar Devices

The physically transmitted baseband signal represents a ‘digital-over-digital’ transmission of pulse trains. In modern context of 3G through 4G considerations and associated LTE implications, the baseband data handled in the infrastructures of smartphones (and similar devices) is used at specific versions of processors with chip-designs and system-on-chips (SoCs) that accommodate generous audio, and video digital signal processing. Such processors are required to meet multi-standard integration, reduced power dissipation and facilitate extra key functions for next-generation smart, handheld devices. Relevantly, baseband processors provide efficient operations with cost-effective multimedia application-specific processing for entry-level 3G as well as next-generation/evolving 4G systems. Further, in such complex baseband chip-specific operations, the underlying applications invariably dictate the use of high-speed bit rates.

For example, considering video-processing support for 10/12 Mpixels imaging and 720p video-playback plus accelerated 2D/3D graphics, operational needs push the processor speeds up to 1GHz or even higher. Concurrently, related transmissions point out the gravity of multiple high-speed transports on the limited-space circuit-board (and/or flexible-board)
layouts. Together with the packaging designs of the components and chips on the board, the interconnections that support the said digital transports are crowded and routed haphazardly. Hence, the transmission-lines (traces) envisaged thereof are high in density (per unit area) and of varying lengths. Therefore, the digital transports end up in TIE-related issues that call for effective.

2.4 Architectural Layouts of Baseband Infrastructures

Commensurate with the types of digital processors and interconnections mandated at the baseband infrastructure, the circuit-board and/or flex-boards have to be carefully designed in practice and traces should be laid out with minimized lengths and routing to avoid not only the TIE, but also crosstalk effects. Specifically, the items of planar structure needed for TIE mitigation via inductor emulations as delay-lines are described below with relevant basics. Such planar inductors are viable substitutions for the traditional (3-dimensional) bulk solenoidal structures. the planar structures allow compact designs compatible for space-constrained warless devices.

2.5 Planar Inductors: An Overview

Variety lies in conceiving delay-line topologies and basically, planar delay-lines are made using meander-lines or spiral-line configurations. Functionally, a delay-line offers a desired extent of time-delay between circuit components. In digital domain such delay requisites have been achieved classically with phase-shifting electronic switches [2.12]. However, considering component reduction efforts and miniaturization warranted in systems like mobile devices, planar passive delay-lines are more congenial and are often resorted to. Typically, the meander-line that has a serpentine form of a closely-packed transmission-line structure can be designed with high density per square mm of circuit-board space.
Figure 2.4: Equivalent circuit representation of a planar inductor conceived with a spiral (L: Inductance, $R_s$: Inherent series resistance, $R_p$: Leakage resistance, and $C_p$: Parasitic capacitance)

Figure 2.5: A: Single circular loop; B: multiple circular-loop spiral; C: Multiple square-loop spiral and D: Meanderline
However, such serpentine delay structures may introduce spurious dispersions that signal appear along with the signal as if, it is arriving earlier than would be expected, as decided by the total electrical length of the line. This is typical with the disposition of two or more adjacent lines closely spaced; further, such proximal layout would lead to electromagnetic (EM) coupling as well and related crosstalk effects [2.13-2.14].

The adjacent line interaction and related skew on the digital waveform is also decided by the loss-tangent of the circuit-board material implicating the associated mutual capacitive and inductive effects on the signal. In order to avoid such laddering effects [2.4], a tangible pursuit is to have some planar geometry laid out in sections over a permissible area. For example, using typical circular and square spiral-lines, a few of such geometries can be interconnected into a fractal forms as illustrated earlier in Figure 2.2. Hence, proposed in the present study is a novel technique to realize a class of inductors based on a distributed set of spiral inductors framed in fractal geometry. Such a line is studied to emulate delay-line corrections in timing sensitive circuits of the baseband infrastructure in smart handheld devices.

Traditionally, as mentioned earlier, fractal structures on printed circuit-boards have been advocated in practice toward emulating fractal antennas, fractal capacitors and fractal inductors [2.3-2.11]. All such efforts aim at down-scaling/sizing the passive planar component dimensions for applications on the printed circuit-boards. In contrast with inductors of solenoidal form (of three-dimensional structure requiring large space), the fractal curve geometries are evolved in 2D with a potential solution toward compact inductance realization.
Table 2-1: Typical planar geometries (of Figure 2.5) that can be used to emulate inductance and related delay-lines

<table>
<thead>
<tr>
<th>Planar geometry (Figure 2.5)</th>
<th>Inductance value</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>( L/p = 2 \times \ln \left( \frac{5p}{w + t} \right) ) nH/cm ( \text{for } p/(w + t) \geq 5 )</td>
<td>p: Mean perimeter of the loop w: Width of the conductor trace t: Thickness of the conductor trace on PCB</td>
</tr>
<tr>
<td>B</td>
<td>( L/p = 0.0215 \times N^{5/3} \times \ln \left[ \frac{8a}{d} \right] ) ( \mu \text{H/cm} ) ( \text{for } p/(w + t) \geq 5 )</td>
<td>a = ( (R_1 + R_2)/2 ) c = ( (R_2 - R_1)/2 ) a: Mean radius N: number of turns d: Radial depth of winding</td>
</tr>
<tr>
<td>C</td>
<td>This geometry offers slightly higher value of inductance (about 10 %) more than the circular-loop or spiral</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>( L = \lambda \times L' ) ( L' = Z_W/v )</td>
<td>( Z_W: ) Characteristic impedance of the line v: Transmission velocity on the line L': Typically has a value in the order of 10 nH/cm</td>
</tr>
</tbody>
</table>

Higher order fractal curves are characterized with good space-filling properties and tend to show better efficiency than standard inductance structures having the same overall dimensions. As such, fractal-based RF structures have emerged successfully in making of capacitors, antennas and related resonating components. Fractals are a class of non-Euclidean geometries with unique attributes. A fractal design conforms to a self-similar geometry that maximizes the length or increases the parameter of a unit in emulating a desired EM characteristic within a given total surface area or volume. Fractal structures, in general, are referred to as multilevel and space-filing curves with the repetition of a motif over two or more scale sizes. With the iteration of the motif thereof, fractal structures are compactly formed. For example, as proposed in the present study, a fractal inductance can be formed as a space-filling curve in the shape of a shrunken fractal helix (Figure 2.2). And,
the resulting structure is studied of its delay-line characteristics compatible for use in the baseband infrastructure of smartphone etc. Described below are some fundamental considerations in designing simple fractal delay-line structures.

Basically planar components like capacitors and inductors can be fabricated as printed elements with small tolerances using the modern artwork of photolithographic process relevant to printed-circuit boards [2.2]. Traditional, stand-alone meander and spiral structures conceived are illustrated with descriptive notes in Table 2-1 with typical design (empirical) parameters concerning various inductor geometries illustrated. Using such basic 2D geometries, their fractal forms can be obtained with necessary analogies and tests. The fractal version of using the stand-alone units, for example, relevant to a circular spiral loop as adopted in the present study is shown in Figure 2.2(a) and 2.3. It is essentially a planar single-layer two-port structure. It can be equivalently modeled by a standard π-network to include any associated parasitic and conductive (resistive) properties such as, the board-leakage and series self-resistance of the copper traces. The overall equivalent circuit of inductance emulation with the associated parasitics is shown in Figure 2.4 with reference to a single spiral.

Figure 2.5 are typical planar geometries adopted in practice to emulate inductances on PCB that can also be used as compatible delay-lines. Indicated in Table 2-1 are pertinent details of the geometries in Figure 2.5. Relevant formulations are mostly empirical but, are very useful in practical designs.

2.6 Test Inductance/Delay-line: Description and Measurements

The test inductor for the intended delay-line application is fabricated as a single-layer copper trace structure on the top of a standard printed circuit-board using conventional
photolithographic process. As illustrated earlier in Figures 2.2 and 2.3, the test unit has eleven circular spirals with overall dimensions and details as given in Table 2-2.

Measurement studies on the test fractal inductor are performed to estimate the time-delay on a signal at a given frequency that can be achieved by considering two or more spirals at a time. Relevant circuit used for testing is shown in Figure 2.6 and the corresponding time-delay data measured is presented in Figure 2.7 as a function of the test frequency. This delay is obtained in terms of the phase-shift observed relevant to the input and output waveforms of the test circuit. Typical scope-plots are shown in Figures 2.8 and 2.9 at two exemplar measurement frequencies of 40 MHz and 80 MHz (relevant to series-connected 5 and 10 spirals in the test fractal geometry respectively). The time-delay ($\delta$) is obtained from the measured phase shift ($\phi$) across the series-connected L-structures used in the test. It is presented in normalized values with respect to the signal period ($T$) in Figure 2.7 as a function of frequency.

![Measurement setup](image)

**Figure 2.6: Measurement setup**
Figure 2.7: Measured delay ($\delta$) normalized with respect to the signal period (T), versus signal frequency (f) in MHz, (L₁ to L₁₁ etc.: Number of spirals in the fractal geometry cascaded and tested)

Table 2-2: Dimensional details of the test fractal inductor (Figures 2.2 and 2.3)

<table>
<thead>
<tr>
<th>Units of the test structure</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single spiral structure</td>
<td>Width of the trace: 1 mm</td>
</tr>
<tr>
<td></td>
<td>Number of turns: 3</td>
</tr>
<tr>
<td></td>
<td>Distance between the center and the extreme trace: 10 mm</td>
</tr>
<tr>
<td>Total elements of the fractal inductor</td>
<td>Number of spirals: 11</td>
</tr>
<tr>
<td></td>
<td>Distance between the center-to-center of the spirals: 35 mm</td>
</tr>
<tr>
<td>PCB substrate</td>
<td>Material: Fiber-glass FR 408</td>
</tr>
<tr>
<td></td>
<td>Thickness: 1 mm</td>
</tr>
</tbody>
</table>
Dielectric constant: 3.75
Loss-tangent: 0.012 at GHz spectrum

Figure 2.8: Waveforms measured at the input and output at 40 MHz for 5 spirals (L₁ through L₅ serially connected in the fractal structure)

Figure 2.9: Waveforms measured at the input and output at 80 MHz for 5 spirals (L₁ through L₁₀ serially connected in the fractal structure)
As indicated, the set of graphs furnished corresponds to measured values of the normalized delay offered by two or more spirals taken in succession. Hence, the top-most curve conforms to the case with the largest inductance due to all the eleven spirals cascaded; and, the bottom-most curve corresponds to the last-two spirals (L10 and L11) of the fractal geometry. It can be consistently observed in Figure 2.7 that the variation of time-delay (or implicitly, the phase-shift) increases monotonically with signal frequency. However, the test curves also show peaks and valleys at certain frequencies implying possible resonances due to the associated parasitic capacitances of the system and related Q factors.

2.7 Remarks Inferential

The prototype studies presented here indicate the possibility of realizing a class of fractal inductors with the potential to obtain a required time-delay for use in baseband architectures that support delay-sensitive high-speed transmissions of digital waveforms. The fractal curve geometries are amenable for fabrication on smaller chip area as pointed out in [2.15-2.18]. However, relevant studies leave open-questions as regard to the following: (i) The choice of fractal curve geometry, (ii) estimation of element parameters (inductance and resistance values), (iii) deducing the parasitic effects and, (iv) fabricating the test fractal structure within the available space.

2.8 Closure

Based on the novel concept structure and achievable delay demonstrated in the prototype model studied, more work can be exercised as regard to other fractal structures such as square-loop version, Koch fractal geometry, Hilbert fractal curve etc. Fabrication issues like ground-plane/ground counterpoise effects and circuit-board layer considerations need more careful studies. Relevant work is suggested as an effort for future studies.
CHAPTER III

PERFORMANCE ASPECTS OF BASEBAND INFRASTRUCTURE OF SMART WIRELESS DEVICES: PART A. 2 - EMI AND CROSSTALK ADVERSITY ACROSS RANDOMLY-PATTERNED MULTIPLE TRACES

3.1 General

Focused effort of research deliberated in this chapter is designated as Part A. 2, which refers to deducing the electromagnetic interference (EMI) and related crosstalk implications seen across densely-packed cluster of traces forged on the printed circuit board (PCB) in the baseband section of smart wireless devices.

In the state-of-the-art wireless devices accommodating a dense layout of copper traces on the associated PCB (single and/or multi-layered), is inevitable. Relevantly, considering the baseband level of audio and/or multimedia sections in smart handheld devices, ad hoc routing of traces, patterned zigzag on the printed-circuit board (PCB) often prevails; hence, a unique modeling strategy is required to address the extent of crosstalk victimization of trace-lines located proximally to the aggressing signal paths. Hence, the present study is devised to address and evaluate the performance integrity of a smart device with a PCB at the baseband section infested with a random cluster of traces; and, the associated high-speed digital transport on a trace (called aggressor) is assumed to induce unwanted crosstalk across victim traces in the vicinity. Relevant probabilistic attributes of randomly-dispersed trace patterns on the PCB invoking nondeterministic
values of crosstalk are considered in this study; and, corresponding near- and far-end cross-talk (NEXT and FEXT) values are estimated. Such details can lead to compatible suggestions on crosstalk mitigation pursuits appropriate for baseband sections supporting high-speed digital transports. Results gathered from experimental studies are presented and corresponding theoretical estimates of NEXT and FEXT are cross-validated.

3.2 Introduction

The scope of this chapter is to devise a method to evaluate the performance integrity of a smart handheld device having a printed-circuit board (PCB) at its baseband section, infested with a random cluster of traces [3.1-3.17]. The associated transport of high-speed signals (audio and/or multimedia) on a specific trace (called, “the aggressor”) and the corresponding high-speed digital signal-processing (DSP) would invariably culminate in causing unwanted crosstalk across nearby traces (dubbed as “victims”) commensurate with the associated electromagnetic (EM) coupling between the lines.

The probabilistic attributes of such randomly-dispersed trace patterns on the PCB invoke nondeterministic values of near- and far-end crosstalk (NEXT and FEXT) values in the victim traces [3.2] [3.4] [3.7-3.9]. However, knowledge on such parameters would lead to compatible suggestions and possible design-reviews concerning mitigation pursuits at baseband sections of smart handheld wireless devices.

In the present study, experimental studies are performed on a test PCB as well as the theoretical estimates of NEXT and FEXT are made and cross-validated with measured values. The theoretical heuristics proposed, computational effort exercised and experimental results obtained thereof are cohesively presented to portray the efficacy of the study and its usefulness. This chapter is organized as in sections as follows: In the following section
(section 3.3), necessary background details are furnished as regard to modern wireless handheld devices vis-à-vis the digital-signal transport characteristics at their baseband sections supported on a cluster of PCB traces. In Section 3.4, an overview on the electromagnetic interference (EMI) across the random cluster of PCB traces is presented. Furnished in Section 3.5 is a statement on the theoretical heuristics pursued along with descriptions on crosstalk estimation under discussion. In Section 3.6, the inter-trace coupling factor (F) is defined and evaluated via EM field considerations. For analysis and computational study (and eventual experimental efforts), a test layout of PCB is described in Section 3.7. Presented in Section 3.8 is the analytical framework pursued. Measured and computed data are presented and elaborated in Section 3.9. Lastly, in Section 3.10 closing remarks are furnished along with inferential details and suggestions on cross-talk mitigation vis-à-vis PCB configurations.

3.3 Digital Signal Transport at Baseband Section of Wireless Handheld Devices

In modern context, the gamut of modern wireless devices supports a variety of diverse data applications (DDA) with outputs culminating in audio, video and alphanumeric displays. Specifically, considering the smart handheld devices in vogue, the terminal phase of information in such devices invariably refers to an infrastructure of screen-display and/or audio output [3.17]. These displays/outputs normally stem from a host of baseband-signal processed and conveyed via a densely-packed set of copper-traces routed on rigid and/or flexible PCB frames (single or multilayered) to the terminal sections of a touch-pad screen, loudspeaker and microphone devices. Thus exists between signal-processing electronics and final display-sections in handheld wireless devices are scores of transmission-lines manifesting as copper-traces that connect the source nodes and terminal points as necessary;
and, these traces often meander randomly (to and from the sending and receiving ends). Furthermore, they are mostly packed to a very close extent with a format of parallel and/or nonparallel fan-outs often seen as two-dimensional (2D) routing patterns. Also, such traces may prevail on a single-layer PCB and/or they could be stacked across multiple layers as necessary.

Considering, the plan of layout and topology of traces on a PCB as outlined above, they could in general, be classified into two types: (i) They may represent a simple pattern with each trace being parallel to others, but all traces being highly proximal to each other. (ii) Alternatively, such traces though non-crossing, may denote a complex pattern with traces routed zigzag with no deterministic rule, but decided mostly on ad hoc based connectivity compatible for the required signal-flow. (In case, if some traces are required to cross each other, they would be kept separated layer-wise, by resorting to multi-layered PCBs).

Exclusive to baseband sections of handheld devices, the types of traces on a PCB described above are also required to support digital signal transports at very high bit rates. For example, with reference to state-of-the-art smartphones and other mobile/handheld devices, the data bit-rates adopted at baseband levels could be significantly high (~ 500 Mbps); further, such streams of high-speed bits are often transferred between chips and/or various circuit nodes during baseband signal-processing, for example, between an image-sensor and an image sensor processor (ISP) [3.17]. To negotiate such transfers as mentioned earlier, an extensive count of copper-traces is envisaged at the board-level (formed either on a single surface or in multiple board/flex stacks). Further, these trace-lines could be of different lengths so as to accommodate the digital transits as necessary between the pins of any two devices placed at distinct locations on the board.
The physically transmitted baseband signal in essence represents a "digital-over-digital" transmission of pulse trains. In modern context of 3G through 4G considerations and associated LTE implications, the baseband data handled in the infrastructures of smartphones (as well as in similar devices) is relevant to specific versions of processors with chip-designs and/or system-on-chips (SoCs) that accommodate generous audio, and video digital signal-processing (DSP) schedules. Such processors are further required to meet multi-standard integration, reduced power dissipation and facilitate extra key-functions for the next-generation of smart, handheld devices. Relevantly, the associated baseband processors provide efficient operations with cost-effective, multimedia application-specific processing for the entry-level 3G as well as next-generation/evolving 4G systems.

In those complex baseband infrastructure and chip-specific operations mentioned above, the underlying applications invariably dictate the use of high-speed bit rates, which are placed on proximally located traces crowded and routed almost randomly as necessary. For example, considering video-processing support for 10/12 M-pixels imaging and 720p video-playback plus accelerated 2D/3D graphics, the operational needs push the processor speeds up to 1GHz or even higher. Concomitantly, related electrical transmissions of data point out the gravity of multiple high-speed transports on the limited-space circuit-board (and/or flexible-board) layouts. The underlying issue arising thereof can be summarized as follows: Together with the packaging designs of the components and chips placed on the board, the interconnections that support the said digital transports would invariably be in juxtapositions with close proximity; as well as, they could be routed and in transit unpredictably as necessary. Also, the transmission-lines (traces) deployed would occupy significantly of high density (per unit area) on the PCB and of varying lengths.
The digital transports in PCB contexts of baseband infrastructure described above often culminate in posing unique crosstalk issues that call for effective mitigations [3.4,3.9,3.12,3.14-3.16]. That is, considering the PCB layouts with the disposition of two or more adjacent lines closely spaced, the proximity of such traces as indicated earlier would lead to a strong EM coupling between them. That is, the EM forces caused by the time-varying signal transport on the traces would interact across adjacent lines leading to EMI. It amounts to crosstalk meaning unintentional transfer of signal waveform signatures from one-line (named earlier as the aggressor and also known as the infector) to neighboring lines (designated earlier as victims). Such observed crosstalk effects are largely decided by the extent of induced electromagnetic forces decided by relative signal voltage, $v(t)$ and current $i(t)$ entities, transported on the traces. Further, the traces depict a set of transmission-lines with distributed resistive, inductive and capacitive characteristics; and, the lossy dielectric characteristics of the circuit-board material supporting the traces will also play a role in deciding the EM propagation characteristics of the signal transmission implicating signal attenuation, as well as dispersive capacitive and inductive effects on the signal transported.

3.4 EMI on the Cluster of PCB Traces: An Overview

At system-level perspectives, a “trace” on a PCB refers to a transmission-line segment of an overall interconnection mostly comprised of a driver, the associated packages, one or two connectors plus vias etc. A typical wire-board package with traces fanning out is illustrated in Figure 3.1.

Predicting EMI proliferation on the PCB and the associated coupling behavior between the traces for the purpose of evaluating the resulting crosstalk is rather cumbersome especially, when the traces are arbitrarily off-set, laid non-parallel and randomly-spaced with
respect to each other. Exact analytical solutions are not in general easy and mostly impractical. However, approximate modeling and deducing simulated results pertinent to simple, parallel topology of traces have been obtained in the past [3.10, 3.11].

Figure 3.1: Trace clusters fanning out on a PCB: For example, in the baseband infrastructure of a handheld device

Assessing crosstalk influence quantitatively becomes even more difficult when the signals traversing the traces correspond to high-speed digital waveforms with sharp rise-time characteristics. The corresponding inter-trace EM coupling and crosstalk may introduce time-interval-error (TIA) in pulsed waveforms due to spurious dispersion of EM energy, as indicated by the authors elsewhere in [3.17].

3.5 Crosstalk Estimation: Statement of the Problem and Description

In view of the state-of-the-art aspects of crosstalk issues vis-à-vis PCBs exclusive to modern handheld wireless devices, the present study is indicated to address such problems pertinent to densely-packed traces on PCBs, when the lines are either parallel and/or laid out
in zigzag patterns with the lengths of line-segments being of random values; further, all the lines are assumed to be designed so as to support high-speed, sharp rise-time pulsed waveforms, which are likely to cause significant EM energy dispersions [3.12, 3.17] in the composite PCB structure with metallic traces laid on dielectric board; and, the resulting pervasive electromagnetic interference (EMI) on the board would manifest as crosstalk in victim traces.

Figure 3.2: A parallel set of hypothetical victim traces \( \{ V_T \}_{v = 1, 2, \ldots} \) and an aggressor trace \( (A_T) \) on a PCB. The terminal nodes of the aggressor and the victim are shown with the associated voltages, \( \{ v_s, u_s \} \) and \( \{ v_L, u_L \} \) respectively corresponding to source and load-ends

<table>
<thead>
<tr>
<th>Hypothetical set of aggressor victim pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Proximal turning-point in the victim trace convex to the aggressor</td>
</tr>
<tr>
<td>![Diagram A]</td>
</tr>
<tr>
<td>B: Off-set turning-point in the victim trace concave to the aggressor</td>
</tr>
<tr>
<td>![Diagram B]</td>
</tr>
</tbody>
</table>
Figure 3.3: Set of possible layouts of aggressor (A_T) and victim (V_T) traces showing their relative, non-parallel geometrical dispositions on the PCB with one, more or zero turning-points seen on the victim traces

The generic layout of a pair of traces on a PCB that encounter crosstalk problems as relevant to this study is illustrated in Figure 3.2. The aggressor-victim pair need not imply
parallel traces. In general, such pairs can be non-parallel as illustrated in Figure 3.3. Further, illustrated in Figure 3.3 is a more comprehensive illustration of multiple victim traces \( \{ V_T \} \) infected by an aggressor, \( A_T \). In general, all such traces, may pose statistically undulating paths and as such, each trace can be characterized by a root-mean squared (RMS) value of undulation geometry observed on the 2D-plane of the PCB. Hence, shown in Figure 3.4 is a value \( X_A \) of such RMS value for the aggressor, \( A_T \); and, the set \( \{ X_V \} \) denotes corresponding values for the victim set \( \{ V_T \}_{v=1,2,...} \). (Note: The victims are identified by the index, \( v = 1, 2, 3, \ldots \)). Commensurate with the scope of the present study outlined above, the underlying objectives aim at deducing a coupling index that would measure implicitly the induced electric (\( E \)) and magnetic (\( H \)) field components in the victim traces as a result of high-speed signal transported on an aggressor line expressed in terms of the time-varying voltage, \( v(t) \) and current \( i(t) \) functions. If the values of \( E \)- and \( H \)-field components are estimated, it is proposed here that they would implicitly allow inferring the associated EMI and hence lead to deducing the relevant crosstalk coupling coefficient of interest. The traditional EMI and crosstalk modeling in such ambient would involve determining the inductive (\( L \)) and capacitive (\( C \)) effects perceived on the traces on the basis of reactive (mutual) impedance considerations [3.6].
Figure 3.4: Randomly-patterned set of victim traces \( \{V_T\}_v = 1, 2, \ldots \) disposed with respect to an aggressor trace (\( A_T \)) on the PCB. The entities \( X_A \) and \( \{X_V\} \) denote respectively, the RMS values of random geometrical undulations of the respective traces on the PCB 2D-plane.

However, in such L- and C-based EMI evaluation (and in relevant crosstalk estimation), the underlying estimates may become computationally intensive, inasmuch as the associated inductive and capacitive effects have to be ascertained (mostly numerically) across the extensive framework of grids within which, the victim traces and the aggressor are situated. In other words, the underlying inter-trace coupling when viewed in terms of classical inductance and capacitance considerations implies reactive influence (that is, voltage-current relational phenomenon in Kirchhoff's sense) experienced across a huge number of
distributed set of nodes and loops modeled on a two-dimensional grid depicting the 2D-pattern of meshes, each with characteristics transmission-line features of the traces involved.

However, as mentioned earlier, it is proposed here that the coupling index (F) of interest can be alternatively defined (in lieu of L and C perspectives) via the assessments of E and H field components across the framework of victim traces due to time-varying signal voltage and current entities. Corresponding coupling index (F) can be expressed as follows [3.18]:

\[
F = \sum_{k=1}^{K} |J(k)| \cdot \Delta A(k)
\]

(3.1)

where \( |J(k)| \) denotes the magnitude of displacement current density (in A/m\(^2\)) at the center of \( k^{th} \) mesh of the matrix, \( K: [I \times J] \) depicting the complete victim trace layout on the PCB. That is, considering the area wherein the victim traces reside on the PCB, it is divided into \( K \) meshes as shown in Figure 4.5; and, \( \Delta A(k) \) is the area (in m\(^2\)) of the \( k^{th} \) mesh with the coordinate \((i, j)\) in question. Hence, F in equation (4.1) represents the gross influence of all displacement currents perceived as a result of E- and H- field forces on the PCB summed over the entire victim-trace layout.
Figure 3.5: A matrix $K: [I \times J]$ meshes conceived on the 2D-plane of the PCB layout infested with victim traces.

It is shown in [3.18], such an approach towards deducing EMI effects via equation (3.1) is as good as 98% of the results obtained by traditional capacitance-inductance estimation method. But, the advantages of using the approach via equation (4.1) are as follows:

- It is independent of the position of victim traces across the layout surface
- It is computationally less complex; (and, traditional finite-difference, finite-element or moment method (FDM, FEM and MM methods) can be adopted to determine numerically the associated $E$- and $H$- components of the interference leading to the estimation of the coefficient, $F$
- It is highly suitable for the random pattern of the victims versus aggressor lines; and, details as regards to exact dispositions of Kirchhoff's nodes and loops deciding the [L] and [C] are not per se, required [3.19-3.21].

In view of the above, the present study is focused on deducing the coefficient (F) via E- and H-field components so as to specify the near- and far-end crosstalk (NEXT and FEXT) implications experienced in a typical complex trace-pattern, for example, as illustrated in Figure 3.5. The notions of [3.18] and equation (3.1) are used, but significantly modified in this study specifically focused on PCB layouts of handheld wireless devices.

The crosstalk-induced coupled currents on the victim lines manifest as NEXT and FEXT. In a simple pair of parallel traces (with matched terminations), the aggressive (driven) line (1) would electromagnetically couple with the victim (un-driven) line (2), via two EM considerations namely, (i) the Columbic force field due to charges on the lines (traditionally implied as capacitive (C) effects); and, (ii) Faraday's induction force field due to time-varying magnetic coupling between the lines, commonly regarded as inductive (L) effects. A pair of inductance and capacitance (m × n) matrices is normally indicated to analyze the underling EMI. For example, in the case of an aggressor-victim pair of lines (1 and 2), relevant L-C matrices can be written as follows [3.19-3.21]:

\[ [L] = \begin{bmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{bmatrix} \quad \text{and} \quad [C] = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \]

(3.2)

where \( L_{11} \) or \( L_{22} \) implies the self-inductance (henry per unit length) of lines 1 or 2; and, \( L_{12} \) or \( L_{21} \) line denotes the mutual inductance (henry per unit length) between the lines, 1 and 2. Similarly, \( C_{11} \) or \( C_{22} \) depicts the self-capacitance (farad per unit length) of the lines 1 or 2 (measured with respect to ground) and \( C_{12} \) or \( C_{21} \) is the mutual capacitance (farad per unit length).
length) between the lines 1 and 2 per unit length. Correspondingly, the near- and far-end
crosstalk voltages induced can be written as follows:

\[
V_{\text{NEXT}} = \frac{v_s}{4} \left[ \frac{L_{12}}{L_{11}} + \frac{C_{12}}{C_{11}} \right]
\]

\[
V_{\text{FEXT}} = \frac{v_s}{4} \left[ \frac{L_{12}}{L_{11}} + \frac{C_{12}}{C_{11}} \right] \times \left( \frac{\ell(L_{11}C_{11})^{1/2}}{2t_r} \right)
\]  

(3.3)

where \(v_s\) is the source voltage impressed on the aggressor line (Figure 3.2); and, \(\ell\) is the
length (in m) of the trace-lines; further \(t_r\) is the rise-time (in s) of the input signal, \(v_s(t)\); and,
\(\ell(L_{11}C_{11})^{1/2}\) denotes the propagation delay (in s) encountered along the line of length, \(\ell\)
meters.

3.6 Inter-trace Coupling Factor (F) Estimation \textit{via} EM Field Considerations

\textit{In lieu} of the traditional way of estimating the inter-trace coupling coefficient in
terms of L and C considerations indicated above, as mentioned earlier the present study is
devised to formulate an alternative approach based on EM field parameters to deduce the
crosstalk related coupling across PCB traces. It is surmised that the proposed method is more
appropriate for randomly patterned traces. Relevant underlying heuristics are as follows:
Consider a PCB layout with a victim trace (\(V_T\)) and a noise (aggressor) trace (\(A_T\)) as
illustrated earlier in Figure 3.2. The crosstalk coupling between \(V_T\) and \(A_T\) is decided by an
EM emission map overlapping \(V_T\) and \(A_T\) across the domain in a layout on a two-
dimensional plane layout.

The traces (\(V_T\) and \(A_T\)) on the PCB in practice can be represented by segments joined
up by a set of turning-points (Figures 3.3 and 3.4). The number of such turning-points (N)
and their locations on the PCB would depend on the electronic interconnections required as
necessary. The coordinates of these turning-points are however, known \textit{a priori} and therefore, deterministic. That is, they represent locales with defined coordinates on the 2D geometry of the PCB layout designed. Further, the terminal points (two for $V_T$ and two for $A_T$) of the traces are also deterministically specified at known (predefined) coordinates; and, in general, all traces are assumed to be of same width (w meters). Given the trace details as above, the study in hand has the following motives:

a) To determine the $E$- and $H$-field components of the EMI on the trace domains of interest and knowing these components at the defined locations of turning-points

b) To calculate the overall resulting coupling index, $F$ for any specified victim trace with respect to an aggressor trace

c) To assess the corresponding NEXT and FEXT levels at the terminal nodes

d) To verify experimentally the theoretical heuristics proposed and computational assessments made

e) To seek and suggest methods to mitigate (reduce) the crosstalk coupling involved

3.7 Test PCB Layout for Analysis, Computational and Experimental Study

To illustrate the method of assessing the NEXT and FEXT for a random pattern of trace layout, the test PCB plus the overlaid traces on it considered is shown in Figure 3.5. Suppose the traces as shown are such that the victim traces are laid to join fixed terminals $\{P_1\}$, $\{P_2\}$ and such traces are assumed to be confined within a certain rectangular area. The aggressor trace is sourced by $v_s(t)$, normally a high-speed pulsed voltage, that produces EM-field components extended into the vicinity and invades the entire domain of victim traces.

The objective of the study is as follows: (i) To analyze the associated electromagnetics and infer the $E$- and $H$-field components specifically at the turning-points of interest; (ii) to assess thereof, the NEXT and FEXT levels in any given victim trace; and
(iii) hence, to realize eventually a layout of victim traces with minimized NEXT and FEXT levels as an EM compatible alternative to the original PCB design.

Figure 3.6: Victim and aggressor traces: Terminal nodes and turning-points

Figure 3.7: Set of victim (P₁ - P₂) and aggressor (Q) trace-layouts each with varying number of turning points (N)

In addition to a typical aggressor versus victim pair node-to-node EM coupling illustrated in Figure 3.6, possible examples of victim traces positioned between start and end nodes, P₁-P₂ with varying number (N) of turning-points are shown in Figure 3.7. The layout (a) in Figure 3.7, with the victim (P₁ - P₂) having no turning-points is taken as the reference and assuming the standard case of parallel traces, the NEXT and FEXT can be deduced deterministically via coupling matrix relations of equations (3.2) and (3.3). That is, in terms of [L] and [C] of
equation (3.2), the following EM-field relations can be written toward inductive (IC) and capacitive coupling (CC) influences:

\[
[v(t)]_{IC} = -[L] \times \frac{d[i(t)]_{IC}}{dt} \quad (3.4a)
\]

\[
[v(t)]_{CC} = \frac{1}{[C]} [i(t)]_{CC} dt \quad (3.4b)
\]

where \( v_{IC} \) and \( v_{CC} \) are voltages induced on unit length of the victim due to inductive and capacitive effects respectively. Corresponding relations written in terms of magnetic (\( H \)) and electric (\( E \)) fields are given by:

\[
v_{IC}(t) = -\mu[L] \times \frac{d[H(t)]_{IC}}{dt} \quad (3.5a)
\]

\[
v_{CC}(t) = \frac{\varepsilon}{[C]} \left[ \frac{d[E(t)]_{CC}}{dt} \right] dt = \frac{\varepsilon}{[C]} E_{CC}(t) \quad (3.5b)
\]

Hence, the net superimposed coupled EM-field relation is given by:

\[
[v_{IC} + v_{CC}] = \left[ -\mu[L] \times \frac{d[H(t)]_{IC}}{dt} \right]_{HC} + \left[ \frac{\varepsilon}{[C]} E_{CC}(t) \right]_{CC} \quad (3.6)
\]

Suppose the turning-points (nodes) on the victim trace appear randomly located with respect to the aggressor trace so that, for a given set of \([L] \) and \([C]\). The corresponding \( E \)- and \( H \)-components can then be specified as perturbed entities along the test traces. The fractional change in coupling influence thereof can be written as follows:
\[
\frac{\Delta F}{F} = \frac{\partial}{\partial t} [\Delta \mathbf{H}(t)] + \frac{\Delta \mathbf{E}(t)}{\mathbf{E}(t)}
\]

(3.7)

3.8 Analysis

Consider the total space (\(\Omega\)) of PCB layout wherein, as indicated earlier there could be a number of traces routed randomly on \textit{ad hoc} basis, but placed proximal to each other. For example, a hypothetical layout on a given single layer is illustrated in Figure 3.8 (where no physical crossings are assumed to be present).

Suppose AA' denotes the aggressor (infector or driven trace) supporting a trail of high-speed binary information along time-scale. Let YY' be a vertical line-of-separation on the PCB assumed to bifurcate the domain \(\Omega\) into two regions, \(\Omega_1\) and \(\Omega_2\) denoting the near- and far-end sides respectively as shown. With reference to the spaces \(\Omega_1\) and \(\Omega_2\), and in terms of classical reactive coupling heuristics, each space has its own capacitive \([C]\) and inductive \([L]\) coupling matrices. These matrices can be alternatively viewed via electric \((\mathbf{E})\) and magnetic field \((\mathbf{H})\) components that emanate from the common aggressor line AA' and interfering on (or placing crosstalk into) the set of victim lines bb', cc', dd' etc. That is, relevant to \(\Omega_1\) and \(\Omega_2\), the capacitive and inductive couplings can be implicitly specified in term of the associated \(\mathbf{E}\)- and \(\mathbf{H}\)-field components respectively by a set of matrices as follows: \(\Omega_1 \Rightarrow [\mathbf{E}]_1\) and \([\mathbf{H}]_1\) and \(\Omega_2 \Rightarrow [\mathbf{E}]_2\) and \([\mathbf{H}]_2\).
Correspondingly, each of $\Omega_1$ and $\Omega_2$ can be attributed with certain levels of susceptibility, $S_1$ and $S_2$ respectively to crosstalk on victims as a result of EM excitation stemming from the aggressor trace, AA'. In other words, the EM-field induced due to the signal-flow in AA' (aggressor) will cause a trail of susceprtance to EMI point-by-point on the victims; and, relevant values can be denoted as $\{S_i\}_1$ and $\{S_j\}_2$ respectively in $\Omega_1$ and $\Omega_2$ as shown for example, in Figure 3.9, assuming an exclusive scenario of the victim bb' versus the aggressor AA'. For the purpose of analysis, the domains $\Omega_1$ and $\Omega_2$ in Figure 3.9 are further divided into grids (meshes) as illustrated in Figures 3.10 and 3.11. Further, specific to the domain $\Omega_1$, the coordinate of a mesh is $(x_m = 1, 2, ..., M, y_v = 1, 2, ...)$.
Figure 3.9: Illustration of bifurcated domains $\Omega_1$ and $\Omega_2$ with the set of susceptibility indices $\{S_i\}_1$ and $\{S_j\}_2$ respectively; and, $\alpha$ and $\beta$ denote NEXT and FEXT levels respectively on the victim trace.

Likewise, for the domain $\Omega_2$, the coordinate of a mesh is specified as: $(x_n = 1, 2, \ldots, N, y_v = 1, 2, \ldots)$. And, the interfering field vectors $E$ and $H$ are assumed to vary mesh-by-mesh along x and y directions, point-by-point. Therefore, considering, the nodes representing the grids in the matrices of $\Omega_1$ and of $\Omega_2$, each node can be prescribed with a crosstalk susceptibility value $(S_n)1$ and $(S_n)2$ in $\Omega_1$ and $\Omega_2$ respectively. Further, the presence of $\{S_m\}_1$ and $\{S_n\}_2$ are denoted for example, as point-by-point values on the victim trace $bb'$ in Figure 3.10 with respect to the aggressor $AA'$.

Therefore, considering the nodes at the extremities of the victim $bb'$, when $m = 1$ (in $\Omega_1$), $\{S_m = 1\}_1$ denotes the NEXT; and, when $n = N$ (in $\Omega_2$), $\{S_n = N\}_2$ refers to the FEXT. Further, the elements of $\{S_m\}$ and $\{S_n\}$ are taken as normalized values (between 0 to 1); and, the normalization is done with respect to the signal (or EM-field) level enforced (by the signal) at the sending-end of the aggressor line. In moving along the victim line (say $bb'$), the step-by-step one-dimensional spatial progress of crosstalk influence (from mesh-to-mesh)
can be specified by the associated randomness of EM-field influence (interference) on the victim. Relevant heuristics are as follows:

Figure 3.10: Point-by-point representation of the susceptibility indices at nodes specified within each mesh of the matrix drawn on the 2D-plane of victim layout

Figure 3.11: Illustration of hypothetical sets \{m \times v\} and \{n \times v\} meshes prescribed for \(\Omega_1\) and \(\Omega_2\) respectively. (The victim traces are denoted by the index v both in \(\Omega_1\) and \(\Omega_2\) as identified in the text)

Relevant to the 2D framework of victim traces on the PCB, as indicated earlier, the media-line YY’ divides the 2D domain into two sections, \(\Omega_1\) and \(\Omega_2\) corresponding to the NEXT and FEXT regions respectively. Further, these sections are divided into mesh sets of
\{m \times v\} and \{n \times v\} meshes as illustrated in Figure 3.11. Each node corresponds to a mesh, where the EMI-based E- and H-fields induced render the nodes susceptible for crosstalk. The EMI coupling influence across the traces and the resulting susceptibility at each node to crosstalk is specified by \((S_{m, v})_{1}\) and \((S_{n, v})_{2}\) for the domains \(\Omega_{1}\) and \(\Omega_{2}\) respectively.

Considering an \(m^{th}\) node in \(\Omega_{1}\) and an \(n^{th}\) in \(\Omega_{2}\), the EMI coupling-influence proliferating (along such nodes in the row) conforms to a Poisson process; and as such, the dynamics of susceptibility values at \((m + 1)^{th}\) and \((n + 1)^{th}\) nodes can be written in terms of corresponding values at \(m^{th}\) and \(n^{th}\) nodes can be expressed as step-by-step proliferation as follows:

\[
(S_{m + 1, v})_{1} = \lambda \left[ 1 - \exp(-\lambda t) \right] (S_{m, v})_{1} \quad (3.8a)
\]

\[
(S_{n + 1, v})_{1} = \lambda \left[ 1 - \exp(-\lambda t) \right] (S_{n, v})_{2} \quad (3.8b)
\]

where \(\lambda\) is a field-decay constant along the row (that is, \(x\)-direction and \(t\) is the instant of occurrence of the interference).

Similarly, the progress of EMI coupling along the column of meshes (in the \(y\)-direction, that is along the meshes at \((v = 1, 2, \ldots)^{th}\) locations can also be written in terms of a Poisson process dynamics. However, the \(x\)- and \(y\)-directed coupling events can be regarded as two independent spatiotemporal processes over the 2D-neighborhood in question. Hence, the dynamics of the susceptibility index \((S)\) assumed as a random variable can be written in terms of the following two independent stochastic, partial differential equations. With the coordinates of nodes designated as \((x_{m, y_{v}})\) and \((x_{n, y_{v}})\) for \(\Omega_{1}\) and \(\Omega_{2}\) respectively, relevant equations are as follows:

Along the \(x\)-direction:
\[
\frac{\partial S(t; x_m, y_v)}{\partial t} = S(t; x_m, y_v) [G - hS(t; x_{m+1}, y_v)]
\]

(3.9a)

\[
\frac{\partial S(t; x_n, y_v)}{\partial t} = S(t; x_n, y_v) [G - hS(t; x_{n+1}, y_v)]
\]

(3.9b)

And, a similar pair of partial differential equations can be specified for y-direction also. In
equation (3.9) G denotes the spatial proliferation rate of EMI and h is a local coefficient that
weights the newly perceived EMI coupling of \((m + 1)\)th or \((n + 1)\)th node due to the dynamics
of proliferation.

The aforesaid differential equations refer to logistics growth models for the
spatiotemporal evolution of EMI-induced susceptibility levels at the nodes considered.
Relevant solutions assume the sigmoid format. That is, the susceptibility levels implicitly
declare corresponding probabilities of EMI prevailing at the nodes along the grid; and, they
can be written as sigmoidal solutions of equation (3.9) as follows [3.17] [3.22, 3.23].

\[
p(x_m, y_v)_{|\Omega_1} = \frac{1}{2} \left[ 1 + \tanh \left( \frac{S_m^0 + S_n^{(1-\theta)}}{2} \right) \right]
\]

(3.10a)

and

\[
q(x_n, y_v)_{|\Omega_2} = \frac{1}{2} \left[ 1 + \tanh \left( \frac{S_m^{(1-\theta)} + S_n^0}{2} \right) \right]
\]

(3.10b)

where \(\theta\) is the fraction equal to the ratio of the fractional node population in \(\Omega_1\) with respect
to the total nodes across the entire framework of \(\Omega_1\) and \(\Omega_2\); that is, \(\theta = \) (Number of nodes
in \(\Omega_1\)/Total number of nodes in \(\Omega_1\) and \(\Omega_2\)).

The aforesaid notions and results can be arrived at by following the probabilistic-
theory of uncertainty applied to the random invasion of crosstalk proliferation in the
domains of interest. Relevant outline is as follows: Proportion of net EMI-induced influences in the regions \( \Omega_1 \) and \( \Omega_2 \) can be deduced on the basis of statistical uncertainty of the EM coupling involved across victim traces due to the signal transits of the aggressor line. Given that the finite number of total nodes in the entire framework of \( \Omega_1 \) and \( \Omega_2 \) is \( \mu_T \) and those victimized are (\( \mu_1, \mu_2, \mu_3 \ldots \) etc.) with distinct susceptibility levels 1, 2, 3,…etc., the resulting statistical extent of uncertainty (\( \theta \)) of EMI coupling in \( \Omega_1 \) and \( \Omega_2 \) can be written in terms of the associated entropy (\( \zeta \)) considerations expressed in Bernoulli forms as follows [3.24]:

Referring to \( \Omega_1 \), corresponding \( \zeta_1 \) along x-direction can be specified \textit{via} entropy functional as follows:

For the region \( \Omega_1 \),

\[
\zeta_1 = \frac{1}{\mu_T} \ln \left[ \frac{\mu_T!}{\mu_1! \mu_2! \ldots \mu_M!} \right]
\]  
(3.11a)

 Likewise, for the region \( \Omega_2 \),

\[
\zeta_2 = \frac{1}{\mu_T} \ln \left[ \frac{\mu_T!}{\mu_1! \mu_2! \ldots \mu_N!} \right]
\]  
(3.11b)

Therefore, \( \theta \) indicated above would correspond to the ratio \( \zeta_1/\zeta_2 \) of relative uncertainty (of EMI influences) associated in the regions \( \Omega_1 \) and \( \Omega_2 \); and, \( \zeta_1/\zeta_2 \) approximately reduces to, \( \theta = (\text{Number of nodes in } \Omega_1/\text{Total number of nodes in } \Omega_1 \text{ and } \Omega_2) \).

Correspondingly, relevant to the randomness of trace-layout, the following (normalized) coefficients (0 to 1), R_N and R_F can be attributed to NEXT and FEXT in the \( v^{th} \) victim of \( \Omega_1 \) and \( \Omega_2 \) respectively consistent with the relations in equation (3.10):
\[(R_{N})_{V} = \frac{1}{2} \left[ 1 + \tanh \left( \frac{\sum_{m=1}^{S_{m}=1} + \sum_{n}^{(1-0)}}{2} \right) \right] \Omega_{1} \]  \hspace{1cm} (3.12a)

\[(R_{F})_{V} = \frac{1}{2} \left[ 1 + \tanh \left( \frac{\sum_{n=1}^{S_{n}=N} S_{n}^{(1-0)}}{2} \right) \right] \Omega_{2} \]  \hspace{1cm} (3.12b)

The concept of deducing NEXT and FEXT specified by equation (3.12) \textit{via} probabilistic attributes of crosstalk susceptibility at the nodes of interest implies the following: The logistic functional aspect of equation (3.12) suggests that the pervasion of crosstalk along the nodes of a victim trace would increase (or decrease) as the level of susceptibility of coupling due to \textbf{E}- and \textbf{H}-fields on the victim (emanating from the aggressor) increases or decreases. Further, the statistically-implied gross influence of susceptance in \( \Omega_{1} \) and \( \Omega_{2} \) results from the superposition of such influences at the nodes \( \{m\} \) and \( \{n\} \) of \( \Omega_{1} \) and \( \Omega_{2} \) respectively. As stated earlier, in classical perspectives of EMI estimation, the extent of overall EMI susceptibility is decided by EM coupling expressed \textit{via} \( [C] \) and \( [L] \) deduced in a deterministic framework in terms of current-voltage based impedance relations (in Kirchhoff’s perspectives).
Figure 3.12: Geometrical parameters of the traces and the associated distance values of node separation, \((\ell_v, v = 1, 2, \ldots)_N\) and \((\ell_v, v = 1, 2, \ldots)_F\) pertinent to the set of victims \(\{v = 1, 2, \ldots\}\) experiencing the NEXT and FEXT respectively.

In contrast, the present study follows the associated statistical attributes dictated by random perturbations of the values in the matrices \([\Delta E]\) and \([\Delta H]\) corresponding to the victim nodes of interest. As mentioned before, such randomness is largely imposed by the stochastic aspects of the geometrical layout due to random routing and/or geometrical spacing between the aggressor AA' and the victim bb' illustrated for example, in Figure 3.3. When the inter-trace coupling is viewed in terms of EM-field components, it can be quantified by the factor \(F\) deduced using \(E\) and \(H\) related entities and their relative perturbed values (caused by randomness) across the test area. That is, the invasion of \(E\)- and \(H\)-field components from the aggressor on the victims is assumed to cause corresponding random perturbations of coupling observed via differential values of \([\Delta E]\) and \([\Delta H]\) components;
and, the result would be the crosstalk parameters manifesting as probabilistic values specified via equation (3.12).

Hence considering the transfer of signal across the traces (endorsing undesired crosstalk coupling), it can be viewed in terms of relative EM-field components (specified implicitly via $F$) line-to-line (starting from the aggressor line) along the set of victim traces, \( \{v = 1, 2, \ldots\} \). Further, in terms of $E$ and $H$ related entities, relevant $F$-values can be prescribed using the geometrical parameters depicted in Figure 3.12.

With reference to the geometrical entities of Figure 3.12, the induced EM-field coefficients (0 to 1) in the $v^{th}$ victim trace would depend on the dimensions of the traces and the PCB. Further, the pervading field components (having three degrees of dimensional freedom) would decay with increasing distance of the victim trace from the aggressor. Correspondingly, the following EM field-dependent coefficients can be prescribed [3.27] respectively for NEXT and FEXT evaluations (Figure 3.12):

\[
(F_N)_{v=1,2...} = \left[ \frac{v_s}{v_N \times (t_r/2t_s)} \right] \left[ \frac{v_s}{v_N \times (t_r/2t_s)} \right] \right]^{(3/v)} \times \left( \frac{1}{1 + \left[ \frac{(\ell_v)_v}{d} \right]^2} \right) \times \left( \frac{3/v}{h} \right) 
\]

(3.13a)

and

\[
(F_T)_{v=1,2...} = \left[ \frac{v_s}{v_N \times (t_r/2t_s)} \right] \left[ \frac{v_s}{v_N \times (t_r/2t_s)} \right] \right]^{(3/v)} \times \left( \frac{1}{1 + \left[ \frac{(\ell_v)_v}{h} \right]^2} \right) \times \left( \frac{3/v}{d} \right) 
\]

(3.13b)

where $t_s$ denotes the settling-time of the pulsed signal. It is approximately equal to, (2 to 3) $\times$ (rise-time of the pulse, $t_r$). Further, $v_N$ represents a reference voltage equal to 1 volt and $v_s$ is the applied signal level at the source-end of the aggressor trace.
In addition, the FEXT is also influenced by the propagation delay due to the finite distance from the source to the end-node along the aggressor line (of length $L_T$ m). Corresponding weighting coefficient on the FEXT can be written as follows:

$$T_F = 1/[1 + [t_s (= 3t_r) \times \vartheta/L_T]]$$

(3.14)

Further, $\vartheta$ depicts the velocity of pulse transit on the trace and it can be specified via transmission-line concepts as nearly equal to, $c/(\varepsilon_r)^{1/2}$ where $c (= 3 \times 10^8$ m/s) represents the velocity of propagation of EM wave in free-space and $\varepsilon_r$ is the dielectric constant of the PCB substrate material. Hence, the final expressions for the NEXT and FEXT in the $v^{th}$ victim are respectively as follows:

$$\text{(NEXT)}_v = (R_N)_v \times (F_N)_v$$

(3.15a)

and,

$$\text{(FEXT)}_v = (R_F)_v \times (F_F)_v \times T_F$$

(3.15b)

3.9 Computed and Measured Results and Inferential Remarks

In order to verify the efficacy of the analysis presented and predictive formulations derived for the NEXT and FEXT concerning the test PCB under discussion, a test PCB illustrated in Figures 3.13 and 3.14 is used and the aggressor line marked is excited with pulsed signal at two test frequencies, namely, 40 MHz and 80 MHz. Both the aggressor and the victims are terminated with the impedance of $R_o = 50$ ohm; and, the source impedance ($R_s$) is also equal to 50 ohm.
Figure 3.13: Test PCB with the aggressor plus a set of eight (8) victim traces. The traces are terminated with $R_o = 50$ ohm impedance. The source impedance $R_s$ is also 50 ohm. Each trace has sixteen nodes (including the NEXT and FEXT nodes located at near- and far-ends with reference to the source).

With a known signal voltage $v_s(t)$ at 40 or 80 MHz applied at the aggressor source-node, the resulting (induced) near-end and far-end crosstalk voltages, namely, $(u_N)_v$ and $(u_F)_v$ respectively are measured using a broadband oscilloscope. Corresponding NEXT and FEXT values in the victims $v = 1, 2, \ldots, 8$ are determined respectively as: $(u_N)_v/v_s$ and $(u_F)_v/v_s$.

Further, using the board and trace details of the test PCB, relevant computations on NEXT and FEXT values as given by equation (3.15) are performed. Presented in Table 3-1
are relevant measured values and computed data on NEXT and FEXT observed at the set of victim traces (indexed as \( v = 1, 2, \ldots, 8 \)) and marked in Figure 3.12. These details are also illustrated in Figures 3.15 and 3.16 along with estimated statistical upper (UB) and lower (LB) bounds. These bounds denote the extrema that specify the error-bar on the estimated random entities (depicting the NEXT and FEXT values in question). The UB and LB values are determined by replacing the \( \tanh(.) \) function of equation (3.12) by \( L_q(.) \) where \( L_q(.) \) denotes the Langevin-Bernoulli function given explicitly by the following expression: 

\[
L_q(z) = (1 + 1/2q) \times \coth[(1 + 1/2q)z] - (1/2q) \times \coth[(1/2q)z].
\]

Here, the parameter \( q \) depicts the statistical disorder function [3.22]. That is, when \( q = 0.5 \), it refers to the condition of statistical disorder deciding the upper bound on the randomness of the estimates; and, when \( q = \infty \), it denotes a state of total disorder prescribing the lower bound on the estimation. The concept of evaluating UB and LB values pertinent to the statistical estimates as above is described elsewhere in [3.23] by one of the authors.

![Figure 3.14: The PCB used in the experimental studies](image)
Table 3-1: Measured and computed data on NEXT and FEXT relevant to the test PCB illustrated in Figure 3.13

<table>
<thead>
<tr>
<th>( v_s ) volts (RMS)</th>
<th>f MHz</th>
<th>v</th>
<th>Measured values of crosstalk at the victim trace: Index - v</th>
<th>Computed data: Estimated crosstalk - UB and LB values at the victim trace: Index - v</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>NEXT</td>
<td>FEXT</td>
</tr>
<tr>
<td>2.161</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normalized values of NEXT and FEXT with respect to measured data at ( v = 1 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>0.65</td>
<td>0.61</td>
<td>0.47</td>
<td>0.48</td>
</tr>
<tr>
<td>3</td>
<td>0.48</td>
<td>0.45</td>
<td>0.30</td>
<td>0.31</td>
</tr>
<tr>
<td>4</td>
<td>0.32</td>
<td>0.38</td>
<td>0.22</td>
<td>0.23</td>
</tr>
<tr>
<td>5</td>
<td>0.35</td>
<td>0.34</td>
<td>0.17</td>
<td>0.18</td>
</tr>
<tr>
<td>6</td>
<td>0.22</td>
<td>0.24</td>
<td>0.14</td>
<td>0.15</td>
</tr>
<tr>
<td>7</td>
<td>0.32</td>
<td>0.24</td>
<td>0.12</td>
<td>0.13</td>
</tr>
<tr>
<td>8</td>
<td>0.30</td>
<td>0.32</td>
<td>0.11</td>
<td>0.12</td>
</tr>
<tr>
<td>1.007</td>
<td>80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normalized values of NEXT and FEXT with respect to measured data at ( v = 1 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>0.55</td>
<td>0.43</td>
<td>0.46</td>
<td>0.46</td>
</tr>
<tr>
<td>3</td>
<td>0.22</td>
<td>0.22</td>
<td>0.28</td>
<td>0.27</td>
</tr>
<tr>
<td>4</td>
<td>0.19</td>
<td>0.19</td>
<td>0.20</td>
<td>0.21</td>
</tr>
<tr>
<td>5</td>
<td>0.12</td>
<td>0.07</td>
<td>0.15</td>
<td>0.16</td>
</tr>
<tr>
<td>6</td>
<td>0.72</td>
<td>0.05</td>
<td>0.12</td>
<td>0.13</td>
</tr>
<tr>
<td>7</td>
<td>0.03</td>
<td>0.04</td>
<td>0.09</td>
<td>0.11</td>
</tr>
<tr>
<td>8</td>
<td>0.04</td>
<td>0.03</td>
<td>0.08</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Figure 3.15: Measured and computed values of NEXT and FEXT of the test PCB at 40 MHz. (MV: Measured values and UB and LB denote the upper and lower bounds respectively of the computed data)
Figure 3.16: Measured and computed values of NEXT and FEXT of the test PCB at 80 MHz. (MV: Measured values and UB and LB denote the upper and lower bounds respectively of the computed data)
3.10 Inferential Remarks and Closure

From the results obtained, the following inferences can be made:

- *In lieu* of the traditional method of using LC parameters to assess NEXT and FEXT values in a PCB supporting multiple traces intended for the transport of high-speed pulses, proposed here is an alternative, implicit technique based on evaluating the inter-trace coupling caused by E- and H-field components of the EMI involved.

- The proposed method is comprehensive to include the statistical aspects of high-density traces laid out with random routings on the PCB. Such configuration of traces are common in the baseband sections of modern handheld wireless devices.

- Considering three attributes of the associated EMI phenomenon, namely, (i) EM field, (ii) statistical aspects of the physical PCB constituents and (iii) the transit delay issues of the signal pulse propagation on the traces, a pair of closed-form algorithms are derived (equations 3.15(a) and 3.15(b)) to deduce approximate values of the NEXT and the FEXT on a test PCB. Using the details and data as required, relevant computations of NEXT and FEXT can be done via simple computational effort. This is viably demonstrated with reference to a test PCB.

- The efficacy of the algorithms developed is ascertained by cross-validating the computed details *vis-à-vis* measured data on a test PCB. The results presented in Table 3-1 and in Figures 3.15 and 3.16 thereof indicate that the estimation procedure on NEXT and FEXT as advocated in this study favorably yields results (specified within the binding upper- and lower-limits) close to the measured data.

- The proposal narrated here is a motivated effort to alleviate the non-prevailing status of a comprehensive method available to determine the NEXT and FEXT coefficients pertinent to the test PCB described infested with a random layout of traces. That is, with the advent of PCBs required to possess a high-density of traces with random signal transit paths as well as supporting high-speed pulses of DDA category (as warranted in modern wireless handheld devices), estimating the associated inter-trace EMI coupling and crosstalk efforts is imminent; however, no straightforward theoretical and/or computational strategy appears to be in vogue (to the best of authors’ knowledge). As such, the present study is offered.
The study performed also provides some conclusive observations as regard to EMI and crosstalk infestation in the class test PCB described. Typically, the following may be noted;

- The crosstalk values (NEXT and/or FEXT) are decided not only by the traditionally known mutual proximity of the victims (as well as with respect to the aggressor) but also implicated by the number of turning points on each trace. Such turning points depict discontinuities on the transmission-line with corresponding distorted E- and H-field distributions pervasively coupling onto the nearby lines.
- The victim trace closest to the aggressor may suffer crosstalk effects intensely.
- Not only the geometry of trace routes, the mutual disposition of turning-points nodes in the adjacent traces would decide the NEXT and FEXT level (Figures 3.3 and 3.7).
- The net effect of crosstalk is decided by the following: (i) Pervasion of E- and H-fields across the random traces; (ii) randomness of the geometrical layout of traces and (iii) signal pulse characteristics.

Considering studies on the practical issues in high-speed PCB designs [3.2,3.4], relevant objectives culminate in deducing tangible solution towards EMI suppression and formulating EM compatibility (EMC) considerations toward crosstalk minimization [3.6-3.9, 3.12, 3.15,3.16, 3.25, 3.26].

Based on the observations made in the present study concerning the crosstalk perceived in the test PCB (having a cluster of randomly displaced traces), the following are suggested toward possible crosstalk mitigation efforts:

- Design the PCB layout with optimally separated traces
- Minimize the number of turning-points nodes on the traces
- If a directional change is inevitable for a trace, possibly make the associated turn smooth, rather being abrupt

Crosstalk mitigation efforts should also be done concurrently with minimizing the TIA considerations elaborated in [3.17].
In closure, the topic discussed in this chapter is a novel concept of deducing the EMI/crosstalk performance of PCB level, especially when the board is infested with a random cluster of traces supporting high-speed digital transports. To the best of author's knowledge no such similar effort is available in open-literature. Further, the underlying analysis can be extended to any other clustered transmission-line infrastructure, such as in the back-plane section of large-frame computers, servers, etc.
CHAPTER IV
PERFORMANCE ASPECTS OF RF-SECTION INFRASTRUCTUE OF SMART
WIRLESS DEVICES: PART A. 3 - EMP-EMI EFFECTS AND PROTECTION SCHEME
FOR DEVICE OPERATION UNDER E3 SITUATIONS

4.1 General

This chapter outlines the studies serviced out to ascertain the performance details pertinent to the RF section of smart wireless devices, when such devices are exposed to electromagnetic environmental effect (E3) caused by electromagnetic pulse (EMP). That is, the influence of EMP-EMI is analyzed with reference to the RF sections of smart wireless devices. The thematic aspect of this chapter is a focused review on the EMP-EMI threats faced by smart, mobile/fixed and wearable devices of modern wireless systems supporting a gamut of Internet-of-Things ((IoT). Relevant heuristics attempt to model the undesirable EMP/EMI-to-device coupling incurring in the state-of-the-art such wireless devices, which typically accommodate a dense layout of copper-traces on (single and/or multi-layered) printed-circuit boards (PCBs). Hence a performance assessment is done vis-à-vis non-catastrophic effects due to EMP-EMI relevant to the front/back-end RF sections in the test wireless devices exposed to and being highly receptive to energy stemming from various electromagnetic environmental effects (E3). The extent of EMP-EMI induced voltages in the circuits thereof would depend upon the severity of EMP an on the geometrical aspects of the exposed RF sections. Considering the ad hoc routing of traces, patterned randomly, zigzag on the PCB of the test devices, a unique modeling
strategy is required to estimate the extent of EMP-EMI victimization so as to consider adequate and proactive hardening methods and suggest possible protection strategies thereof.

This study is objectively tailored to formulate the analyses towards evaluating the performance integrity of smart wireless devices/systems at the RF section exposed to E3. EMP-EMI influence transported \textit{via} random cluster of lines/traces inflicting catastrophic damages and/or causing soft-errors (meaning undesirable logic upsets) at the interconnected chips is modeled and evaluated. Compatible suggestions on mitigation pursuits appropriate for RF front/back-end sections of smart wireless devices towards EMP-EMI \textit{via} protection by improvising a lossy distributed compensating network are furnished. The theoretic heuristics and practical considerations are illustrated with results due to simulation exercises.

Hence, relevant mitigating/protection methods is sought and studied. The scope of this chapter governs Part A. 3 of the research objectives. Background details are as follows:

4.2 Introduction

An \textit{electromagnetic pulse} (EMP) refers to an extremely short duration burst of energy emitted by a source creating an ambient of transient electromagnetic (EM) disturbance. The resulting \textit{electromagnetic environmental effects} (abbreviated as E3) include massive invasion of electronic systems in the form of radiated EM field that adversely interferes with the associated circuits as a conducted electrical disturbance. Typically, an EMP may manifest as single-shot impulse or as a repetitive pulse trains depending on the source involved. The entities of EMP are spectrally broadband but, they could excite a relatively narrow-band, damped sinusoidal response while interacting in the victim circuitry infested with lossy and reactive components.
The origin or source of EMP could be natural or man-made. Lightning and unintentional electrostatic discharge (ESD) are typical examples of natural EMP events; and, commonly observed such man-made EMP arise from switching transients/surges in power transmission and distribution systems [4.1]. More specific and distinct class of EMP that invariably poses a threat to critical electronic devices and systems refers to military-related ambient. It is classified as non-nuclear EMP (NNEMP) and nuclear-EMP (NEMP) and high altitude nuclear EMP (HEMP) [4.2 - 4.4].

The NEMP is an abrupt pulse of EM radiation caused by nuclear explosion; and, when a nuclear warhead is detonated hundreds of kilometers above the Earth's surface, it will induce HEMP. Such nuclear explosions create high-energy impulse of electromagnetic energy that can disrupt electronics at far distances. That is, the associated, rapidly changing electric (E) and magnetic (H) fields would couple with electrical/electronic systems located in the near and far zones and produce damaging current and voltage surges in the circuitry. (The EMP stemming from a nuclear explosion is due to the associated phenomenology deliberating high electromagnetic energy released by Compton-recoil electrons and photoelectrons scattered in the materials of the nuclear device and/or in the surrounding medium).

The NNEMP is mostly a military-specific event caused by nonnuclear weapons specifically designed to produce (intentional) EMP with maximized energy so as to induce damaging and adverse effects in the electronic systems (of the enemy) across a wide geographical area. Such NNEMP devices are typically conceived with a large low-inductance capacitor bank discharging into a single-loop antenna connected to a RF (microwave) generator; and, a compressed flux of RF energy is explosively released as EM radiation (depicting thereof the NNEMP in question). Examples of such operations include
creating intentional EMP, detrimental to enemy’s sensitive C³I (command, control, communication and information) electronic systems (including radars) that are critically required (on the enemy side) for robust operation and maneuvering of their combat vehicles and/or airborne systems. Relevant EM compatibility (EMC) requirements warrant the use of EMP-hardened devices and protection schemes. Devices/systems equipped with such EMP tolerant methods [4.5] [4.10] in general, are tested in specialized EMP simulator facilities, for example, in the US Navy facility called the Electro Magnetic Pulse Radiation Environmental Simulator for Ships I (EMPRESS I).

EMP-specific electromagnetic interference (EMI) or the so-called EMP-EMI could catastrophically or otherwise damage the electronic systems at various strata – from the chip to equipment and system levels. Further, depending on the associated energy levels [4.11] of the pulses and proximity of the victims to the source, the extent of EMP-EMI can be such that it would cause gentle soft-errors in the system functioning or it may induce irreversible (catastrophic) damages on devices. In modern contexts, management of such EMP effects and searching for relevant mitigations constitute a major branch of EMC engineering directed on EMP-EMI related issues.

As stated earlier, concerns pertinent to EMP-EMI in modern contexts are two-folded: (i) With the advent of critical electronics and communication systems profusely adopted across societal utility services, EMP arising from natural sources such as lightning, solar storms, electrostatic discharges (ESD) and unintentional electric power-distribution anomalies (like internally generated transients) is inevitable. Relevant concerns and EMC considerations have been the focus of interest in the last several decades; and, comprehensive strategies have been pursued to contra the underlying interference as well as the resulting effects by resorting to various custom-designed filter technologies towards
hardening solutions *vis-à-vis* EMP-EMI suppression and protection and schemes towards EMC needs. (ii) The second arena of EMP-EMI invasion refers to more mission-critical domains supporting defense-related systems/equipment ambient seen under nuclear/non-nuclear environment. The associated vital communication links (like, ground-borne and/or satellite links), electronics of massive computer networks and large power-grid systems etc. are such entities in the state-of-the-art EMP-EMI studies. In general, the whole gamut of resulting electromagnetic environmental effects (abbreviated as “E3”) are identified targets of interest and specific exercises are being developed to understand the underlying cause-effect implications of EMP-EMI and related EMC requirements.

An exclusive set of systems a modern interest that are highly prone and susceptible in the state-of-the-art, E3 refers to inevitably proliferated use of highly miniaturized, compact (chip-to-board level) electronic wireless devices. These include for example, mobile/handheld and wearable devices as well as fixed entities having wireless connectivity such devices are rendered smart and invariably designed to accommodate intense electronic-processing units in the miniaturized segments at RF, baseband, power-system and display sections. The associated chips/integrated circuits plus various interconnects (on the single and/or multi-layered PCB) depict a clustered topology of circuits randomly laid out at board-level on *ad hoc* basis; and, they can be regarded as being highly prone to EM coupling and immensely receptive to E3-specific EMP-EMI exposures. Though, their hardening portfolio improvised may meet the E3 aspects of simple EMP-EMI aggressions (such as, lightning and/or power transients), it is yet unknown of possible implications that would be encountered under severe and extreme physical ambient *vis-à-vis* military standards and requirements posed by NEMP and/or NNEMP events. In such stringent EMP-EMI-specific conditions, suppose the smart mobile/handheld/wearable and/or fixed devices are required to
be robustly operational (as in war-front E3 scenario implying threats due to EMP-EMI from high-power microwave weapons). Then, considering the underlying (both military and civilian networks) plus the C³I entities that are intended to support constantly, the transceiver signals (through cell phones, tablets, wrist-top and other devices) via wireless-wireline connectivity – the possibility of pervading EMP interference of high as well as low intensity is a reality of significant concerns that need imminent mitigating efforts.

Therefore, a niche exists to study and evaluate the performance aspects of such small, smart handheld (fixed and/or mobile) devices deployed in all related mission-critical applications (such as, battlefield (land/air/ship) electronics, vehicle electronics, wearable units, fixed smart ad hoc units, GPS systems etc.), which are critically required to remain operational even under severe E3 conditions of EMP-EMI and protected from all related threats. Guidelines of MIL-STD-188-125-1 (on permanent facilities), MIL-STD-188-125-2 (on land mobile vehicles) and MIL-STD-461 establish certain baseline performance and testing requirements on systems and devices deployed in mission-critical C4ISR (Command, Control, Communications, Computer, Intelligence, Surveillance and Reconnaissance) tasks.

Notwithstanding such prescribed norms on possible hazards and mitigation suggestions towards EMP hardening and protection, efforts on assessing the underlying performance exclusive to mini/micro-sized, mobile/handheld/wearable and/or fixed smart wireless devices envisaged in mobile or in fixed platforms and facing the “ill-fated” E3 due to EMP-EMI are however, sparse. Both extreme catastrophic failures due to high-intensity pulses as well as, gentle but adverse soft-failures (sometimes, intentionally imposed by hardware-specific cyber-attacks) caused by relevant EMP and E3 situations can be of pragmatic concern in all such cell phones, tablets wireless wearable units and other mobile devices – (even if they are in sleeping-mode but deployed/used in E3 ambient).
Hence, objectively this study reviews and outlines the underlying EMP-EMI threats to such mobile/fixed smart devices caused by device-to-EMP/EMI coupling. Specifically, in the state-of-the-art wireless smart devices (mobile/fixed) that accommodate a dense layout of copper traces on single and/or multi-layered PCB [12], the encroachment aspects of EMP-EMI is focused and performance evaluation is duly modeled for mitigation efforts.

The antenna located in the front/back-end RF sections of wireless devices are highly prone to receive the EMP of the E3. The resulting EMP-EMI viewed at the circuit level manifests as surge voltages and currents. The hazards implicated thereof would depend upon the severity of source-dictated EMP as well as on the geometrical aspects of the exposed RF sections [4.13] [4.14], (which may consist of ad hoc routing of traces, patterned randomly, zigzag on the PCB). Often such induced voltages and currents could be well in excess of the catastrophic tolerance of the sensitive front/back-end electronics or, they can cause adverse logic upsets (soft-errors) in the invaded section. Therefore, in order to address the extent of EMP-EMI based victimization and improvise adequate protective methods and/or EMP-hardening strategies, unique modeling strategies are required to devise a method of evaluating the performance integrity of a smart device at RF level vis-à-vis EMP-EMI aggression perceived in the context of random cluster of lines/traces laid across the interconnected chips and components on the PCB.

Hence, a formal evaluation of relevant probabilistic aspects of randomly-dispersed trace patterns on the PCB transporting EMP-induced currents is objectively attempted in this study; and, by determining the corresponding effects at the receiving chips, relevant details are acquired that lead to compatible suggestions on mitigation pursuits appropriate for RF front/back-end sections of smart wireless devices towards EMP-EMC. Presented below are theoretical heuristics and practical considerations in formulating the necessary algorithms.
4.3 Theoretical Considerations and Analysis

Illustrated in Figure 4.1 is a hypothetical exemplar of PCB section with a dense set of copper-traces laid out on *ad hoc* basis. Considering the clustered (and often randomly) laid such traces on the PCB at to the RF section (front-/back-end) of a device, the associated level of susceptibility to transient nature of $\mathbf{E}$- and $\mathbf{H}$-fields (caused by EMP-EMI), refers to a statistically-implied gross influence at vulnerable nodes across the spatial layout (in the RF domain, $\Omega$) on the PCB. Classical perspectives of estimating the associated extent of overall EMI susceptibility in PCBs would normally follow the suite of deciding the associated EM-coupling expressed *via* a set of distributed capacitance, $[C_{ij}]$ and inductance $[L_{ij}]$ values at any desired $n^{th}$ node identified by a set of coordinates ($n; i,j$) in the RF domain, $\Omega$. 
Figure 4.1: Geometrical details of an arbitrary, hypothetical set of randomly-routed traces laid on the PCB at the RF section \( (\Omega) \) nodes \( \{n = 1, 2, \ldots, N\} \) experiencing the fluence of EMP striking at a vulnerable reference node. The victim site is divided into a set of 2D matrix-grids; and, the nodes of interest namely, \( \{n = 1, 2, \ldots, N\} \) are identified at these grids by the coordinates, \( \{i, j\} \)

The sets \( [C_{ij}] \) and \( [L_{ij}] \) can be deduced approximately in a deterministic framework of current-voltage based impedance relations (in Kirchhoff’s perspectives) provided that the nodes in questions are almost equi-spaced and deterministically known \textit{a priori}. However, if
the trace layout and nodes are randomly dispersed, a more rigorous approach is needed. It
should accommodate the underlying statistical attributes and hence, decide on the random
perturbations of vector entities, namely the electric and magnetic field components, \( \mathbf{E} \) and \( \mathbf{H} \) respectively. Corresponding randomly perturbed values are denoted respectively as, \( [\Delta \mathbf{E}] \) and \( [\Delta \mathbf{H}] \) in the space \( \Omega \). Such randomness is largely imposed by the stochastic aspects of
dimensionally-implied random routing and spacing of the traces involved for example, as in
Figure 4.1. Hence, the invading \( \mathbf{E} \)- and \( \mathbf{H} \)- field components due to EMP-EMI correspond to
causing random perturbations of RF coupling observed \emph{via} time-dependent, transient-state
of differential components, namely, \( [\Delta \mathbf{E}(t)] \) and \( [\Delta \mathbf{H}(t)] \); and, in the presence of random
attributes of traces and nodes on the PCB, it is more appropriate to evaluate the EMP-EMI
susceptibility in terms of the perturbed \( \mathbf{E} \)- and \( \mathbf{H} \)-components \emph{in lieu} of the classical entities,
namely, the distributed L and C parameters.

With reference to a hypothetical geometry of random traces laid on a PCB at an RF-
section as illustrated in Figure 4.1, the induced EM-field coefficients (expressed as a
normalized value between 0 to 1) at any node residing on a victim trace would depend on the
dimensions and random pattern of the traces on the PCB; and, the proliferating EM-field
components (with three degrees of dimensional freedom) would propagate with a complex
propagation constant \( \gamma \) across the traces. Suppose the EMP fluence strikes the PCB at an
arbitrary reference node, identified with a grid coordinate \( (i_R, j_R) \) and the other nodes on the
PCB (assumed to be randomly dispersed with respect to this reference node) are at the
coordinates \( (i, j)_n = 1, 2, 3, \ldots N \) each depicting the location of discretized grids in a 2D-matrix
representing the domain, \( \Omega \); and, \( N \) denotes the total number of nodes in that domain. Then,
the corresponding coefficient of susceptibility due to EM-field induced at an \( n^{th} \) node, \( (n; i, j) \)
namely, \( k_{(n; i, j)} \) in time-domain can be approximately specified for \( \Omega \) as
\[
k_{(n; i, j)} = v_{sn}(\omega t)\big|_{(n; i, j)}
\]
where \( v_{sn}(ot) \) is the peak EMP surge at the victim node, \((i_R, j_R)\) and \([v_Z]\) represents the superposition of voltages induced across the entire (discretized) N nodes in the domain \( \Omega \) as a result of EMP invasion. The corresponding coefficient \( k_{(n; i, j)} \) is given by:

\[
k_{(n; i, j)} = \frac{\left[ \left( \frac{(l_{ng})}{d_{ng}} \right)^2 / \left( 1 + \left( \frac{(l_{ng})}{h} \right)^2 \right) \times (3/N) \right]_{(n; i, j)}}{\left[ \left( \frac{(l_{ng})}{d_{ng}} \right)^2 / \left( 1 + \left( \frac{(l_{ng})}{h} \right)^2 \right) \right]_{(n; i, j)}}
\]

where, \( l_{ng} \) is the distance between the \( n^{th} \) node and the nearest ground-node, \( d_{ng} \) is the average spacing between adjacent traces on which the \( n^{th} \) and \((n + 1)^{th}\) nodes are located; and, \( h \) is the thickness of the substrate as shown in Figure 4.1. Further, \( t_s \) denotes the settling-time of the impulse (EMP), which is approximately equal to, \((2 \text{ to } 3) \times (\text{rise-time of the impulse}, \ t_r)\). Also, considering the propagation of EM fluence across the finite distance \((L_T \ m)\) between \( n^{th} \) node under observation \((n; i, j)\) and the ground-node, the corresponding delay \( T_R \) (in normalized form) can be evaluated as follows:

\[
T_R = 1/[1 + \{t_s (= 3t_r) \times \theta L_T\}]
\]

where \( \theta \) depicts the velocity of impulse transit on the trace; and, it can be specified via transmission-line concepts as nearly equal to, \( c/(\varepsilon_r)^{1/2} \) where \( c (= 3 \times 10^8 \ m/s) \) represents the velocity of propagation of EM wave in free-space and \( \varepsilon_r \) is the dielectric constant of the PCB substrate material.
In terms of the coefficient \( k_{(n; i, j)} \), a related parameter \( K(\omega; t_r)_{(n; i, j)} \) can be derived to denote approximately the overall EMP influence on the test section in frequency-domain. It will depend on the amplitude density function \( V_s(\omega) \) in dB versus frequency in Hz [4.11].

Corresponding Fourier/Laplace transform relation is given by: \( V_s(j\omega) \leftrightarrow v_s(\omega t) \). An ideal EMP is a delta-Dirac function; however, in practice the EMP namely, \( v_s(\omega t) \) would depict approximately a transient function; and, this transient voltage would typically exhibit a Fourier spectrum of the type shown in Figure 4.2 with characteristic corner frequencies as marked [4.11].

Figure 4.2: Spectral representation of the envelope of a typical transient EMP: Amplitude density function \( V_s(\omega) \) in dB versus frequency in Hz [4.11]
By using Parseval’s theorem, the approximate energy content of the EMP transient, $v_s(\omega t)$ striking at a reference node on the PCB can be expressed in terms of a normalized coefficient (via frequency domain parameters), $K(\omega; t_r)|_{(n; i, j)}$ as follows:

$$[K(\omega; t_r)|_{(n; i, j)}] = \frac{\left[\left(\frac{\ell_{nG}}{d_{nG}}\right)^2 / \left[1 + \left(\frac{\ell_{nG}}{h}\right)^2\right]\right]_{i,j} \times (3/N)_{n,i,j}}{}$$

with

$$[D_2^{v}] = \sum_{i,j; n = 1, 2, \ldots, \nu} \left[\left(\frac{\ell_{nG}}{d_{nG}}\right)^2 / \left[1 + \left(\frac{\ell_{nG}}{h}\right)^2\right]\right]_{i,j} \times (3/N)_{n,i,j}$$

and

$$[D_N^{2}] = \sum_{i,j; n = 1, 2, \ldots, N} \left[\left(\frac{\ell_{nG}}{d_{nG}}\right)^2 / \left[1 + \left(\frac{\ell_{nG}}{h}\right)^2\right]\right]_{i,j} \times (3/N)_{n,i,j}$$

where, $v$ depicts the achieved number of victim nodes influenced by the EMP out of the total number of $N$ nodes on the PCB section exposed.

Further, the system upon EMP excitation may become oscillatory, if the associated damping factor, $\xi \leq 1/\sqrt{2}$. Other entities of the Fourier spectrum of the EMP transient having characteristic resonant peaks are indicated in Fig 4.2.

$$\zeta = \left[\left[|V_s(\omega)|^2 \times \omega_r / 2\right] \times \left[1 + (\omega_r \times \omega_c) / \{\omega_o\}^2 \times \sqrt{2}\zeta\right]\right]$$

(4.4)
Figure 4.3: EMP waveform functions: Amplitude, $v_s(t)$ versus time, $t$. (a) Ideal EMP waveform with an impulsive instantaneous, amplitude (corresponding to a delta-Dirac function); (b) Practical EMP exhibiting a rectangular pulse shape with extremely small, finite pulse-width, $\tau$. (c) Transient trend of EMP waveform manifesting as a double-exponential curve with a very sharp leading-edge reaching the maximum level in an extremely short duration with a finite rise-time, $t_r$. (d) EMP waveform seen as a damped sinusoidal function depending on the damping factor, $\xi$, as decided by lossy and reactive components dispersed in the receptive domain, $\Omega$.

In addition, while deducing the EMP-related (approximate) expressions as above, it is assumed that the energy content viewed in frequency-domain beyond the sections cornered
at $\omega_{-60\text{dB}}$ (corresponding to the slope, $\approx -60$ dB/decade slope or greater) are negligible and therefore ignored. Then, the approximate energy content ($\zeta$) in terms of the spectral constituents of Figure 4.2 is given by [4.11].

As stated earlier, an EMP manifests mostly as a short burst of electromagnetic energy; as such, it is ideally a delta-Dirac function (with zero width and infinite amplitude) having a flat-frequency Fourier spectrum stretching into an infinite range of frequencies. However, practical EMP impulses are of finite width and amplitude. Corresponding transient fluence of EM encroachment on the test PCB typically refers to a set of waveform profiles as illustrated in Figure 4.3. Transient EMP events (as in Figure 4.3) would induce a corresponding signal waveform (expressed in terms of current-voltage relations) in the victim circuits. Typically, the resulting Fourier spectrum of the signal intercepted gets band-limited over a narrow frequency band (due to resonant and lossy network components being present); and, consequently, as shown in Figure 4.3, a characteristic signal waveform (double-exponential curve or damped sinusoidal function) is impressed across the victim nodes.

In practice, depending on the source, the EMP energy may directly recreate impulses posing catastrophic threat or it may induce low-energy artifacts causing circuit malfunctions such as soft-errors. High-energy level EMP (such as those sourced by NEMP and HEMP) would invariably induce catastrophic and irreversible damages in electrical systems, totally disrupting the underlying functions. Apart from EMP-EMI due to nuclear explosions, the non-nuclear EMP (NNEMP) is deliberately introduced to cause a state of E3 in a warfront so as to disrupt the mission-critical tasks on the enemy side. Relevant EMP-EMI could be of low-energy level, but enough to cause operational malfunctions in Command, Control, Communication, Computers, intelligence, Surveillance and Reconnaissance (C4ISR)
infrastructure on the enemy side. In any case, the threat from EMP needs to be controlled and most control measures focus on reducing the susceptibility of the electronics to EMP effects via hardening the devices and protecting the system as necessary. That is, specific EMC considerations are designed to ensure robust operation of the systems even in the presence of EMP and E3 situations.

4.4 Simulation Experiments and Results

Application of the formulation (equation 3) deduced to infer the normalized coefficient $K(\omega; t_r)_{(n; i, j)}$ is outlined here in terms of simulation exercises performed on a hypothetical test PCB structure of the RF section subjected to typical E3 considerations. Referring to Figure 4.1, the test PCB can have random as well as deterministic geometrical attributes. Likewise, the encroaching EMP can be described in terms of its associated deterministic as well as random characteristics. As such, the resulting EMP-EMI specified in terms of frequency-domain parameter, namely, $K(\omega; t_r)_{(n; i, j)}$ would be a random parameter consistent with the associated stochastic and deterministic attributes of PCB geometry and EMP waveform. Hence, it is appropriate to exercise and apply Monte Carlo simulation tool to accommodate such (deterministic and random) causative factors so as to yield the corresponding results on $K(\omega; t_r)_{(n; i, j)}$. Further, such simulations are iterated (each time with random assignments to the ensemble set of input nominal variables) and the resulting ensemble of output data is gathered on $K(\omega; t_r)_{(n; i, j)}$. Thus, the Monte Carlo simulation carried out performs a goal-seeking output analysis by building models of possible results and substituting a range of input values (with a specified probability distribution) conforming to the inherent uncertainty of the associated variables. Typically, if all nominal values are assumed to have an equal chance of occurring with defined extrema, (namely,
their maximum and minimum limits), then the statistics of input variables is uniformly distributed. This is pragmatic when no prior details (except possibly on extrema limits) are available; and hence Laplacian hypothesis of equally-likely consideration can be validly invoked. So, in order to emulate the wide scope of EMP-EMI involvement, in the present case of simulations, the geometrical attributes of the PCB and waveform characteristics of the EMP are presumed to be uniformly distributed variables.

Monte Carlo simulation is performed hundreds of iterations so as to accommodate the global extent of uncertainties involved within the ranges specified for each randomly perturbed variables. The following example illustrates the simulation done with reference to a hypothetical RF-section on a PCB subjected to EMP-EMI with assumed nominal parameters grouped as two sets \( \gamma_1, 2, \ldots \) and \( \{1,2,3\ldots\} \) as listed in Table 4-1. Using the data on nominal parameters as above, Monte Carlo simulations are performed by changing randomly each nominal value \( X \) of the set \( \{\gamma_1, 2, \ldots\} \) for a stretch of rise-times of the EMP in the range, \( t_r = 10^{-6} \) to \( 10^{-25} \) s. The nominal value \( X \) in question is randomized as follows: In each iteration, a pair of uniformly distributed independent random variables \( y_1 \) and \( y_2 \) are specified within a limit and the randomized value of \( X \), namely, \( X' \) is generated as follows: \( X' = (\text{Nominal value } X) + [(100 \% \text{ of } X) \times (\text{Random number, } y_1: 0 \text{ to } 1) - (50 \% \text{ of } X) \times \text{Random number } y_2: 0 \text{ to } 1] \).

The simulation exercised as above is iterated over \( \beta \) times (say, 1000) so as to get an ensemble of data on EMP-EMI susceptibility coefficient \( |K(.)| \) versus the rise time \( (t_r) \). Presented in Figure 4.4 are computed results obtained via simulation experiment as above and relevant details are explained in the following section.
Table 4-1: Assumed nominal parameters relevant to a hypothetical test PCB and EMP waveform/spectrum

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Group</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance between n&lt;sup&gt;th&lt;/sup&gt; node and the nearest ground node,</td>
<td>( \gamma_1 )</td>
<td>( \delta_{NG} = 20 \text{ mm} )</td>
</tr>
<tr>
<td>Average spacing between the adjacent trace on which the n&lt;sup&gt;th&lt;/sup&gt; and (n + 1)&lt;sup&gt;th&lt;/sup&gt; nodes are located</td>
<td>( \gamma_2 )</td>
<td>( d_{NG} = 2 \text{ mm} )</td>
</tr>
<tr>
<td>Distance between nth node and fixed RF-GND node</td>
<td>( \gamma_3 )</td>
<td>( L_T = 150 \text{ mm} )</td>
</tr>
<tr>
<td>Thickness of PCB substrate</td>
<td>( \gamma_4 )</td>
<td>( h = 1 \text{ mm} )</td>
</tr>
<tr>
<td>Number of ungrounded active RF nodes</td>
<td>( \gamma_5 )</td>
<td>( N = 200 )</td>
</tr>
<tr>
<td>Number of victim nodes influenced by EMP out of total N nodes: (3D equi-partitioned concept)</td>
<td>( \gamma_6 )</td>
<td>( \nu \equiv (1/3) \times N )</td>
</tr>
<tr>
<td>Dielectric constant of PCB substrate</td>
<td>( \gamma_7 )</td>
<td>( \varepsilon_r = 5 )</td>
</tr>
</tbody>
</table>

**EMP waveform/spectral details vis-à-vis deterministically chosen rise-time**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Group</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise-time of the EMP</td>
<td>( \Gamma_1 )</td>
<td>( t_r : 10^{-6} \text{ to } 10^{-25} \text{ s} )</td>
</tr>
<tr>
<td>Settling-time of the impulse (EMP)</td>
<td>( \Gamma_2 )</td>
<td>( t_s \equiv (2 \text{ to } 3) \times t_r \text{ s} )</td>
</tr>
<tr>
<td>Flat-band cutoff frequency</td>
<td>( \Gamma_3 )</td>
<td>( f_r = 1/(3 \times t_r) ); ( \omega_r = 2\pi f_r )</td>
</tr>
<tr>
<td>Resonant (pole) frequency</td>
<td>( \Gamma_4 )</td>
<td>( f_{rc} \equiv 1/t_r ); ( \omega_{rc} = 2\pi f_{rc} )</td>
</tr>
<tr>
<td>Resonant (zero) frequency</td>
<td>( \Gamma_5 )</td>
<td>( f_o \equiv (f_r + f_{rc})/2 ); ( \omega_o = 2\pi f_o )</td>
</tr>
<tr>
<td>Corner frequency at 60 dB/decade</td>
<td>( \Gamma_6 )</td>
<td>( f_{60\text{dB}} \equiv (f_{rc} + f_o)/2 ); ( \omega_{60\text{dB}} = 2\pi f_{60\text{dB}} )</td>
</tr>
<tr>
<td>Damping factor</td>
<td>( \Gamma_7 )</td>
<td>( \xi \leq 1/\sqrt{2} )</td>
</tr>
</tbody>
</table>

4.5 Discussions

Shown in Figure 4.4, are results pertinent to the following three cases: (i) \(|K(\cdot)|\) versus \( t_r \) using the set of nominal values as presumed in Table 4-1 (without any random perturbations); (ii) simulated set of data on \(|K(t_r; X; \{\Gamma\}, \{\gamma\})|\) versus \( t_r \) over \( \beta \) iterations, (say,
\( \beta = 1000 \); and, (iii) a logistic regression of the simulated random values of \( |K(\omega; X:\{\Gamma}, \{\gamma\})|_\beta \) versus \( t_r \) deduced as follows: Suppose \( z = \sum_\beta |K(\bullet)|_\beta \) for all \( \beta \) iterations at a specified value of \( t_r \), the corresponding log-regressed value of \( K(.) \) is given by the logit function namely, \( [1/(1+\exp(-z))] \). Further, for this regressed suite of \( K(.) \) versus \( t_r \), relevant upper- and lower-bounds can be prescribed as follows:

\[
|K(\omega; t_r)|_{UB} = 1/2 + \frac{1}{2} \times L_Q(z/2), \quad Q \rightarrow 0.5
\]

\[
|K(\omega; t_r)|_{LB} = 1/2 + \frac{1}{2} \times L_Q(z/2), \quad Q \rightarrow \infty
\]

(4.5)

where \( L_Q(.) \) denotes the Langevin-Bernoulli function that decides stochastically justifiable upper- and lower-limits as indicated in [4.15]. It is given explicitly as follows: \( L_Q(\alpha) = (1+1/Q) \times \coth[(1+1/Q)\times \alpha] - (1/Q) \times \coth[1/Q] \times \alpha \). Here, the factor \( Q \) denotes an order parameter of the randomness involved; that is, when \( Q \) tends to 0.5, it depicts a total isotropic disorder implying the upper-bound on the uncertainty involved. And, when \( Q \) tends to infinity, it corresponds to the state of total anisotropic order of the stochastic process involved. As such, relevant result with \( Q \rightarrow \infty \) provides the lower-bound on \( |K(.)| \). The vertical range of \( |K(.)| \) between upper- and lower-bounds as above is the statistical extent within which the influence of EMP-EMI can be considered to prevail in the RF-section of the test PCB, for a given set of nominal values as presumed. However, without any loss of generality, the algorithm and simulation procedure narrated above can be applied to any segment of the PCB.

Thus, illustrated in Figure 4.4 are complete details on the clustered data plus the upper- and lower-bound values of \( K(\omega; t_r) \) versus the rise-time in the range, \( t_r = 10^{-6} \) to \( 10^{-25} \) s of the aggressing EMP. Extremely small values of \( t_r \), \( \rightarrow 10^{-25} \) s implies that the EMP
represents an impulse (delta-Dirac) function. Further, it can be observed in Figure 4.4, that, close to the value of \( t_r \approx 10^{-9} \) s, the response of EMP changes significantly from a low value towards the upper bound relevant to the test PCB module being studied with its assumed nominal parameters; and, this critical stage (of \( t_r \approx 10^{-9} \) s) can be approximately regarded as the transition at which the test unit becomes more venerable to EMP-EMI as could be evinced from the increasing trend of the estimated, \( K(\cdot)|_{\beta} \) versus rise time (\( t_r \)). As such, a protection method has to be provisioned vis-à-vis the invading EMP-EMI. Hence, a compatible EMC strategy is proposed here thereof. It is based on a technique indicated in [4.16] by one of the authors using a lossy distributed compensations network, the details of which are outlined in the following sections.

4.6 EMP Protection of the RF-Section in Wireless Devices: The Design Flow

Considering the test unit having nominal geometrical and EMP parameters as assumed earlier, the simulated results (Figure 4.4) show a visible state of transition to more EMP-EMI vulnerability around \( t_r \approx 10^{-9} \) s. Correspondingly, the frequency-domain value of \( \omega \approx 2\pi \times (1/t_r) \), or, \( f_x = 10^9 \) Hz can be regarded as a resonant (RF pass-band) feature at which a shorted quarter-wave stub can be introduced as an input compensating network so as to alleviate the possible, band-limited encroachment of EMP-energy causing possible damages. The design flow thereof is as follows:

Suppose the node \((i_R, j_R)\) is the location of the antenna exposed to E3. Relevant to this site of vulnerability to EMP-EMI, the proposed protection method is illustrated in Figure 4.5. The protection design is interposed between the antenna and the RF front-/back-end. It essentially consists of a lossless quarter-wave (corresponding to, \( \lambda_x/4 \) with \( \lambda_x = c/f_x \)) short-circuited stub. It offers an input impedance, \( Z_2= jR_0 \tan(\lambda_x/\lambda) \) where \( \lambda = c/f \) with \( f \)
being any frequency across the RF pass-band of interest; and, \( R_o = 50 \text{ ohm} \) denotes the characteristic impedance of the line. Using the heuristics of the protection technique as proposed in [4.16] and assuming the width of the trace of the test PCB as \( W \), a lossy \( \lambda_x/4 \) short-circuited stub (of characteristic impedance \( R_o \)) can be designed with an input impedance of 
\[
Z_1(\lambda = c/f) = (8 \frac{R_o^2}{R\lambda_x}) - j(4\pi \frac{R_o\lambda}{\lambda_x}) 
\]
where \( R \) is the resistance per unit length of the lossy line, which can be expressed in terms of skin-depth of the trace.

Explicitly, \( Z_1 \) is evaluated in [4.16] as follows:

\[
Z_1(\lambda = c/f) = [2R_o^2 \times (16W/\lambda_x)^2] \times (\sigma/\pi\mu f)^{-1/2} - j\{4R_o\lambda/\pi\lambda_x\} \tag{4.6}
\]

Now, the net input-impedance \( (Z_{in}') \) at the node \((i_R, j_R)\) is equal to the parallel combination of \( Z_1 \) and \( Z_2 \). That is, \( Z_{in}' = Z_1||Z_2||R_o = (R_{in}' - jX_{in}') \), which has a conjugate asymmetry of \( X_{in}' \) with respect to the normalized frequency \( f/f_x \); hence, an additional compensating, distributed (lossy) inductance can be placed between the antenna node \((i_R, j_R)\) and the stubs as illustrated in Figure 4.5. Suppose the series impedance \( (R_r + jX_r) \) of this lossy inductor is designed such that, \( X_r = X_{in}' \). Then, the net \( Z_{in} \) reduces to \( (R_{in}' + R_r) + R_1 \) (real-part of \( Z_1 \)).

Thus, the structure described is a closed-circuit path formed by two parallel shorted stubs that offer a low pass-band impedance to receive and dissipate the EMP; and, at the same time it has a stop-band characteristic (designed for the RF bandwidth) so as to direct the RF energy into the RF-load steering away from the protector stubs. This protection strategy, thus involves essentially a frequency selective power dividing technique.

Ideally, any EMP protecting network placed across RF-load should not adversely introduce mismatch over the RF-band of interest; that is, the return-loss should be kept better than \(-17 \text{ dB} \) (or, input VSWR < 1.4) so as to maintain less than 0.1dB insertion-loss due to
any input mismatch. At the same time, considering the EMP aggression, the protection circuit should offer a low-frequency (DC) return-path (preferably dissipative). Further, the proposed method as above requires a lossy inductor compatible as a PCB structure. Among various possibilities of such inductor implementation on a PCB, suggested here is a fractal dispersive inductor proposed by the authors elsewhere [4.12]. That is, a class of fractal planar inductors can be designed for use in the EMP-protective scheme improvised in a constrained on-board area with close tolerances as needed. Such fractal structure can be realized conveniently via miniaturized layout strategy being evolved in RF CMOS designs [4.17] [4.18].

In summary, proposed in this study is a design of a lossy distributed network intended to suppress the EMP at a crucial node in the RF-section. Considering the test unit and the nominal values of the associated parameters indicated in Table 4-1, the simulation studies performed yield a value of $f_x \approx 10^9$ Hz. The lossy-line structure (illustrated in Figure 4.5) is designed at least for VSWR $\leq 1.4$ (so that the corresponding insertion-loss due to the protection circuit is less than 0.1 dB enabling a return-loss of $-17$ dB as mentioned earlier). Corresponding designs of the subsections involved are described below [4.15] [4.19-4.21].
Figure 4.4: Computed results on $|K(\cdot)|$ versus the EMP rise-time ($t_r$): Data cluster obtained via Monte Carlo simulations with the algorithmic predictions of the upper- and lower-bounds UB and LB). Computed result obtained using nominal (fixed) values of PCB and EMP parameters as assumed is as presented.
Figure 4.5: Proposed EMP-EMI protection method for the RF-section of the wireless device
4.7 Design of Lossless $\lambda_c/4$ Shorted-stub

In addition to the nominal values assumed for the test PCB as in Table 4-1, the following geometrical dimensions are considered for the traces laid on the PCB: (i) The ratio of inter-trace spacing ($d_s$) and width of the trace ($W$) is set approximately equal to: $d_s/W = 1$; and, the thickness of the copper trace ($t_c$) is taken as 35 $\mu$m so that, a compatible value of the characteristic impedance, $R_o = 50$ ohm can be realized for parallel-tracks. Further, the PCB substrate is presumed to have a typical value of dielectric constant ($\varepsilon_r$) equal to 5.0. Hence, a conventional lossless unit of quarter-wave shorted stub is designed as required in Figure 4.5.

4.8 Design of Lossy $\lambda_c/4$ Shorted-stub

This corresponds to designing the lossy quarter-wave shorted stub. Its dimensions are same as those designed for the lossless version described above. However, the trace-lines can be rendered lossy by using compatible alloy (in lieu of copper) of known conductivity ($\sigma$ in S/m). Correspondingly, its resistance per unit length ($R = (\pi f \sigma \mu)^{1/2}/W$ in ohm per meter) can be calculated for the trace (of given width, W meter) at the operating frequency $f_x$ (in Hz). Further, the trace-material being nonmagnetic its permeability, $\mu = \mu_o (= 4\pi \times 10^{-7}$ H/m) corresponding to free-space permeability.

4.9 Design of Lossy Compensating Inductor

This component is introduced to realize a (lossy) inductance value $L$, henry such that, it offers a positive reactance $+ jX_r = + j\omega L$ at the resonant frequency $f_x$ Hz. This positive reactance is selected to cancel the negative reactance, $X_{in}$ as explained earlier. A variety of PCB compatible planar inductors can be designed thereof [4.12].
Suppose the selected version of the planar inductor for example, offers an inductance value per unit length, \( L'_c \) H/m. The corresponding \( L_c \) (in H) = \( (L'_c \) in H/m) × (length of the lossy inductor-line = \( l'_c \) in m). Further, this track can be made lossy by resorting to using a compatible alloy and designed to have the same geometrical cross-section as the PCB trace. This inductance value, \( L_c \) should in essence neutralize the net capacitive reactance offered by the structure resonating at \( f_x \).

![Smith Chart](image)

Figure 4.6: A Smith-chart representation of the input VSWR characteristics of the final test structure improvised for EMP-EMI protection: It is assumed in the calculations the unloaded-Q as 2; and, the corresponding bandwidth is: \( \Delta f = 500 \) MHz at \( f_x = 1000 \) MHz.

That is, \( |\omega_x L_c| = 1/\omega_x C'_in \) where \( C'_in \) denotes the effective capacitance due to the reactive part of the input impedance, \( Z'_in = Z_1 \parallel Z_2 \parallel R_o (= 50 \Omega) \). Note that the design of \( L_c \) as above at the desired frequency \( f_x \) may have to be trimmed to accommodate concurrently the
required RF pass-band width, so that a desired return-loss and mismatch characteristics lead to \( VSWR \leq 1.4 \) across the RF pass-band.

Assuming a pass-band of 750 MHz through 1250 MHz (at \( f_x = 1000 \) MHz) yielding an unloaded Q approximately equal to 2, the input VSWR characteristics of the final structure using a meander-line planar inductor (offering \( L_c' \) in \( \text{H/m} = \frac{R_o \times \varepsilon}{\sqrt{\varepsilon} \cdot c} \), where \( c = 3 \times 10^6 \text{ m/s} \)) can be obtained as illustrated in the Smith-chart of Figure 4.6. (Supplementing the details in [4.16] and [4.19-4.21], the technique of designing lossy transmission-lines is elaborated in classical books like [4.22] and [4.23], where excellent presentations on relevant theoretical considerations are available).

4.10 Concluding Remarks and Closure

This study offers a review on possible EMP-EMI threats specific to wireless devices (portable/fixed and wearable) operated under E3 ambient. Considering the practical aspects of the infrastructure of those devices, the extent of EMP-EMI susceptibility at RF-sections is estimated in this study via Monte Carlo simulation exercised using an appropriate algorithm derived thereof. This simulation duly accounts for random attributes of the geometrical parameters at the PCB level and includes the characteristics of the EMP impressed on the unit. That is, random attributes of the parameters involved are superimposed on the corresponding nominal (deterministic) values pertinent to a given device; hence, the simulated results represent a cluster of ensemble data on probabilistically estimated EMP-EMI susceptibility, namely, \( |K(\cdot)| \) versus rise-time, \( t_r \) of the test structure exposed to E3.

In summary, as shown in Figure 4.4, the proposed algorithms yield results relevant to the following: (i) \( |K(\cdot)| \) versus rise-time \( (t_r) \) deduced using the nominal (deterministic) values of the PCB-unit under test plus deterministic EMP features adopted in the computations. (ii)
Corresponding UB and LB limits of the results in (i) are also estimated; and, (iii) an ensemble of clustered data is obtained via Monte Carlo simulations incorporating random perturbations on the test PCB and EMP parameters. From these results, the following inferential observations can be made:

- For a given RF-section with PCB details known a priori, relevant deterministic computations of equation (3) enable deducing $|K(\cdot)|$ versus rise-time ($t_r$) characteristics with an upper-bound (UB) tending to 1; and, relevant lower-bound (LB) tends to 0.5 for the limiting case of $t_r \rightarrow 0$, (meaning ideal delta-Dirac EMP) as evinced in Figure 4.
- However, considering the Monte Carlo simulations on the same RF-section with PCB details set randomly (perturbing the nominal values), relevant computations of equation (4.3) enable deducing an ensemble of (random) data on $|K(\cdot)|$ versus rise-time ($t_r$) characteristics as shown in Figure 4.4. These simulated results show their lower limit closer to the deterministic LB (tending to 0.5) of $|K(\cdot)|$ regardless of the values, $t_r \rightarrow$ (high or low); on the other hand, the simulated results overshoots the UB for small values of $t_r \rightarrow 0$. It implies the criticality of EMP-EMI influence on the test unit when the EMP conforms to impulsive attributes with sharp rise-time characteristics (akin to a delta-Dirac function).
- Another observable, interesting feature of $|K(\cdot)|$ versus rise-time ($t_r$) characteristics is that, around a specific value of $t_r$, the profile of $|K(\cdot)|$ shows a transition from the LB towards the UB. For example, as marked in Figure 4.4, this transition is close to, $t_{rx} = 10^{-9}$ s and it represents approximately the resonance at, $\omega_{rc} \approx 2\pi \times (1/t_{rx})$ shown in Figure 4.2. That is, the estimated value of $f_x$ (as adopted in the computations) is 1000 MHz ($= 1/t_{rx}$). Further, the stretch of $t_r$ approximately, from $10^{-13}$ to $10^{-9}$ s denotes the implied transition towards the severity of threats due to narrow EMPs. This stretch of time-domain values transform to depict in the frequency domain (Figure 4.2) characteristics with the slope changing from $-20$ to $-60$ dB/decade
- Relevant to simulated details for a given test unit on $|K(\cdot)|$ versus rise-time ($t_r$) characteristics and estimating the value of $f_x$, the present study proposes an EMP protection scheme as illustrated in Figure 4.6 compatible for RF pass-band
applications. EMP protection has been a topic of utmost importance in the decades of the past and studied comprehensively in both civilian and military contexts. However, the vulnerability of modern wireless devices (such as smart fixed/mobile and wearable units) to E3 is even more severe. Relevant threat due to EMP-EMI could be devastating as rightly pointed out by Kyle in [4.3].

- Wrist-top and other wearable wireless devices (WWD) with densely-packed and compactly designed infrastructure enabling smart and sophisticated functionality are gizmos of reality for state-of-the-art civilian users of IoTs. Before long, (if not already) such devices would also find inevitable usage and prolific penetration in military scenario involving system-on-person (SoP) operational applications. Then such military operations will be at stake with the imposed vulnerability to failures thanks to SoP exposure to E3 and the associated EMP-EMI [4.24]. Therefore, relevant proactive EMC measures warrant exclusive EMP hardening as well as built-in protections in the aforesaid devices, specifically at the PCB sites of RF-section naked to E3 exposures. The present study can serve as an overview on such EMP-EMI issues and related protection pursuits.

In all, smart and sophisticated wireless devices find immense proliferation in defense and war-zone applications with inevitable possible exposure to E3; and it is a recognized fact that the associated EMP-threat is a reality of grave concern [4.25-4.26]. So, a focused and exclusive study relevant EMP-EMI and EMC issues concerning mobile/fixed and wearable wireless devices with IoT connectivity is obviously imminent and strategically important. The present work is indicated as a prelude thereof.
CHAPTER V

WIRELESS NETWORKS SUPPORTING SMART DEVICES AND SERVICES: PART B.

1- EVALUATION OF RELATIVE TECHNOECONOMICS- BASED PERFORMANCE INDEX (RTPI)

5.1 Introduction

The scope of this study is to evolve a rational strategy to prescribe a performance measure on the prevailing mobile services and platforms that support emerging smart devices concurrent to traditional incumbents of feature cell phones. It is a motivated effort to judiciously include the economics-related parameters in conjunction with technology-specific details so as to deduce a cohesive performance metric in order to compare the state-of-the-art mobile services and related operations. In relevantly existing strategies, such performance comparison of mobile services is done purely on the basis of technology-dictated parameters on the speed of wireless traffic (in bps). The so-called PCMag.com assessments prescribe thereof, a mobile speed index (MSI) to determine the performance of mobile networks and identify the "fastest network" that prevails in a service area. However, while deducing such MSI values, the approach pursued does not include any underlying economics-related facts relevant to service areas and/or periods of assessment.

Hence, the present study is done to elucidate a coherently viable, technology-cum-economics based performance metric on mobile services in vogue. A technoeconomic parameter is identified thereof, and it is termed as relative technoeconomic performance index (RTPI); hence, a comprehensive comparison is furnished on the MSI values (of
versus the RTPI values pertinent to set of available data. Concluding remarks on the pros and cons of adopting ‘technology-alone’ details (sans economics parameters) in decision-making on relative performance of mobile services (especially in the contexts of supporting smart- and feature-devices) are presented.

5.2 Background

In the ambient of highly competitive and globally deregulated market, conceiving performance models of business structures on mobile communication services and related systems is vitally important. Relevant efforts should emphasize estimating the relative performance concerning mobile platform industry vis-à-vis the growth prospects of various services facilitated to subscribers. In the state-of-the-art contexts, mobile service performance assessment is pertinent to the quality-of-service (QoS) expected with a variety of end-devices supported [5.1] [5.22] [5.33] on the network. Such wireless devices supported in essence, include the mobile versions (handheld and wearable) as well as, the fixed entities like table- and bench-top units. Typically, subscribers of wireless services to a large extent, actively use the “smart devices” and are diminishingly dependent on traditional feature phones (or the so-called, “dumb devices”) for their routine communication purposes [5.1].

Considering such global mobile services and make a judicious performance comparison of underlying service-provisioning plus operational activities, it is necessary that, both technology-specific features as well as economics-related/market details are cohesively considered; and, the associated technoeconomics is analyzed with an emphasized focus on the following issues: (i) Evaluating the engineering considerations and protocols of communications on all versions of wireless devices; and, (ii) archiving relevant information
on the business economics that covers the details on beneficial suites seen by service providers in terms of return-on-investments (RoI) and by the customers on the advantageous price structure, acceptable QoS and satisfactory performance (utility) of the services facilitated.

Mobile services (supporting App-intense, smart-devices) are vastly proliferating across the world with foreseeable long-term evolution (LTE) projections; and, conjecturally, demand for smartphones is expected to grow \cite{5.3} \cite{5.4} \cite{5.10} \cite{5.19} \cite{5.21} \cite{5.22} \cite{5.31} with the associated market dynamics of mobile operating systems drifting extensively and posing an unique trend. Relevant paradigm shift has moved both mind- and market-shares propelling the mobile business forward at an extraordinary phase \cite{5.10} \cite{5.14}. Further, the impact on local economics of gigabit networks and associated transmissions (both on wireless and wireline transports) has been grossly large, requiring new ways to model and measure the profiles of supply and demands of the services involved.

In the context of wireless services envisaged in modern context, the focus of present study is devised to prescribe a metric on mobile services that can assess the net service performance constrained by available technology options and the associated, economics-related, market penetration issues. Hence, the scope of this study is to develop and utilize technology-specific performance indicators along with marketing dashboard displays, so as to measure rationally, the effective prospects of growing mobile communication industry that have adopted new devices and related infrastructure across the telco turfs.

The metric designed thereof, would depict a cohesive technoeconomic index; and, its role is to point out the relative performance of competing and evolving mobile services. Corresponding strategies on product development, logistics of service provisioning and capturing the market with minimal customer-churning pursued to realize the optimal RoI
(via QoS implementation) are regarded as technoeconomic growth precursors of interest \textit{vis-à-vis} the overall performance profile of the networks concerned. In other words, the relative performance metric being evaluated in this study on technoeconomics basis would give each mobile industry an opportunity to observe its own performance trend, as well as those of its competitors and set its course of operation towards yet better performance and higher revenue.

Commensurate with the scope as above, the overall technoeconomic performance of the wireless network systems envisaging smart and traditional mobile devices on appropriate service types is analyzed here with forward-looking prospects of the LTE [5.20] in mind. Hence, the intended efforts in this study are as follows:

- To evolve a performance metric of competing wireless networks supporting smart-devices so as to assess the associated, (a) technology-centric capabilities and (b) current and near-future market penetration status
- To blend thereof, the technological factors and economics parameters in order to construct a combined analytical framework and evaluate rationally, the relative overall performance of such networks by deducing a technoeconomic performance metric.

Hence, the intended pursuit would eventually enable, (i) investigating the sufficiency of technology-based engineering parameter such as, the so-called mobile speed index (MSI) proposed by the PCMag.com [5.25]-[5.30] in dictating the prominence of a specific wireless network against the other existing in the current market with LTE trends; (ii) analyzing the \textit{pros} and \textit{cons} of co-existing and coevolving wireless networks that compete for introducing new options on the vertical services supporting customer-oriented Apps with relevant consumerism and associated price structure; and, (iii) deciding eventually, which wireless
network in vogue that would outperform the market diffused with near-future generation of smart-devices and related App-intense mobile services.

In all, the objective of this study is to obtain a single technoeconomic-based performance indicator, which duly accounts for both technological aspects of mobile services supporting feature and smart devices as well as, it includes the synergetic dynamics of the economics profile coexisting in the service area. This performance measure is named here as the relative technoeconomics performance indicator (RTPI).

This chapter is organized as follows: In the next section (Section 5.3), the existing perspectives on assessing the performance aspects of wireless networks that support a variety of smart devices using techno-centric details are outlined; and, pertinent details on the technology-specific parameters required to assess the performance of mobile networks are explained in Section 5.4. Also presented in Section 5.4, is a method (with necessary formulations) of combining such techno-centric details via logistic regression towards establishing a compatible performance measure. This measure refers to the MSI advocated by PC.Mag.com in [5.25]-[5.30] as mentioned earlier. Further, considering the statistical aspects of the variables used in the logistic-regression, a method to introduce an error-bar on the values of the evaluated MSI is also described in Section 5.4, by prescribing a pair of statistically-justifiable upper- and-lower bounds (UB and LB).

Next, the role of service-related parameters of the economics is identified in Section 5.6. Subsequently, the rationale behind combining the economics-related parameters of the subscriber-base and the technology-specific details of the wireless network operations is discussed in Section 5.6. Hence, the method of evaluating the RTPI values is described. Again, considering the associated stochastic attributes of the variables involved, a way to
include the underlying randomness in assessing the overall technoeconomic performance of mobile services via statistical bounds is indicated.

The computational details on combining the MSI values and the economics-related parameters are furnished in Section 5.8 towards determining the proposed RTPI with its statistical error-bar, established in terms of the associated UB and LB limits. Lastly, discussions on the outcomes of the study are presented in Section 5.9 with closing remarks in Section 5.10.

5.3 Performance Aspects of Wireless Networks vis-à-vis Smartphone Technology

As stated earlier, the realm of telecommunications supporting wireless networks and services has taken a new turn in the recent past with the advent of profusely proliferated smart-devices and related systems in the wireless service areas across the world. Relevant to this global scenario, lessons drawn from classical operations of telecommunication companies (telcos) supporting the feature devices of yester years, show an inevitable trend of fused economics and engineering considerations in providing the utmost customer satisfaction and allowing the telco industry to gain maximum RoI benefits [5.24]. Therefore, any performance measure intended to evaluate the modern wireless telco operations, should reflect the underlying synergism of technology and economics. However, the trend pursued in prescribing a relative performance index (across the wireless networks that shoulder the smart-device terminations) is poised one-sided, mostly on technology details [5.25] - [5.30]. In contrast, it is opined here that, for realistic and open deliberations on the performance, both economics and engineering suites should be concomitantly accommodated in the associated business modeling strategies. For example, in the assessments of comparing mobile networks via the MSI as proposed in PCMag.com [5.25] - [5.30], emphasize has
been placed solely on technology-dictated “fastest” mobile services, decided in terms of the bits-per-second (bps) transported and extended to the customers. Hence, all the related technological features namely, the download speed, the upload speed, the success probability of user data protocol (UDP) streams, the http-download success probability and the proportion of downloads exceeding a certain nominal bit rate (such as, 144 kbps) are considered; hence, a regressed model on the performance is specified in terms of the MSI, as reported in [5.25] - [5.30].

However, such MSI-specification lacks three considerations namely, (i) no economics-related parameters are implicated in scaling the performance while declaring the "fastest mobile network of the year" [5.7] – [5.9]; (ii) the statistical variability in the variates lassoed and regressed while modeling the MSI is altogether missing; and, (iii) the ultimate performance declaration of the network (in terms of the MSI) is rather rigid; and, neither an error-bar nor a cone-of-variation with upper and lower binding limits, is prescribed.

Therefore, proposed in this study, is a more general and comprehensive performance suite evolved to compare mobile networks. This technique upgrades the status of the relative performance schedule prescribed by the PCMag.com (in terms of the MSI); and, it uses the data concerning the underlying economics, consistent with all the three items of concern listed above. Hence, an appropriate algorithm is derived, wherein the same survey data of [5.25] - [5.30] procured and compiled in several test cities evenly spread across the US over a specific period (2010 through 2013) by PCMag.com are adopted. Additionally, a set of economics variables is collected relevant to the surveyed regions (and the test duration) and included appropriately in deducing the modified performance metric.

In summary, the proposed performance model outlined above is formulated with explicit inclusion of the following: (i) Technology-centric details of the state-of-the-art
mobile services that cater immensely to the growing smart-device applications and (ii) necessary information on the economics of the underlying business. Further, the parameters of both technology and economics are regarded mostly stochastic rather than of deterministic values. As such, the deduced technoeconomic performance is specified within a cone-of-error bound by upper and lower limits of variability [5.18].

5.4 Relative Performance of Mobile Networks: PCMag.com Heuristics on the MSI

Prior to deducing the proposed RTPI, first the technological details that are used in formulating the MSI values (by PCMag.com) versus different mobile services in the surveyed areas are summarized below. Hence, the heuristics of determining the MSI are described in this section considering an appropriate example of the service area studied by PCMag.com [5.25]-[5.30]. In the subsequent subsection, details on economics-related parameters are identified and described

5.4.1 Service-related Technological Details

The technology-centric parameters in the context of modern mobile communications conform to a set of turf details, traffic requirements and operational protocols facilitated in the services that support smart-devices in conjunction with traditional (feature-phone) cellular telephony. Such parameters are “snap-shot” data acquired by PCMag.com [5.25]-[5.30] on the associated speeds of data transmission and on the other statistical details concerning the network load, integrity of establishing the wireless connectivity etc. These techno-centric details are defined explicitly below. They lead to a performance assessment suite, which is indicated in [5.25] - [5.30] to rank the wireless operations in order to declare “the fastest network” in the service area.
5.4.1.1 Definitions and Details of Techno-centric Parameters Adopted by PCMag.com [5.25] – [5.30] in Evaluating the MSI

*Download speed (DLS):*

It is the speed (expressed in bps) of the information traffic in the down-link with which, the subscriber downloads any entity of triple services from the network (Specified as average and maximum values in Mbps)

*Upload speed (ULS):*

It is the speed (expressed in bps) of the information traffic in the up-link with which, the subscriber uploads any entity of triple services from the network. (Average and maximum values in Mbps).

*UDP stream success probability (P-UDPS):*

Whenever data-streaming is done as per UDP in the ambient of time-sensitive transmissions, the data may appear delayed at the destination; as such, they may get dropped and the resulting loss in throughput details may lead to specifying a corresponding success probability of transmission. That is, the effectiveness/integrity of UDP-specified data streaming is implicitly specified via probabilistic norms. (The time-sensitive transmissions refer to voice/music and video data streamed)

*Probability of success of HTTP down-load transport (P-HTTP: DL):*

The foot-print of coverage can be sparse in wireless communication systems; and, in the worst-case scenario, the streaming-media and/or related http-specific downloads can be accomplished only with a specific probability of success

*Proportion of downloads at unspecified bit rates (UBR) in excess of nominal bit rates, such as 144 kbps (P-UBR):*
In the traditional 2G-wireless, a nominal rate of 144 kbps is prescribed for mobile users and 2 Mbps for stationary users. (The nominal rate, 144 kbps is derived from the net bit rate of classical land-line ISDN2 Basic Rate Interface (2 B-channels + 1 D-channel) of (2 × 64) +16) = 144 kbps (payload data rate) with D-channel signaling rate being 16 kbps). Any down-loads done at a speed in excess of 144 kbps refers to the UBR traffic; and, relevant proportion of the load is expressed as a percentage.

*Time-to-first-byte (TFB):*

This is a measurement adopted as an indication of the responsiveness of a webserver or other network resources. It refers to the duration from the virtual user making an HTTP request to the first-byte of the page being received by the browser. This time includes the socket-connection time, the time taken to send the HTTP request and the time taken to get the first-byte of the page. Typically, the TFB is measured using tools like, the WebPageTest

*Average web download speed (WDLS):*

Depending on the type of connection (whether a shared or a dedicated bandwidth version), if downloading several small files is exercised, then the associated speeds would be low because, for each file, there should be a connection establishment and termination procedures that would consume time and hence, limit the speed. As such, the web sites from which the downloading is done would generally place a limit on “per file download speed”. Correspondingly, an average web download speed is specified for any wireless network operation

*500 kbps streaming success probability (P-500: SS):*

The target audience of large-scale, live video-streaming has asymmetric broadband access. For example, while the average residential broadband download rates in the United States are around 2.8 Mbps, the corresponding upload rates average to only about 500
kbps (as per current statistics). Clearly, it is not possible to support any live-streaming at rates greater than 500 kbps with a pure peer-to-peer (live-streaming) solution, even though the download rates allow offering MPEG-1 or better quality streams. Thus, in strictly peer-to-peer live transmissions, the success probability of streaming 500 kbps rate is normally considered towards describing the network performance while facing the competitive pressures.

**Probability of successful 3G transits (P-3G:ST):**

With the advent of 4G-system placed into telco operations, the wireless network services concurrently started supporting both 4G and the existing 3G infrastructure. Though the average download speeds of 3G are relatively much lower than those of 4G-system, PCMag.com tests reveal “a value of steadiness” of 3G networks; hence indicated thereof in [5.28], is a 3G success probability exclusively for the year 2011, which encountered the 3G-to-4G transition.

**Proportion of web page completion (P-WPC):**

In the Internet usage, a website may begin to “bog” down after a prolonged period of time. The reason is as follows: The frontend files of the web downloads, may contain exaggerated blocks of code or locked, hidden bits. This is most commonly seen happening within JavaScript files or images and it would lead to Internet jams, bogging down the delivery of videos and other online contents. Therefore, downloads of web pages may not be completed as a result of the aforesaid bogging down; and, relevant (partial) web-page completion (in percentage) is a performance indicator of the network involved.

**Consistency parameter (CPR):**

In the studies by PCMag.com, a consistency parameter on the assessed values of the MSI for each network in the year, 2010 is indicated. Expressed in percentage, this parameter implies the extent
to which the network operations (in a given service area tested) have yielded consistent and repeatable results on the assessed techno-centric entities.

5.5 Evaluation of the MSI

With reference to the data specific to technological/speed-related factors and other network performance parameters listed above, (and assessed in the surveys by the PCMag.com [5.25] - [5.30]) are described underneath. Hence, the proposed method of deducing the MSI values with the prescription of relevant UB and LB limits is elaborated. These bounds, as stated earlier, enable placing a statistically-justifiable error-bar on the deduced value of the MSI and, the error-bar accounts for possible statistical variations in the parameters used in evaluating the MSI values.

Though not explicitly derived, the MSI values as evaluated by PCMag.com (and reported in [5.25] – [5.30]), conform to an algorithm based on logistic-regression of the technological parameters. That is, the MSI in essence, is dictated by a set of variables \( \{z_1, z_2, \ldots, \} \) constituted by the techno-centric parameters listed earlier. Suppose \( Z = (a_1 z_1 + \ldots + a_i z_i + \ldots) \) with, \( \{z_1, z_2, \ldots, z_i, \ldots, \} \) denoting the contributory set of predictive regressors; and, the other constituents of the set, namely, \( \{a_1, a_2, \ldots, a_i, \ldots, \} \) are regression coefficients properly assigned to ‘weigh’ the predictive variables. That is, the regression coefficient prescribes a prorated influence on how each explanatory variable contributes to the probability of the regressed outcome. Larger the regression coefficient, higher is its influence on the probability of the outcome.

Thus, \( Z \) represents the total contribution of all the (weighted) independent variables. In the relevant context, the feature vector set \( \{z\} \) can be classified as belonging to a fluffy
class (based on conditional probability heuristics); and correspondingly, a logistic-regression algorithm can be specified as follows:

\[ p(z) = \frac{1}{1 + \exp(a_0 + a^T z)} \]  

(5.1)

where \( p(z) \) depicts the possibility (probability) of realization of the class defined by the feature vector set, \( \{z\} \); and, the regression parameters \( \alpha \) and \( \alpha_o \) are decided by optimizing the associated likelihood statistics. In general, the set of technological parameters gathered in the studies, such as in [5.25]-[5.30], denotes a complex and unstructured (“fluffy”) set of entities. Further, the set of such gathered technological features depicts a grouped case and the scope of the test trials is such that, the probability \( p(z) \) is estimated in terms of the set \( \{z\} \); and, the regression via equation (5.1) allows a computational solution of \( p(z) \).

In the relevant pursuit, use of logistic-regression model allows identifying the observations that provide independent information with respect to the likelihood of the outcome pertinent to a given data set, like \( \{z_i\} \). That is, the logistic function, namely,

\[ f(Z) = \frac{1}{1 + \exp(-Z)} = [1/2 + 1/2 \times \tanh(Z/2)] \]  

(5.2)

with \( Z = (a_1z_1 + \ldots + a_iz_i + \ldots) \) conforms to establishing a relation between the possible outcome versus a set of surrogate observations. Hence, the computation of MSI conforms to using the explanatory variable set, \( \{z_i\} \) and evaluating the logistic-function (or, the logit-function), \( f(Z) \) constructed. The associated rationale behind adopting the logistic-regression is as follows: The heuristics of obtaining the MSI value relies on using a set of technological parameters that transform the associated quantitative features into meaningful engineering information. Suggested here is that, this pursuit of determining the MSI, can be accomplished via logistic regression (in lieu of linear regression), inasmuch as, the logistic-regression minimizes the usual sum-of-squared errors as well as, it inherently enables
improvising a shrinkage on the outcome of the selection method by placing upper- and lower-bounds. Also, it produces sparse solutions and hence, allows only a subset of the features in the model [5.5] [5.34]. In general, the logistic regression function, \( f(Z) \) represents a nonlinear sigmoid (S-shaped); and, for large values of \( Z \), (that is, when \( Z \rightarrow \infty \)), \( f(Z) \) asymptotically tends to 1. Likewise, as \( Z \rightarrow 0 \), \( f(Z) \) will asymptotically approach 0. That is, the outcome of logistic-regressed solution sought remains squashed between 0 and 1. Further, the sigmoidal aspect of the logit-function implies an associated nonlinearity between the input and the output. Such nonlinear considerations are consistent with the heuristics described in [5.16] by Neelakanta and De Groff, which can be summarized as follows: Suppose a linear relationship exists between two variables, \( u \) and \( v \) such that, \( v = ku + c \), where \( k \) and \( c \) are constants. Should a nonlinear relation prevail otherwise between \( v \) and \( u \), a fractional change in \( u \), namely \( \Delta v/\Delta u \), with respect to a change in the input \( \Delta u \) will be decided by the functional relation, \( (1/v)dv/du = F(v) \) or \( dv/du = vF(v) \), where \( F(v) \) denotes an arbitrary function that would decrease, as \( v \) increases; and, at a certain stage, the increase in \( v \) with respect to \( u \) would cease (or saturate). Suppose \( F(v) = (a - bv) \) with \( a \) and \( b \) being constant. Then, the model \( dv/du = u(a - bv) \) represents a simple, nonlinear first-order differential equation known as logistic equation. Its properties are enumerated in [5.16]. Typically, the constant \( b \) decides the effect of squashing influence perceived as a result of the increasing trend of output entity, \( v \); and, the ratio \( a/b \) decides the stability of the system. Specifically, when \( a = b = 1 \), the solution of the aforesaid nonlinear differential equation is given by: \( v = (1/2) + (1/2) \times \tanh(u/2) \). It represents a unipolar sigmoid, bounded or squashed between the limits 0 to + 1. In the present study, \( v \) denotes the function \( f(Z) \) of equation (5.2) adopted in the context of determining the MSI as described earlier.
In the method of assessing the MSI values via logistic regression as indicated above, it is assumed that, \((a_1 = a_2 = \ldots = 1)\). That is, all the contributory variables presumably impact the net outcome, equally-likely. (This statistical attribute of uniform distribution concerning the contributory variables is justifiable under the Laplacian hypothesis, implying that relevant stochastic details are unavailable a priori, otherwise).

So, the procedure of determining the MSI values involves two steps: (i) Given a set of relevant data \(\{z_1, z_2, \ldots, z_i, \ldots\}\), each parameter is taken in a normalized form; and, (ii) the MSI being sought conforms to the outcome of logistic-regression of the normalized set, \(\{z_1, z_2, \ldots, z_i, \ldots\}\).

The MSI as conceived by PCMag.com, in essence, refers to determining the net statistical outcome on the performance of the wireless service rendered in a particular year by provisioning a specific service type at a given service area. Considering the set of technocentric factors listed earlier and adopted by PCMag.com \([5.25]-[5.30]\) to determine the MSI, an exemplar set of such details pertinent to the service area, namely, Boston Metro, USA across 2010 through 2013 is presented in the Tables A-I and A-II of the Appendix. These details are adopted here for illustrative calculations.

The step-by-step algorithmic suite thereof, presented to determine the MSI is furnished in a pseudocode later in this section. In addition to evaluating the MSI, it is also proposed here a method to prescribe a pair of upper- and lower-bounds (UB and LB) on the MSI values so that, these bounds specify an error-bar (on the ascertained values of the MSI) in order to account for the statistical variations in the underlying endogenous and exogenous variables. The proposed strategy is briefed below and illustrated subsequently via pseudocode descriptions.
The logistic function considered earlier, namely, \( f(Z) = 1/[1 + \exp(-Z)] \equiv [1/2 + 1/2 \times \tanh(Z/2)] \) with asymptotically limiting bounds from 0 to 1, represents rather a deterministic solution (of a nonlinear differential equation). That is, the variables involved are assumed to be entirely deterministic. However, if the variables (both endogenous and exogenous) used in the logistic-regression are stochastic in nature, equation (2) should be modified to include the associated statistical variability. Hence, a stochastically-justifiable, logistic function has been proposed by Neelakanta in [14] and by Neelakanta and De Groff in [5.16]. Relevant formulation duly accounts for the random attributes and non-deterministic considerations tied to the entities (regressors) of the variable set involved. As such, in lieu of equation (5.2), the following nonlinear function as proposed in [5.14] and [5.16] is suggested as an alternative for the logistic-regression relation, \( f(Z) \) of equation (2):

\[
\hat{f}(Z) = (1/2) + (1/2) \times L_Q(Z/2)
\]  
(5.3)

where, \( L_Q(\cdot) \) denotes the so-called Langevin-Bernoulli function (LBF) with \( Q \) depicting an order-parameter that decides the extent of underlying stochastic features. Explicitly, the LBF is given by [5.14] [5.16]:

\[
L_Q(x) = \left(1 + 1/Q\right) \times \coth\left[(1 + 1/Q)x\right] - \left(1/Q\right) \times \coth\left[(1/Q)x\right]
\]  
(5.4)

Here, the order parameter \( Q \), specifies the statistical bounds on \( L_Q(x) \) such that, as \( Q \to 1/2 \), the function \( L_Q(x) \to \tanh(x) \) depicting the UB; and, as \( Q \to \infty \), the function \( L_Q(x) \to [\cot(x) - 1/x] \) represents the LB. Thus, when the LBF is prescribed towards logistic-regression, it enables specifying two stochastically-justifiable bounds on the outcome. In summary, the UB indicated denotes the outcome corresponding to the variables of the stochastic domain assuming a total isotropic disorder; and, the LB , conforms to the
variables assuming a state of total anisotropic order. Thus, the choice of $L_Q(.)$ allows realizing a stochastically-justifiable sigmoid with statistical upper- and lower-bounds, which place an error-bar on the regressed outcome.

Commensurate with the present study, the $MSI_{\text{year}}$ values are deduced by PCMag.com [5.25]-[5.30] using the technological factors, presumably considered as deterministic values. As such, they are specified without any statistical bounds. However, if the MSI values are ascertained as proposed here (using the LBF), the results would explicitly possess statistical upper- and lower-bounds. The procedures towards determining the MSI values with and without statistical bounds are detailed in the following pseudocode.

---

**Pseudocode I: Algorithmic pursuit to determine the MSI and its bounds (UB and LB)**

**Initialize**

**Input**

→ Data and details on the network and services rendered

← Name of the service area

→ (Example: Boston Metro, MA: USA)

← Service period

→ (Example: 2010 – 2013)

← Names of the mobile service providers

→ (Example: AT & T, SPRINT, T-MOBILE, VERIZON and Metro-PCS)

← Service type evolution


→ Data and details on the technological factors (PCMag.com specific) [5.25] - [5.30]:

← Down-load link speed in Mbps (DLS):

→ Average and maximum values of DLS: $D_{\text{max}}$ and $D_{\text{ave}}$

← Up-load link speed in Mbps (ULS):

→ Average and maximum values of ULS: $U_{\text{max}}$ and $U_{\text{ave}}$
Perform

Normalization of the data listed above, as necessary: Suppose $\beta_{i,j}$ is a techno-centric entity (having a specific unit) of the $i^{th}$ service provider in the $j^{th}$ year. Corresponding normalized value of $\beta_{i,j}$ is obtained as follows:

$$[\beta_{i,j}]_{\text{Normalized}} = \frac{[\beta_{i,j}]}{[\beta_{i,j}]_{\text{Maximum}}}$$

List

Normalized parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Normalized values:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[\beta_{i,j}]$</td>
<td>$0 \leq [\beta_{i,j}]_{\text{Normalized}} \leq 1$</td>
</tr>
</tbody>
</table>

← On down-load link speed in Mbps (DLS):
→ Normalized values of DLS: Maximum and average $d_{\text{max}} \& d_{\text{ave}}$

← On up-load link speed in Mbps (ULS):
→ Normalized values of ULS: Maximum and average $u_{\text{max}} \& u_{\text{ave}}$

← On average web down-load speed in Mbps (WDLS):
→ Normalized values of WDLS $w$

← Probability of success of UDP stream transport (P-UDPS):
→ Voice/music $0 \leq p_1 \leq 1$
→ Video $0 \leq p_2 \leq 1$

← Probability of success of HTTP down-load transport (P-HTTP:DL) $0 \leq p_3 \leq 1$

← Probability of 500 kbps successful streaming (P-500:SS) $0 \leq p_4 \leq 1$
Proportion of unspecified down-loads:
- At link speed > 144 kbps (P-UBR) \[0 \leq f_1 \leq 1\]

Proportion of web page completion (P-WPC) \[0 \leq f_2 \leq 1\]

Proportion of successful transit of 3G (P-3G: ST) \[0 \leq g \leq 1\]

Time-to-first-byte (TFB)
- Normalized values of (TFB) \[\tau\]

Consistency parameter (CPR)
- Normalized values of (CPR) \[c\]

---

**Compute**

Estimating the MSI values via logistic-regression without statistical bounds

- Mobile speed index (MSI) – PCMag.com
- Algorithm: Based on logistic-regression principle

Determine: \[Z_{\text{year}} = \text{Sum of all technological parameters}\]

\[= [(d)_{\text{max}} + (d)_{\text{ave}} + (u)_{\text{max}} + (u)_{\text{ave}} + (w) + (p_1) + (p_2) + (p_3) + (p_4) + (f_1) + (f_2) + (g) + (\tau) + (c)]_{\text{year}}\]

**Next**

- Compute the logistic-regression of \(Z\) via \(f(Z)\) of equation (5.2) [5.5][5.34]

\[f(Z) = \frac{1}{1 + \exp(-Z)} = \frac{1}{2} + \frac{1}{2} \times \tanh(Z/2)\]

**Next**

Prescription of statistical UB and LB on the estimated values of the MSI

LBF: \[L_Q(x)\] is defined via equation (5.4)

- Compute the logistic-regressed values of \(Z\) with the associated UB and LB via equation (3):

\[f(Z)|_Q = \left[ \frac{1}{2} + \frac{1}{2} \times L_Q \left( \frac{Z}{2} \right) \right]\]

\[Z \rightarrow Z_{\text{year}} \quad \text{Sum of all technological parameters}\]

\[Q \rightarrow 1/2: \quad \text{Upper-bound (UB) values}\]

\[Q \rightarrow \infty, \ (\text{say}, \ 10,000): \quad \text{Lower-bound (LB) values}\]

**Results**

- Tabulate the computed values of the MSI and the bounds

\[\text{[MSI}_{\text{year}} \ (0 \ to \ 1)]_{\text{PCMag.com}}\]

\[\text{[MSI}_{\text{year}} \ (0 \ to \ 1)]_{\text{UB and LB}}\]

- Sample results
Table 5-1: Test service area: Boston Metro, MA: USA; Service period: 2010 to 2013

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSI*</td>
<td>MSI-UB</td>
<td>MSI-LB</td>
<td>MSI*</td>
<td>MSI-UB</td>
</tr>
<tr>
<td>AT &amp; T</td>
<td>0.76</td>
<td>0.84</td>
<td>0.68</td>
<td>0.56</td>
</tr>
<tr>
<td>AT &amp; T 3G</td>
<td>0.41</td>
<td>0.46</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>AT &amp; T 4G LTE</td>
<td>0.92</td>
<td>0.87</td>
<td>0.74</td>
<td>0.95</td>
</tr>
<tr>
<td>AT &amp; T HSPA</td>
<td>0.39</td>
<td>0.33</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>Sprint 3G</td>
<td>0.96</td>
<td>0.74</td>
<td>0.58</td>
<td>0.42</td>
</tr>
<tr>
<td>Sprint 4G/LTE</td>
<td>0.56</td>
<td>0.57</td>
<td>0.44</td>
<td>0.45</td>
</tr>
<tr>
<td>T-Mobile</td>
<td>0.69</td>
<td>0.87</td>
<td>0.71</td>
<td>0.63</td>
</tr>
<tr>
<td>T-Mobile  HSPA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Verizon</td>
<td>0.69</td>
<td>0.70</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>Verizon 3G</td>
<td>0.50</td>
<td>0.55</td>
<td>0.42</td>
<td>0.40</td>
</tr>
<tr>
<td>Verizon LTE/4G</td>
<td>0.99</td>
<td>0.99</td>
<td>0.85</td>
<td>0.72</td>
</tr>
<tr>
<td>Metro - PCS</td>
<td>0.41</td>
<td>0.46</td>
<td>0.34</td>
<td>0.31</td>
</tr>
</tbody>
</table>

For a select set of other cities in the US (Dallas, TX, Miami, FL, San Francisco, CA, New York, NY and Charlotte, NC), the computed results on the MSI (and the bounds) across the same service period (2010 – 2013) are presented in the Table A-III of the Appendix.

End

5.6 Role of Service-related Economics Parameters of Wireless Networks

In addition to techno-centric based performance evaluation of mobile services (as conceived and specified by PCMag.com), such mobile services and operations also warrant a better comparative study that involves cohesively, the associated economics details of the
service area concurrent to the underlying technology information. In other words, as contended in the present study, the MSI has to be modified to include comprehensively the technoeconomics details. Relevantly, the approach involves gathering necessary economics details; and, the relative performance of wireless service providers is deduced in terms of both techno-centric, as well as economics-related parameters. Hence, described below are details in formulating a newer performance measure in lieu of the MSI originally proposed by PCMag.com in [5.25]-[5.30].

Considering an entity of economics (such as a product or a service) marketed, its popularity at a given instant of time in a competitive market and in salability contexts could be constrained by prudent risks and decision-theoretics exercised by the manufacturer of the product (or, by the provider of the service). With reference to mobile services, staying robustly in the competitive market is consistent with supply and demand situations in the volatile service market vis-à-vis the quality of the product that enables a high economic utility. Further, in the state-of-the-art mobile service industry, evolution of smart-phone versus feature-phone services has a marked infusion of competition posing significant market-related issues and economics considerations. Also, with the advent of smart handheld devices (plus the added burden of Apps), the associated service penetration across the subscriber base has been very significant in the US as well as, in the global wireless market.

A bird-view study projected in [5.31] portrays how ‘the smart-phone market will look like in 2015’. In essence, considering the overall outlay of modern mobile services supporting the coexisting status of traditional feature phones and the new arrival – smartphones plus Apps, eventually it appears that the smartphones would outsmart the feature version in the market [5.31]; and, it is expected that the service providers would face corresponding technoeconomic implications in their telco business. Therefore, necessary
factors of economics deciding the relative performance of mobile operators need to be comprehensively identified consistent with the supply and demand aspects of wireless services handled by the networks supporting the coexisting smart and feature devices. In addition, such economics details should explicitly address relevant information pertinent to the subscribers, such as: (i) per-capita income (PCI); (ii) customer demography and (iii) the dynamics of societal life-style parameters in the service area. Further, factors of productivity in the subscriber base governing the details on land, labor, capital, information and management, should be duly considered inasmuch as, they implicitly influence the individual wireless operation exercised in a service area.

Thus, in summary, it can be stated that, telco-specific technoeconomic data should be tracked and analyzed in terms of both customer-specific economics as well as technology-driven variations in the business, in order to specify rationally the underlying service performance. In addition, the principle of proportional fairness [5.15] can be introduced in the performance model, where it is presumed that the users express their willingness-to-pay (WP) in terms of dollars for the network resources allocated to them. This would in turn, implicate the underlying consumer economics versus the infrastructure of the mobile network.

Considering the subscriber demography in a given service area, the population of device users and their PCI indices can be gathered and used in the computations of deducing the performance profile of the network operators. In the present study, such values are gathered and prorated with respect to those of national average; and, the resulting fractions are used in the subsequent computations. For example, shown in Table 5-2 are details pertinent to Boston Metro, MA: USA, for the census period 2000-2010. Further, furnished in
Table 5-3 is an illustrative example on the extent of relative sales penetration of smartphones nationwide in the quarterly periods of 2010 to 2011.

Table 5-2: An example of: Census data on population and PCI: USA and Boston Metro, MA: 2000-2010

<table>
<thead>
<tr>
<th>Population</th>
<th>Relative PCI of Boston Metro, MA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boston Metro, MA 2010</td>
<td>USA 2010</td>
</tr>
<tr>
<td>617,594</td>
<td>30,874,5538</td>
</tr>
</tbody>
</table>

Table 5-3: US Smart-phone sales penetration relative to feature phone sales [5.19]

<table>
<thead>
<tr>
<th>2010</th>
<th>2011</th>
<th>2011</th>
<th>2011</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>4th quarter</td>
<td>1st quarter</td>
<td>2nd quarter</td>
<td>3rd quarter</td>
<td>4th quarter</td>
</tr>
<tr>
<td>0.29</td>
<td>0.36</td>
<td>0.41</td>
<td>0.44</td>
<td>0.48</td>
</tr>
</tbody>
</table>

5.6.1 Mobile Carriers Mobile Growth vis-à-vis Productivity-related Economics

In deducing the relative performance of wireless operators using both technology details and the economics parameters, an additional consideration that can be included refers to a productivity-related contribution arising from intense proliferation of mobile devices in the business structure of non-telco sectors. That is, a significant growth of mobile service observed in a service area can be directly linked to the awareness in the non-telco business sector at large, in the augmented use of mobile devices in their business activities. This leads to an impetus towards consistently increasing usage of mobile units and related smart-devices in the work premises (of non-telco operations), so as to obtain enhanced productivity. Such options in non-telco businesses, have implicitly implicated to a significant extent, the positive side of economics in the telco industry. That is, mobile devices and related services are proliferating more and more in business environment thanks
to the growing interest and thrust in such non-telco business sectors seeking high-productivity work ambient. Such efforts in their operations target enhanced productivity of its associates at all levels - the business executives, the field personnel, the technicians and the sales professional. Further, by virtue of facilitating mobile devices in business operations, it has also enabled work-place flexibility with corresponding boost in productivity.

The plethora of vast mobile-device related activities across the business operations in a service area includes: (i) Mobile website explorations and/or related Apps development; (ii) mobile-commerce; (iii) mobile-marketing; (iv) mobile-communications; (v) mobile-technology hardware/software management and (iv) GPS tracking. The associated traffic influx would concurrently invoke inevitable infrastructure enhancements and augmented resources in the mobile networks.

Hence, the performance of mobile services and service providers in any given service area should include cohesively, the productivity-specific economics parameters of the businesses at large in the service area, caused by adopting mobile devices in their work premises. Typically such parameters are listed below as a set \( \{X\}_{1,2,...,8} \) attributed to the productivity stemming from: Business professionals and executives \( (X_1) \), workplace flexibility \( (X_2) \), field/turf personnel \( (X_3) \), sales personnel \( (X_4) \), accessibility of subscriber/service profile and data \( (X_5) \), managing decentralized workforce via mobile service \( (X_6) \), employee retention \( (X_7) \) and employees using consumer devices \( (X_8) \). Typical fractional values of the set \( \{X\}_{1,2,...,8} \) as available in [5.4] are listed in Table 5-4.

Table 5-4: Relative economics productivity parameters \( \textit{vis-à-vis} \) smart-phone deployment in the business suites [5.4]
5.7 Relative Technoeconomic Performance Index (RTPI) of Mobile Carriers

As stated earlier, the efforts by PCMag.com are primarily based on the technology framework of mobile carrier infrastructure; and, such efforts are objectively aim at knowing the “fastest mobile carrier” in the area. However, it is surmised here that, evaluation of performance outcomes based on the hybrid of technology- and economics-related parameters in general, may turn out to be somewhat distinct from those indicated by PCMag.com in terms of the MSI values.

Hence, proposed in this study is an algorithm to evaluate the RTPI of modern mobile carriers. This index duly accounts for the underlying technical as well as economics details. Also, specified on the results of the RTPI is a statistical error-bar deduced by prescribing the UB and LB on the elucidated values of the RTPI. As mentioned earlier, this error-bar indicates the stretch of random variability of constitutive technoeconomic parameters used in the computations. Presented below are details on evaluating the RTPI values using an exemplar set of data relevant to the service area, Boston, MA: USA across the service period, 2010 - 2013.

In short, commensurate with the proposed objective of this study, it is attempted here to define and deduce the RTPI of mobile network services by fusing the economics-related information into the technological details of network infrastructure. This RTPI measure denotes a modified version of the wireless network performance index assigned to mobile
carriers on the basis of comprehensive technoeconomics considerations. It is determined again by resorting to logistic-regression principle; but, the regressors involved are distinctly of two subsets, namely, the variables of the technology details and the parameters of subscriber economics. Further, in order to duly account for any statistical variability of the regressor parameters, necessary upper- and lower-bounds are prescribed on the deduced RTPI values so as to place an error-bar on the estimated values. The procedure conceived to establish the RTPI plus its bounds is outlined briefly in the following subsection followed by a pseudocode.

5.7.1 Evaluating RTPI: An outline

As mentioned above, the RTPI depicts the mobile service performance duly accounting for both technological and economics details of the service and network operations. Considering the economics details exclusively, a pertinent feature parameter, dubbed here as economics-related index (ERI)\textsubscript{year}, can be specified to relate the mobile service evolution in the service area vis-à-vis the underlying economics. This (ERI)\textsubscript{year} should explicitly portray all the relevant data and details on economics-related factors of the service area considered. Further, such factors should include the status of the subscriber demography, the proportionate volume of sales of the service product, the relative \textit{per capita} income in the service area and the set of productivity-specific details, namely, \{X\}_1, 2, ..., 8 pertinent to non-telco businesses adopting mobile devices in their work premises [4], as described earlier.

Using the economics-related features (regressors) enumerated above, again the logistic-regression procedure can be used to obtain the ERI. Then, this ERI values and the MSI values are rationally “mixed” to arrive at the technoeconomics-based RTPI values. That
is, the MSI and the ERI values should be judiciously combined to formulate the RTPI. For this purpose, proposed here is the following strategy based on mixture-theoretics considerations: It involves in the present context, elucidating the effective, statistical mixture characteristics of two entities, namely, the \( \{[\text{MSI}]_{\text{year}}\} \) and the \( \{[\text{ERI}]_{\text{year}}\} \). The resultant value of the mixed-feature is denoted as \( \eta \) and it is given by:

\[
\eta = \{[\text{MSI}]_{\text{year}}\}^\theta \times \{[\text{ERI}]_{\text{year}}\}^{(1-\theta)} \tag{5.5}
\]

where \( \theta \) denotes the fraction of influence of technological factors on the overall performance of the system of the statistical mix of techno-centric and economics variables; and, equation (5.5) is based on the so-called Lichtenecker-Rother formulation (LRF) of statistical mixture theory. The heuristics of LR formula was originally developed as reported in [5.6][5.12], to estimate the resultant property (such as, the dielectric permittivity) of a statistical mixture medium constituted by two or more media. The underlying concept is based on describing the effective property of a mixture medium made of randomly dispersed inclusions in a host receptacle, in terms of a value that lies between two extrema of limits, known as the Wiener bounds.

Considering a mixture medium composed of “m” constituents, suppose \( \pi_i \) denotes the property of the \( i^{\text{th}} \) constituent that fills the statistical mixture medium to an extent of \( \theta_i \). Then, the corresponding so-called Wiener inequality can be written as follows:

\[
\left[ \sum_{i=1}^{m} \theta_i / \pi_i \right]^{-1} \leq (\pi^*) \leq \sum_{i=1}^{m} \theta_i \times \pi_i \tag{5.6}
\]

where \( \pi^* \) is the effective property of the statistical mixture.
Now, considering a two-phase mixture medium, $\pi^*$ can be deduced via the LR relation, namely, $\ln(\pi^*) = [\theta_1 \times \ln(\pi_1) + (1 - \theta_1) \times \ln(\pi_2)]$. Widely known as, the “logarithmic law of mixing”, this LR formulation and/or its modified versions have been extensively adopted to describe the properties of a statistical mixture medium largely in the contexts of elucidating the property (like, the effective permittivity) of a mixture medium. However, explicit use of statistical mixture theory to describe the effective characteristics of a domain of non-physical items mixed statistically is rare, and sparsely addressed. Yet, specific to technological and in technoeconomic contexts, use of the LR formula has shown an acceptable trait as indicated in [5.35]. Therefore, it is applied in the present case, to deduce the resulting status of statistically mixed entities, namely, the MSI and the ERI. Hence, an effective value, $\eta|_{\text{year}}$ denoting the desired $(\text{RTPI})|_{\text{year}}$ of the overall mobile service and network operation in a service area, is estimated. That is, by mixing the MSI and the ERI values logarithmically using the LR formula, the result leads to the required performance index, namely, the $(\text{RTPI})|_{\text{year}}$ value.

Lastly, on the estimated RTPI values, statistical upper- and lower-bounds can be prescribed using the Wiener limits defined via equation (5.6). A step-by-step pursuit towards developing a computational procedure thereof, is furnished in the following pseudocode.

---

**Pseudocode-2 on the algorithmic pursuit to determine the RTPI and its bounds**

**Initialize**

```
%% This computation again refers to the exemplar service area considered earlier towards the evaluation of the MSI values: Boston Metro, MA: USA over the service period: 2010 – 2013.
```

**Input**

**Recall**

120
All techno-centric data on the services rendered relevant to the service area Boston Metro (MA:USA) during the service period 2010-2013 and used in estimating the MSI values:

The estimated MSI values

→ Mobile speed index (MSI) – PCMag.com

List

→ Data and details on economics-related factors: (0 to 1)

← Relative status of population in the service area
(taking the value as 1 at the start, in 2010):

POP

← Relative volume of sales of the service in question
in the service area, (POP × relative sales in that year):

PPS

← Relative per capita income in the service area:

PCI

← Set of productivity-specific economics parameters -
(Normalized values of productivity pertinent to non-
telco businesses in the service area as a result of
adopting mobile devices in their work premises [5.4]
as described in the text:

\{X\}_{1,2,...,8}

Compute

→ \((ERI)_{\text{year}}: \xi_{\text{year}}\) that implicates the mobile service evolution in the service area

→ Algorithm

← Determine: \(\xi_{\text{year}}\)

= [Sum of all the normalized economics-related
parameters]

= \([(POP) + (PPS) + (PCI) + (\sum X_{1,2,...,8})_{\text{year}}]\)

→ Compute the logistic-regression of \(\xi: p(\xi)\)

← \(p(\xi) = 1/[1 + \exp(-\xi)] = (1/2) + (1/2) \times \tanh(\xi/2)\)

→ \(p(\xi) = [ERI]_{\text{year}}\) (0 to 1)

Next

Compute

→ \((RTPI)_{\text{year}}: \eta_{\text{year}}\) that decides the overall mobile service performance in the service area

→ Compute the statistical mixture value of: \{[MSI]_{\text{year}}\} and \{[ERI]_{\text{year}}\}

← \(\eta = [MSI]_{\text{year}}^0 \times [ERI]_{\text{year}}^{1-0}\)
→ {Lichtenecker-Rother (LR) formulation based on statistical mixture theory as described in the text}

← θ = {Fraction of influence of technological factors on the overall performance of the system}

← (1 − θ) = {Fraction of influence of economics on the overall performance of the system}

Next
← Evaluation of the RTPI in the service area within Wiener bounds as decided by: θ and (1 − θ)
← Determine: Effective (RTPI)|year

% Effective (RTPI)|year → [η|year] lies between the Wiener bounds
→ \{[η]|year|\text{W-LB} \leq [η]|year| \leq \{[η]|year|\text{W-UB}\}

% Comment on the effective value of (RTPI)|year = [η]|year| being deduced: This is a statistically implicated parameter (in technoeconomic sense) as decided by the mix of random variables, namely, the MSI and the ERI subspaces existing in the stochastic samplespace. Each of these subspaces is partitioned to an extent as decided by the filling fractions (θ) and (1−θ) respectively. That is, in the context of unbiased statistical mixing, the constituents (namely, the MSI and the ERI) blend to yield an effective value given by: [η]|year| = [(θ) × (ϕ[MSI]|year|) + (1 − θ) × (ϕ[ERI]|year|)] where ϕ depicts an arbitrary function. In other words, the functional attributes of individual mixture constituents weighted by their fractional existence add to form a simple arithmetic mixing process. In the case of material science and associated evaluation of effective mixture properties, a number of functions for ϕ(.) have been prescribed; and, the LR formula is one of them with ϕ(.) being a logarithmic function.

Within the extrema of Wiener bounds, suppose the geometric mean of [MSI]|year| and [ERI]|year| is considered. It would amount to an equally-weighted central disposition of \([(θ) × (ϕ[MSI]|year|) + (1 − θ) × (ϕ[ERI]|year|)]\) when θ = 0.5. This can be currently adopted to yield a statistically-dictated probable value of [η]|year| in the presence of both technological and economics-related considerations.
→ [η]|year| = \{([MSI]|year| × [ERI]|year|)^θ\}^{1/2}
→ Effective (RTPI)|year
→ Geometric mean of: [MSI]|year| and [ERI]|year|
Compute

→ Upper Wiener bound (W-UB) and lower Wiener bound (W-LB) on the relative performance index: 

\[ \text{(RTPI)}_{\text{year}} \equiv \eta |_{\text{year}} \]

← Determine: \[ \{\text{(RTPI)}_{\text{year}} \equiv \eta |_{\text{year}} \} \text{W-UB and W-LB} \]

→ \[ \eta |_{\text{year}} \text{, W-UB} = [\theta \times ([\text{MSI}]_{\text{year}}) + (1 - \theta) \times ([\text{ERI}]_{\text{year}})] \]

→ \[ \eta |_{\text{year}} \text{, W-LB} = \left[ \frac{\theta}{([\text{MSI}]_{\text{year}})} + \frac{1 - \theta}{([\text{ERI}]_{\text{year}})} \right]^{-1} \]

Output

List

→ All input data

→ Service area, period of study, mobile services deployed (service providers), types of service, measured technological parameters of the mobile services in question (as per PCMag.com survey), estimated values of the MSI evaluated by PCMag.com, economics-related parameters in the service area (population fraction, user fraction of mobile services, per capita income and relative productivity entities \(\text{vis-\-à-\-vis}\) mobile service usage)

→ All computed data

→ The MSI values and corresponding upper- and lower-bounds decided via LB-function, the economics-related indices (ERI), effective RTPI values and the associated Wiener bounds (W-UB and W-LB)

Tabulate

→ I(a) Technological factors measured and regressed (by PCMag.com) to obtain the MSI values in the service areas across the test period

I(b) Computed values on the upper- and lower-bounds of the MSI values in the service areas across the test period

→ II(a) Economics-related parameters of the test service areas during the period of study adopted to obtain the RTPI values in the service areas across the test period

II(b) Set of specimen values (the normalized exemplars) of productivity factors influencing the ambient of economics \(\text{versus}\) mobile service usage in the businesses at large, in the service areas across the test period

→ III Computed values of the RTPI: (i) Statistically specified probable (effective) value of \([\eta_{\text{eff}}|_{\text{year}}]\); and, (ii) the Wiener bounds (W-UB
and W-LB) on the RTPI, estimated for the test service areas during the period of study

Plot

→ Set of graphs illustrating the estimated values of: (a) the MSI/PCMag.com: $[\zeta_{\text{year}}] = [\text{MSI}]_{\text{year}}$; (b) statistically-specified RTPI $=[\eta_{\text{eff}}|_{\text{year}}]$ and the Wiener bounds (W-UB and W-LB) on the RTPI: $\{[\eta]_{\text{year}}|_{W-LB}, \leq [\eta_{\text{eff}}|_{\text{year}}] \leq \{[\eta]_{\text{year}}|_{W-UB}\}$

End

---------------------------------------------------------------------------------------------------------------------

5.8 Computed Data

A. *The MSI values and their bounds*

As discussed earlier, the relative performance of mobile service providers supporting smart-devices and the associated service provisions/platforms elucidated and reported by PCMag.com covers comparative details on such services (expressed in terms of the MSI values), entirely based on technological factors. No economics indicators that may influence the gross performance index are specified in the studies reported in [5.25]-[5.30]. Further, the results and the data presented in [5.25]-[5.30] specify rigid values without the imposition of statistical error-bounds.

On the contrary, in any such evaluations (even with known technological details), due consideration is necessary to account for the accompanying statistical variations. Though to a large extent, the technological infrastructure parameters are deterministic, the operational features could however, be fluctuating. For example, the listed techno-centric items adopted by PCMag.com in computing the MSI values include DLS, ULS, P-UDPS, etc as listed earlier; and, all these parameters however, cannot be per se taken as deterministic entities; and as such, the results obtained on the MSI values are not deterministic either. Hence, as proposed here, the estimated values of the MSI should be obtained as an ensemble set with the imposition of
statistical spread on the technological parameters used. This allows establishing an upper- and lower-

bounds on the estimated MSI values. Indicated in the pseudocode presented earlier, are relevant

algorithms to find these bounds; and, furnished in Table A-III (in the Appendix) is a set of results

pertinent to the computed data on the MSI values and their bounds for the service area of, Dallas

(TX), Boston (MA), Miami (FL), San Francisco (CA), New York (NY) and Charlotte (NC), over the

period 2010-2013 across various platforms of mobile devices.

B. The ERI values

For the genre of mobile services addressed while deducing the MSI values are solely

based on the associated technological factors, the scope of this study, however, directs to

include the associated economics and subscriber population details of the service areas in

question while deducing the overall performance outcomes. Hence, emphasized in this study

is a set of factors of economics, (namely, the relative status of demography in the service

area (POP), the relative volume of sales of the service in question in the service area (POP ×

relative sales in that year: PPS), the relative per capita income (PCI) in the service area and

a set of productivity-specific economics parameters described in the text as {X}1, 2, ..., 8), for

logistic-regression so as to yield an economics-related index (ERI)\text{\_}\text{year}; and, the MSI values

together with the ERI outcomes are considered cohesively in mobile service evolution across

the service areas. Again, the steps involved in deducing the (ERI)\text{\_}\text{year} are indicated via a

pseudocode.

C. Deducing the relative technoeconomics performance profiles of the mobile services:

Computed RTPI values

The present study eventually formulates the RTPI in terms of technologically-
specified operational issues (leading to the (MSI)\text{\_}\text{year outcomes) and the factors of economics

expressed via economics-related index (ERI)\text{\_}\text{year. The heuristics of combining the MSI and

125
ERI values is indicated on the basis of LR formulation pertinent to stochastic mixtures. Using the LR formulation as described in the relevant pseudocode, it is shown that, the deduced $\text{(RTPI)}_{\text{year}} = \eta_{\text{year}}$ corresponds to a statistical mixture value of: $\{[\text{MSI}]_{\text{year}}\}$ and $\{[\text{ERI}]_{\text{year}}\}$.

Hence, the effective overall mobile service performance, namely, the RTPI: $\eta_{\text{eff}}_{\text{year}}$ in the service area is expressed within its Wiener bounds: (W-UB) and (W-LB) as follows:

$\{[\eta]_{\text{year}}\}_{\text{W-LB}} \leq [\eta_{\text{eff}}]_{\text{year}} \leq [\eta]_{\text{year}}\}_{\text{W-UB}}$ where $[\eta_{\text{eff}}]_{\text{year}} = \left(([\text{MSI}]_{\text{year}}) \times ([\text{ERI}]_{\text{year}})\right)^{1/2}$. That is, this effective value denotes the effective $\text{(RTPI)}_{\text{year}}$, given by the geometric mean of: $[\text{MSI}]_{\text{year}}$ and $[\text{ERI}]_{\text{year}}$. Computed results on a select group of platforms (Pre 4G and 4G-LTE) of mobile services: AT & T, Verizon, Sprint, T-Mobile and Metro-PCS) pertinent to the example of service area of Boston over the period 2010 to 2013 are presented in Figure 5.1 where the relative performance is indicated as RPI, (denoting, the MSI, the RTPI and the Wiener bounds of the RTPI values) as a function of the service period: 2010 to 2013.
Figure 5.1: Estimated relative performance indicator (RPI) depicting the MSI, the RTPI and the Wiener bounds of the RTPI values versus the service period 2010 through 2013. Service area: BOSTON, MA:USA (a: MSI [25]-[30]; b: RTPI; c: RTPI: W-UB and d: RTPI: W-LB)

5.9 Discussions and Concluding Remarks

Commensurate with the scope of the study, the efforts exercised mainly refer to elucidating the relative performance details of mobile systems supporting assorted platforms while catering services for the smart and feature devices at the subscriber end. Relevant heuristics cohesively include both technological aspects of the service networks as well as, the economics factors associated with the service areas. The present study is a sequel to the tasks of PCMag.com reported in [5.25]-[5.30], where the relative performance comparisons are restricted to outcomes based purely on technological data. On the contrary, it is surmised in this study that, pertinent conclusions on the performance details should be based on both technological and economics-related details of the services analyzed. As such, proposed in this study, are necessary algorithmic considerations to formulate cohesively, the
technoeconomics-based assertions on the performance issues in question. Hence, in addition to the PCMag.com data on techno-centric details used to deduce the MSI values, the economics-constrained attributes on the mobile service performance are duly considered and marked as economics-related indicator (ERI) values; Thus, the net performance characterization of the mobile services considered and analyzed is expressed in terms of the RTPI obtained by using the mixed details of MSI and ERI values. In all, the evaluated RTPI portrays the overall technoeconomics-based service performance of the test wireless networks.

In addition, considering the statistical features of the underlying parameters used in the computations, a pair of upper- and lower-bounds on MSI and RTPI values is prescribed. Such limiting bounds conform to placing a statistical error-bar that duly accounts for the underlying stochastic variations. That is, the data and details adopted in ascertaining the performance indicators are not just being treated as deterministic entities. Considering the random nature of operational technical features and the variability in the economics of the service area, the associated perturbations are duly accounted for while assessing the values of the MSI and/or the RTPI. However, in the studies due to PCMag.com [5.25]-[5.30], neither such bounds are established nor an error-bar is furnished; as such, the present study can be regarded as more comprehensive in accommodating the economics-related issues and incorporating the statistical bounds on the performance indices deduced.

Pertinent to such cohesively fused technical and economics considerations in the analyses of the present study, some example comparisons can be done against the original PCMag.com data. Tabulated in Table A-IV of the Appendix are example values presented to show the efficacy of the study pursued. These are tabulated results that correspond to the
In conclusion, considering the competitive aspects of various wireless networks in vogue, it has become necessary to establish their relative performance. The efforts due to PCMag.com are motivated exercises thereof, spanning 2010 through 2013, carried out to ascertain the relative performance of high-profile wireless network operations across the country. Hence, the survey conducted by PCMag.com has sieved out the "best" service of network operation in the US (during the survey period of 2010 through 2013) on the basis of evaluating the "fastest" mobile service capabilities, deduced purely by using the technological details behind the test mobile wireless communications [5.7-5.9]. Notwithstanding such observed conclusions by PCMag.com, the present study attempts to make a more realistic comparison across the tested networks by considering both technocentric and economics based parameters. Corresponding analytical and computational tasks enable to reach the following inferences:

- The metric of performance comparison should be specified in terms of both technology and economics factors [5.11] [5.13]
- The performance data computed outlines and verifies whether the technology features alone can be used (in all fairness) to declare the network being the "best"
- The technoeconomics-based comparison advocated here can help assessing the future market structure of mobile networks in terms of their relative performance; and relevantly, possible designs for future pricing of wireless services that support heavy-duty profiles of smart devices can be achieved
- It is queried here, whether it can be decided that, a particular mobile service will outperform and beat the challenges of the deregulated market competition, just by looking at a measure decided by technological factors alone. It is opined thereof, that due considerations on related site-specific economics should also be duly taken into
consideration in deducing the performance metric. Otherwise, a realistic and a justifiable comparison becomes questionable; for example, presented in Table 5-5 are computed data on the RTPI (versus the MSI) values of the incumbent mobile services in Boston, MA: USA in 2013; and, the performance indices visibly show distinct results.

Table 5-5: Summary data on the estimated values of the MSI [5.25] - [5.30] and the RTPI at Boston, MA: USA in 2013

<table>
<thead>
<tr>
<th>Mobile Carrier</th>
<th>MSI</th>
<th>RTPI</th>
<th>Statistical variability of the RTPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT &amp; T</td>
<td>0.95</td>
<td>0.75</td>
<td>+13.54 to − 3.40</td>
</tr>
<tr>
<td>Verizon</td>
<td>0.69</td>
<td>0.66</td>
<td>+24.40 to + 7.45</td>
</tr>
<tr>
<td>Sprint</td>
<td>0.67</td>
<td>0.54</td>
<td>+ 18.10 to + 2.80</td>
</tr>
<tr>
<td>T-Mobile</td>
<td>0.54</td>
<td>0.54</td>
<td>+ 20.40 to + 5.80</td>
</tr>
<tr>
<td>Metro-PCS</td>
<td>-</td>
<td>-</td>
<td>+ 27.10 to + 15.60</td>
</tr>
</tbody>
</table>

The results of Table 5-5 indicate that, the MSI details are optimistic; that is, the technology-alone based indices on the 'fastness' of information traffic (in bps) in the service rendered, may over-judge the performance. In reality, however the combined technology and economics-based index (namely, the RTPI), shows the subdued values with a statistical variability so that, a prudent judgment on the performance of the services can be made. Such considerations are however, absent in the studies due to PCMag.com.

Shown in Table 5-6 are more details with limits of statistical error-bar of the RTPI values deduced in the same service premises of Boston, MA:USA, during the period 2010 through 2013.
Table 5-6: Upper and lower percentages of variability of the RTPI values: (Error-bar limits based on Wiener upper- and lower-bounds). Service area BOSTON, MA:USA; Period: 2010-2013 [5.25]-[5.30]

Service providers: AT & T, Verizon, Sprint, T-Mobile and Metro-PCS

<table>
<thead>
<tr>
<th>Year</th>
<th>Service type</th>
<th>Performance indicators (in normalized fractions)</th>
<th>Limits of error-bar in percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MSI</td>
<td>RTPI</td>
</tr>
<tr>
<td>2010</td>
<td>Pre 4G</td>
<td>0.76</td>
<td>0.68</td>
</tr>
<tr>
<td>2011</td>
<td>Pre 4G</td>
<td>0.56</td>
<td>0.56</td>
</tr>
<tr>
<td>2012</td>
<td>4G/LTE</td>
<td>0.92</td>
<td>0.71</td>
</tr>
<tr>
<td>2013</td>
<td>4G/LTE</td>
<td>0.95</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Service area: Boston – Provider Verizon

<table>
<thead>
<tr>
<th>Year</th>
<th>Service type</th>
<th>Performance indicators (in normalized fractions)</th>
<th>Limits of error-bar in percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Pre 4G</td>
<td>0.69</td>
<td>0.66</td>
</tr>
<tr>
<td>2011</td>
<td>Pre 4G</td>
<td>0.69</td>
<td>0.66</td>
</tr>
<tr>
<td>2012</td>
<td>4G/LTE</td>
<td>0.69</td>
<td>0.66</td>
</tr>
<tr>
<td>2013</td>
<td>4G/LTE</td>
<td>0.69</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Service area: Boston – Provider Sprint

<table>
<thead>
<tr>
<th>Year</th>
<th>Service type</th>
<th>Performance indicators (in normalized fractions)</th>
<th>Limits of error-bar in percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Pre 4G</td>
<td>0.96</td>
<td>0.65</td>
</tr>
<tr>
<td>2011</td>
<td>Pre 4G</td>
<td>0.56</td>
<td>0.51</td>
</tr>
<tr>
<td>2012</td>
<td>4G/LTE</td>
<td>0.45</td>
<td>0.47</td>
</tr>
<tr>
<td>2013</td>
<td>4G/LTE</td>
<td>0.67</td>
<td>0.53</td>
</tr>
</tbody>
</table>

Service area: Boston – Provider T-mobile

<table>
<thead>
<tr>
<th>Year</th>
<th>Service type</th>
<th>Performance indicators (in normalized fractions)</th>
<th>Limits of error-bar in percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Pre 4G</td>
<td>0.69</td>
<td>0.72</td>
</tr>
<tr>
<td>2011</td>
<td>Pre 4G</td>
<td>0.63</td>
<td>0.62</td>
</tr>
<tr>
<td>2012</td>
<td>4G/LTE</td>
<td>0.53</td>
<td>0.59</td>
</tr>
<tr>
<td>2013</td>
<td>4G/LTE</td>
<td>0.54</td>
<td>0.53</td>
</tr>
</tbody>
</table>

Service area: Boston – Provider Metro-PCS

<table>
<thead>
<tr>
<th>Year</th>
<th>Service type</th>
<th>Performance indicators (in normalized fractions)</th>
<th>Limits of error-bar in percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Pre 4G</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2011</td>
<td>Pre 4G</td>
<td>0.41</td>
<td>0.61</td>
</tr>
<tr>
<td>2012</td>
<td>4G/LTE</td>
<td>0.31</td>
<td>0.47</td>
</tr>
<tr>
<td>2013</td>
<td>4G/LTE</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

5.10 Closure

The present study paves the way for future marketing (pricing and tariff) issues vis-à-vis competitive performance of mobile service providers. Especially, it is surmised here that the present pricing structure is mostly, the "same-for-all" namely, the same data-plan pricing
for both smart device users and others. Taking into considerations that the demand for resources by the ‘smart-phone users' being unduly heavy, and still these users pay the same tariff like others (who, exercise less burden on the network), there is an inevitable “tragedy-of-commons”. Further, the network neutrality is not followed: One has to pay more for high-speed, byte-intense downloads of the Apps; otherwise, such downloads are “throttled”.

The mobile service providers may revise their pricing structure to be dichotomous, one for smart-device users and the other for dumb and feature devices using possibly, the technoeconomic performance indicator such as, the RTPI. Relevant aspects of pricing mobile services based on smart-and non-smart devices at the terminus in the contexts of coevolving mobile platforms are being studied in business-centric perspectives.
6.1 Introduction

The present study is conceived to develop a business model based on hedonic heuristics and deduce a performance index in terms of the associated “price-worthiness” aspects of service products offered by modern mobile telecommunication operators. The index so obtained is adopted to compare and evaluate the relative performance of competitive mobile networks deployed in a service area supporting App-intense, smart mobile devices concomitant to traditional feature phones. Relevant technoeconomic details and hedonic considerations are fused to infer the performance metric in question. Available data on relevant mobile networks in typical service areas in the U.S. are gathered and a comparison of services rendered is made using the proposed measure named as hedonic pricing index (HPI). The deduced results thereof on price-worthiness of service products versus the technoeconomic features of incumbent networks being compared are presented and discussed.

6.2 Background

In the contexts of long-term evolution (LTE) of modern wireless networks, a rational strategy to prescribe an apt performance measure on the state-of-the-art mobile services and platforms that support smart devices (concurrent to traditional feature (cell)
phones), warrants an appropriate business model. Traditionally, tariff-related parameters in conjunction with technology-specific details have been regarded as appropriate candidates towards prescribing a cohesive performance metric while comparing the services rendered by telecommunication companies (telcos) and related operations [6.1-6.6]. However, such performance comparison of mobile services is done purely on the basis of visible technology-dictated features (such as the speed of wireless traffic in bps); and, the mobile networks are comparatively assessed by ranking them in terms of being the "fastest network" attribute in the service area considered. Correspondingly, a mobile speed index (MSI) is prescribed in [6.1-6.6]. Sparsely included however, in such performance evaluations are certain economics-related facts and productivity enhancement considerations (as a result of mobile device usage) relevant to services areas across the periods of assessment made. Such performance assessment can however, be specified by a relative technoeconomic performance index (RTPI) as proposed by the authors in [6.7].

The present study, offers yet an extended level of performance comparison of mobile services by including the underlying hedonic heuristics and price-worthiness aspects of such services cast as an overlay information upon MSI and RTPI considerations. Hence, the proposed measure of performance is named as hedonic pricing index (HPI) [6.8-6.11] and it is applied to mobile services, (especially in the contexts of those supporting the co-diffusion of smart- and feature-devices) [6.7]. Further, included in framing the HPI are preferential or “choosy” attitude of subscribers (depicting the hedonic mindset) vis-à-vis their willingness-to-pay (WP) (if necessary even more!) for certain dedicated service profiles of their choice. The HPI is also consistent with the eventual tariff scheme adopted by service providers based on their willingness-to-accept (WA) strategy implicated by return-on-investment (RoI) and budget constraints.
Presented below are relevant background details on such service profiles and related LTE prospects. Also outlined are the underlying hedonic heuristics in prescribing the proposed model for the price-worthiness of such services and deducing thereof, the HPI. Relevant motivational considerations and scope of the present study are presented prior to HPI analysis. Accordingly, this chapter is structured as follows: In the following section (Section 6.3), a review on LTE prospects of mobile networks are presented. The existing practice of assessing the relative performance of mobile networks in terms of MSI and RTPI parameters is outlined in Section 6.4. Commensurate with the proposed method of using hedonic heuristics in prescribing a price-worthiness of services rendered in a service area and deducing thereof, the HPI, a basic tutorial is presented in Section 6.5 on relevant considerations pertinent to hedonic concepts; and, the underlying aspects are extended in Section 6.6 to deduce the HPI. In Section 6, the deduced results pertinent to a set of wireless networks and services on MSI, RTPI and HPI are presented cohesively for comparison. Discussions on the proposed considerations and the results obtained thereof are furnished in Section 6.7; and, the computed details on the relative performance of mobile networks studied are cross-verified against actual price index levied by those incumbent mobile operators in the test service area over a known period. Hence, the observed details are rationally viewed with conclusive remarks in Section 6.8.

6.3 Mobile Networks in LTE Contexts

The LTE technology as specified within the scope of 3GPP/Release has been in vogue across a number of commercial mobile networks around the globe; and, the associated mobile-system technology in modern context is devised to bear an infrastructure that largely supports intense diverse data applications (DDA) with the advent of heavily proliferating
smart devices and related Apps in wireless networks. Concomitantly, such networks are also structured to support operations that oversee the coexistence of traditional feature-phone services as necessary. In essence, the state-of-the-art mobile network services intended for data applications support both simple feature phones as well as smart-devices with App dedication. Correspondingly, the service resources get tied to product characteristics and as such, the observed price or tariff extended to the subscribers is a function of quality-of-service (QoS) being rendered across the differentiated classes of services offered [6.12].

Considering the classical era of telecommunication service industry (wireline and/or wireless), relevant pricing of services rendered and tariff structure imposed was simple; and, such prescriptions were primarily intended for switched-circuit architectures supporting voice and low-bps data transmissions. Subsequent pricing models on telco services included the emerging trends in Internet provisioning. They were developed on the basis of complex system heuristics [6.12] [6.13]. Typically, relevant technoeconomic models that depict a nonlinear evolution of the functional relation concerning the fractional change in consumer reaction (in terms of consumer surplus, V) to changes in Internet pricing was developed. Hence, the price elasticity of demand (E) versus V specific to differentially classifiable services on QoS (DiffServ)-centric Internet architectures has been developed and the model is applied to dynamic-, smart- and static-market pricing schemes as described in [6.12].

Under the scope of wireless services rendered in LTE [6.14] contexts and, with the advent of Internet-enabled DDA transmissions of modern time, there is a plethora of offerings that target different markets, especially pertinent to App-intense, smart handheld devices that coexist with traditional feature phones. Relevant service provisioning target both small and medium enterprises (SMEs) needing business-related DDA support as well as household market where entertainment-specific Apps are in extensive use [6.15] [6.16].
Across the evolution of telecommunications seen in the yesteryears, the physical telephony was largely owned by incumbent local exchange carriers (ILECS) such as, the Bell systems carriers in the US and the British Telecom (BT) in the UK who enjoyed the monopolistic advantage in offering both retail and wholesale telco services. Subsequent to deregulation, the competitive local exchange carriers (CLECs) and Internet services providers (ISPs) stepped in to sell the wholesale services of the ILECs, with limited market share. Later, the telco competition expanded across mobile service operators joining the market (in addition to MSOs) and their share has taken a larger limit thanks to the growing cell-phone users in the initial stages and subsequent proliferation of Internet traffic across wireless media due to extensive demand posed by data transmissions. In the recent times, the trend of such data support has taken a newer dimension with DDA been ushered in, as a result of increased users of coexisting feature phones and smart handheld devices. More so, such DDA demand has leaped forward with the so-called APP-penetration into mobile phones and other handheld devices, which have been turned into architectures having the versatility of computers-in-the-palm via wireless connectivity.

The technological burden on modern wireless operation can be specified by the associated service and resource requirements. Accordingly, the evolution of mobile phone services can be traced to this day with the shifted paradigm to a group of newer technologies known to be called as Fourth Generation Mobile Networks (4G). It is an integrated, global network based on open-systems approach replacing the existing proliferation of core cellular networks with a single standard on worldwide cellular core network using the Internet Protocol (IP) for control, video, packet data, and VoIP services. This integrated 4G mobile system provides wireless users affordable broadband mobile access solutions for applications of secured wireless mobile Internet services with value-added QoS. Further, 4G
enclaves the prospects of LTE and it carries the burden that rests on the shoulders of multiple generations of mobile networks to support the widely used and intensely sought smart applications across the gamut of handheld devices [6.14].

Any pricing model on the mobile services with the burden as above can be directly correlated to the techno-centric requirements vis-à-vis the performance anticipated. Typical technological parameters that influence the eventual pricing structure of mobile services are as follows [6.1-6.6]: 

(i) **Download speed** depicting the speed (in bps) in the down-link with which the subscriber downloads any entity of triple services from the network. In wireless network operations, faster downloads are implied due to accessing preferred entities like pictures, movies, video chat on-the-go etc. 

(ii) **Upload speed** in bps relevant to the up-link with which the subscriber uploads any entity of triple services from the network. Conceived and evolved as 4G LTE service, it allows fast cellular data on the Internet for hand-held devices.

(iii) **UDP stream success probability**: The IETF-RFC 6544 indicates that, “… if a particular media-stream can run over user data protocol (UDP) or transmission control protocol (TCP), the UDP candidates might be … a balance between success probability and the resulting path's efficiency”. Time-sensitive applications (like streaming-media) often use UDP because dropping packets is preferable to waiting for delayed packets, which may not be an option in real-time systems. That is, in order to conserve minimal transactional delay by avoiding large overheads in supporting the data-intense streaming payload, the UDP is prescribed for media-streaming transmissions.

(iv) **http download success probability**: It refers to the probability of realizing a download throughput successfully due to the stochastic nature of throughput-distance parameters within a given radius of coverage.

(v) **Downloads in excess of nominal bit rates (such as 144 kbps)**: Set in the traditional 2G, a nominal rate 144 kbps for mobile users and 2 Mbps for stationary users are prescribed. In
modern mobile communication systems, in addition to serving end units of smart type, substantial service facilitation is pertinent to basic cellular telephony and use of “dumb” devices or feature phones. As such, the traffic supported at the nominal rate is crucial in deciding the performance of the wireless network. (vi) Other technology-centric parameters: There are also other technology-specific and service-related details that need to be duly considered in evaluating the price-worthiness of the services rendered in the context of 3G and (4G, 4G LTE) operations. Relevant technology aspects are decided by end-devices, network infrastructure and various service profiles. Salient technology-related considerations are pertinent to: End-devices, asymmetric communication between the users and serving base-station (BS), capacity (C) of the base-station and maximum rate (R) of information transmission, network types and service coverage. (vii) Service-related economics parameters such as percapita income (PCI) of the subscriber base, customer population, dynamics of societal life-style parameters in the service area and factors of productivity governing land, labor, capital, information and management details. Lastly, (viii) economics attributed to productivity stemming from business professionals and executives, workplace flexibility, field/turf personnel, sales personnel, accessibility of subscriber/service profile and data, managing decentralized workforce via mobile service, employee retention and employees using consumer devices [6.7].

6.4 Performance Measures of Mobile Networks

To compare the performance of mobile services rendered by different competing operators in a given service area, PCMag.com [6.1-6.6] established a mobile speed index (MSI) purely on the basis of techno-centric parameters of the wireless operations. However, if an evaluation of the performance is pursued on the basis of technology plus economics-
related parameters relevant to a service area, it may turn out to be somewhat distinct from MSI values of PCMag.com [6.1-6.6]. That is, a *technoeconomics-based relative performance index* (RTPI) of modern mobile carriers would yield results distinct from those of MSI-based computations as summarized *via* relevant pseudocodes described below (briefing the methods of MSI and RTPI evaluations) by considering exemplar sets of mobile networks in a specific service area in the nation. Notwithstanding such MSI- and RTPI-based performance comparisons of mobile networks is feasible, yet another way of performance assessment is attempted in the present study. As mentioned before, it is based on hedonic heuristics of price-worthiness of the services. That is, the scope of the present study is concerned with developing a business model that indicates a consumer-liking based, adjusted pricing and the associated tariff structure for the services offered in an area by a set of providers; hence, a performance comparison of such services on the basis of underlying hedonic attributes of the products facilitated is carried out by cohesively combining MSI and RTPI attributes with HPI details.

Pseudocode to determine MSI and RTPI of mobile carriers

**Initialize**

**Input**

→ Data and details on the mobile service rendered

← Name of the service area (Example: Boston Metro, USA)

← Service period (i) (Example: 2010-2013)

← Name of the mobile service provider (j): (Example: AT&T Wireless)

← Service type evolution (k):


→ Data and details on the technological factors (PCMag.com specific) attributes ($\ell$) [6.1-6.6]

→ Mobile-speed parameters: \([M_{ij,k}]_{\ell}\)
→ Down-load link speed in Mbps: Normalized with respect to average speed of 4 services (DLS)
→ Down-load link speed in Mbps: Normalized with respect to average speed of 4 services (ULS)
→ Probability of success of UDP stream transport (UDPS)
→ Probability of success of HTTP down-load transport (HTTP-DLS)
→ Proportion of unspecified down-loads at link speed > 144 kbps (UBR)

**Compute**

→ Mobile speed index (MSI) – PCMag.com Algorithm [6.1-6.6]
→ Determine: \[ z_{\text{year}} = \text{Sum of all technological parameters} = [(\text{DLS}) + (\text{ULS}) + (\text{UDPS}) + (\text{HTTP-DLS}) + (\text{UBR})] \]

**Next**

→ Compute the logistic regression of \( z \): \( p(z) = 1/[1 + \exp(-z)] \)
→ \( p(z) = [\text{MSI}_{\text{year}} \ (0 \ to \ 1)]_{\text{PCMag.com}} \)

**Tabulate**

→ Computed \([\text{MSI}_{\text{year}} \ (0 \ to \ 1)]_{\text{PCMag.com}} \) → Table 6-1

**Next**

**Compute**

→ Relative technoeconomics performance index (RTPI) [6.7]

**Input**

→ Data and details on economics-related factors (m)
→ Relative status of population in the service area (taking the value as 1 at the start, in 2010 (PP))
→ Relative volume of sales of the service in question in the service area (PP \times \text{relative sales in that year: PPS})
→ Relative per capita income in the service area (PCI)
→ Set of productivity-specific economics parameters (n) (normalized relative values of productivity pertinent to businesses at large in the service area as a result of adopting mobile devices in their work premises [6.7] as described in Table 6-2: \{X\}_{1,2,...,8}

**Next**

**Compute**

→ Economics-related index (ERI)\_\text{year}: \( \xi_{\text{year}} \) that decides the mobile service evolution in the service area
→ Algorithm
→ Determine: \( \xi_{\text{year}} = [\text{Sum of all economics-related parameters}]_{\text{Normalized}} = [(\text{PP}) + (\text{PPS}) + (\text{PCI}) + (\Sigma X_{1,2,...,8})_{\text{year}}]_{\text{Normalized}} \)
→ Compute the logistic regression of \( \xi \): \( p(\xi) \)
\[ p(\xi) = \frac{1}{1 + \exp(-\xi)} \]
\[ p(\xi) = [\text{ERI}_{\text{year}} (0 \text{ to } 1)] \]

**Next Compute**

→ Relative performance index \((\text{RTPI})_{\text{year}}\): \(\chi_{\text{year}}\) that decides the overall mobile service performance in the service area

→ Compute the statistical mixture value of: \([\text{MSI}_{\text{year}}]\) and \([\text{ERI}_{\text{year}}]\) = \(\eta\)

\[ \chi = \{[\text{MSI}_{\text{year}}]\}^0 \times \{[\text{ERI}_{\text{year}}]\}^{(1-\theta)} \]

→ *Lichtenecker-Rother (LR) formulation: Statistical mixture theory [6.18]*

\[ \theta = \{\text{Proportionate fraction of influence of technological factors on the overall performance of the system on statistical basis}\} \]

**LR formula:** This was originally developed as reported in [6.18] to estimate the resultant electric permittivity of a statistical mixture medium constituted by two or more dielectric media. Relevant concept is described in Chapter 5. Specific to technological and in technoeconomic contexts, it is surmised here that use of LR formula would follow an acceptable trait. Hence, it is applied in the present case to address the status of statistical mixing MSI and ERI in the technoeconomic framework of mobile services. And the effective value, namely \(\chi\), which denotes the relative performance index \((\text{RTPI})_{\text{year}}\) decides the overall mobile service performance in the service area namely, \(\chi_{\text{year}}\)

**Tabulate**

→ Computed \([\text{RTPI}_{\text{year}} (0 \text{ to } 1)]\)

\[ \text{Construct Table 6-2} \]

**Continue**

→ Perform computations for other service operations (j)

\[ \text{Tabulate the results} \]

**Continue**

→ Perform computations for other service areas
Tabulate the results

In addition to service features (characteristics) implicated by MSI and RTPI described above including subscribers’ perspectives that implicitly depict the hedonic attributes in deducing the overall performance of mobile operations is the theme of the present study.

Table 6-1: Evaluation of MSI: Exemplified with relevant turf data of a mobile network provider in a service area

<table>
<thead>
<tr>
<th>Constitutive variables - Vector sets of:</th>
<th>Service area: Boston, MA: USA</th>
<th>Service provider: (j) : AT &amp; T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comprehensive field data on the vector sets: ((M_i)_{jk}) and computed results on MSI [6.1-6.6]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mobile-speed deciding parameters ([M_i]_{jk})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Service period (i)</td>
<td>Service type (k)</td>
<td>Availability status coefficient</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>2011</td>
<td>2012</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Down-load link speed (Normalized with respect to average speed of 4 services): DLS</td>
<td>1</td>
<td>0.21</td>
</tr>
<tr>
<td>Up-load link speed (Normalized with respect to average speed of 4 services): ULS</td>
<td>2</td>
<td>0.30</td>
</tr>
<tr>
<td>Probability of success of UDP stream transport: UDP</td>
<td>3</td>
<td>0.76</td>
</tr>
<tr>
<td>Probability of success of HTTP down-load transport: HTTP-DLS</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>Proportion of unspecified down-loads at link speed &gt; 144 kbps: UBR</td>
<td>5</td>
<td>1.00</td>
</tr>
<tr>
<td>Estimated MSI (from 2010 to 2013)</td>
<td>0.76</td>
<td>0.56</td>
</tr>
</tbody>
</table>
The associated hedonic structure would decide the eventual mobile network performance and correspondingly, the price structure of the tariff plans on services rendered to subscribers will be set by mobile operators.

Relevantly, with necessary constraints imposed (such as byte-size supported) as in the service level agreement (SLA), the method of tariff prescription denotes a *quality adjustment pricing*, which can be modeled in terms of the so-called hedonic pricing concept proposed here. Based on such hedonic heuristics, the price-worthiness of the services are distinguished so as to make a realistic comparative assessment of services and products in question.

Table 6-2: Evaluation of RTPI: Exemplified with relevant turf data of a mobile network provider in the service area

<table>
<thead>
<tr>
<th>Constitutive variables - Vector sets of:</th>
<th>Service period (i)</th>
<th>Service type (k)</th>
<th>Availability status coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2010</td>
<td>2011</td>
<td>2012</td>
</tr>
<tr>
<td>Economic-related relative parameters ((E_i)_{jk})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative population (taking the value as 1 in 2010: 617,594) PP</td>
<td>1</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Relative volum of sales (taking the value as 1 in 2010) PPS</td>
<td>2</td>
<td>1.00</td>
<td>1.36</td>
</tr>
<tr>
<td>Relative per capita incom: PCI</td>
<td>3</td>
<td>1.19</td>
<td>1.19</td>
</tr>
<tr>
<td>([X_i]_{jk}) Relative parameters on</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(m)</td>
<td>(\gamma_m)</td>
<td>(\gamma_m)</td>
<td>(\gamma_m)</td>
</tr>
<tr>
<td>(n)</td>
<td>(\eta_n)</td>
<td>(\eta_n)</td>
<td>(\eta_n)</td>
</tr>
<tr>
<td>productivity due to:</td>
<td>2010</td>
<td>2011</td>
<td>2012</td>
</tr>
<tr>
<td>---------------------------------------------</td>
<td>------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>Professional and executives: PE</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Work-place flexibility: WF</td>
<td>0.93</td>
<td>0.93</td>
<td>0.93</td>
</tr>
<tr>
<td>Field/turf personnel: FP</td>
<td>0.85</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>Sales personnel: SP</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>Accessibility of data on: Subscriber versus service profile: AD</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>Management of decentralized workforce via mobile service: MW</td>
<td>0.44</td>
<td>0.44</td>
<td>0.44</td>
</tr>
<tr>
<td>Employee retention: ER</td>
<td>0.42</td>
<td>0.42</td>
<td>0.42</td>
</tr>
<tr>
<td>Employee using consumer mobile devices: EM</td>
<td>0.39</td>
<td>0.39</td>
<td>0.39</td>
</tr>
<tr>
<td>Estimated RTPI (from 2010 to 2013)</td>
<td>0.68</td>
<td>0.55</td>
<td>0.71</td>
</tr>
</tbody>
</table>

In order to illustrate the proposed approach towards deducing the eventual mobile network performance, an overview on the subject of hedonic heuristics is first outlined in the following section:

6.5 Hedonic Heuristics: An Overview

Hedonic approach basically attempts to guide the selection of characteristics of goods and products by their economic meanings. In such contexts of being economically meaningful or interpretable variables are chosen to prescribe a regression equation on the product characteristics “which not only absorb producers’ resource cost but also generate value to users” [6.19]. Hence, hedonic pricing is based on a multiple regression method and relevant approach signifies the selection process of product characteristics that are used in the regression. This approach was first used to price vegetables [6.20]. Later as described in [6.21], this method was applied to capture the characteristics of automobiles that influence pricing with the characteristics vis-à-vis consumers' "pleasure and comfort," ( - a phrase from which the term “hedonic” was coined).
The following three principles are proposed in hedonic pricing by Triplett [6.19]: (i) The selected variables are homogeneous economic building block from which heterogeneous goods are priced. (ii) The selected variables are valued by both buyer and seller; and, (ii) the price represents the valuation of all the variables combined. Typically, the multiple regression method adopted in hedonic approach is a linear model, which estimates how the dependent variable is predicted by the independent variables. However, the so-called Box-Cox methodology [6.22] provides a means to relax the assumption of linearity by determining the adequate data transformation that gives rise to the best goodness-of-fit. It is an objective estimation method, through which subjectivity could be eliminated in the choice of the functional form for the independent variables [6.23].

6.6 Hedonic Pricing Structure in Telecommunications

To apply hedonic heuristics in the framework of mobile network operations, a class of regression modules can be conceived to include the associated price/tariff structure. It is based on the assumption that a product or a service is perceived to bear a "bundle of characteristics" and the consumers tend to buy such a bundle instead of the product itself. In short, whenever the price adjustment and prescription of tariff by mobile service providers is set vis-à-vis the quality (and not the quantity), the associated modeling can be regarded as hedonic. That is, the hedonic notion suggests a “characteristics-dependent” or “adjusted price index” for the services in question; and, whenever a large amount of product varieties are made available by service providers, the hedonic pricing may turn out to be a win-win strategy. That is, the hedonic pricing options would allow consumers to maximize their utilities and the providers thereof maximize their profits.
The hedonic heuristics can be judiciously applied to modern mobile Internet platforms that provide services to a variety of customers using feature phone as well as smart devices with DDA suites. As such, a diverse set of data transmissions (expressed in terms of bandwidth, bit rate etc.) are facilitated in the mobile network infrastructure – from basic data transmissions to large bandwidth (BW) (or high bit-rate) based App-intense information transits. In other words, there is an inherent heterogeneity of information transmission in mobile Internet services; and, relevant mobile service commodity implies a market that can be aptly described via hedonic or characteristic terms. That is, the services supported can be conceptualized not as a simple homogeneous composite good, but as a bundle of individual attributes, each of which contributes to provisioning one or more specific service types and placing concomitant demand on the associated resource requirements.

Modern telco services (such as those supporting App-intense DDA specific Internet service rendered to smart and feature phone users indicated above) grossly influence the market prices and therefore, the price-worthiness of such services needs a logistic adjudication. This would allow a fair comparison of the performance of network providers who offer competitively similar services to the subscribers in a service area. Evolving thereof a price-worthiness based performance index resides on viewing the price structure of each mobile network in terms of hedonic perspectives so as to assess the economic values of the services offered. In technoeconomics point of view, the associated hedonic regression or hedonic demand theory implies a revealed preference method of estimating the demand or value of the service-product.

The underlying procedure involves decomposing the technoeconomic product into its constituent characteristics and obtains estimates of the contributory value of each characteristic. That is, the composite good (namely, the service under consideration) being
valued is reduced to its constituent parts and, the market values reflect those constituent parts individually. For such individualized valuation, an attribute vector (a dummy or panel variable) is typically assigned to each characteristic or group of characteristics.

As stated earlier, the hedonic pricing method is based on the fact that prices of goods in a market are affected by their characteristics. For example, the price of a telco service will depend on the ease of availability, technology used, popularity of the established service provider, specific needs of the user, etc. Relevantly, hedonic pricing would allow estimating the value of the service commodity of the telco consistent with the dynamics of subscriber’s WP for the commodity as and when its characteristics change.

Pertinent to the telco market, the value of a service product would depend on QoS-based demand and the supply of service rendered thereof. If there is a measurable hike in price of the services offered by a service provider (as compared to other operators in the service areas), the difference in prices would reflect, possibly the exogenic cost of technology introduced towards higher QoS-on-demand. It refers to the marginal WP (in terms of higher service prices) for a given difference in QoS observed between the service rendered by an incumbent operator and those by other operators in that service area. Hedonic regression would then lead to estimating the underlying price differentials.

Hence, the so-called Hedonic Pricing Method (HPM) refers to a revealed preference method of valuation (or prescribing a price-worthiness measure) of the telco service in question and it would also implicitly depict a performance index for the service concerned. In short, a subscriber’s preference towards a particular telco service or operator and paying an extra premium thereof becomes HPM-specific, if the service-related QoS component of the value and the market price are separated. In other words, the market price can be regarded as a surrogate for the QoS value of the service.
A classical hedonic pricing model due to Rosen [6.24] recognized that the market price of complex goods (like, mobile DDA services being considered in the present study to support smart devices) is jointly linked to consumer evaluations of each of the individual services facilitated and by the service provider's offering price for each such services. Corresponding hedonic model or equations denote an envelope of a family of "value functions" conceptualizing consumer utility and another format of "offer functions" describing the tariff economics extended by service providers. Described below are vertical aspects of such a hedonic model and its applicability to the pricing structure sought to prescribe an implicit performance index to compare modern mobile operations in a service area.

Suppose the WP attribute of the consumers (namely, the maximum price the subscriber would be willing to pay) corresponds to alternative bundles of the set \( \{Z_k\}_j = 1, 2, ..., K \) available from \( \{j = 1, 2, ..., J\} \) mobile operators in the service area of interest. Further, for any \( j^{th} \) operator, the offered service bundle \( Z_k \) is assumed to contain varying amount of attributes, \( \{X_s: x_1, x_2, ..., x_s, ..., x_{S_j}\} \) and \( s \in \{\ell, m, n\} \). The set \( \{X_s\}_j \) depicts the assortments of service feature bundle (from the \( j^{th} \) service provider) and the cardinality of the set \( \{X_s\}_j \) namely, \( S \) may vary from provider-to-provider. Now, assuming that the consumer's choice of the price as \( H \), it is consistent with levels of affordability \( (y) \) on the price and a formal expression for \( H \) can be written in terms of an implicit function, \( \Theta(.) \) as follow:

\[
H = \Theta(Z_1, Z_2, ..., Z_k; y, \Omega) \quad (6.1)
\]

where \( \Omega \) denotes a vector of taste (preferential choice of the subscriber); that is, \( \Omega \) represents the choosy domain characteristics of the mobile services (such as preferred Apps). Symmetrically, suppose \( \psi \) is the offer function on the unit price that a telco is willing-to-
accept (WA) for the bundle of services it offers. Then, assuming that telcos in a service area are competitors who rationally maximize their profit and RoI, then Ψ can also be formally written as an implicit function ϕ(.) in terms of \{Z_i\}_{i=1,2,\ldots,k}, bandwidth (BW), capacity of the network (C) and technology-dependent CAPEX ad OPEX liability (L_{co}) on service provisioning. That is,

\[ \Psi = \Phi(Z_1, Z_2, \ldots, Z_k; C, L_{co}) \quad (6.2) \]

In applying HPM toward telco services using the functional considerations of H and Ψ as above, an assumption made is that the value of a service is affected by a particular combination of characteristics that it possesses; as such, better characteristics are graded with higher prices as compared to those with subdued characteristics via the notions of HPM. Thus, the price of a telco service will be influenced by the technology-based feature characteristics (\ell_1, \ell_2, \ldots \text{ etc.}) of the service itself, App-specific QoS parameters (q_1, q_2, \ldots \text{ etc.}), and bundled service characteristics specified by the set, \{X_s\}.

6.7 Comparison of Mobile Networks via Price/Tariff Related Hedonic

Based on mobile service ambient described above and assuming a hedonic price structure plus the prescribed tariff models advocated by the incumbent service providers in the service area, formulating a comparative performance index so as to assess the relative “price-worthiness” of the products of each service provider forms the thematic effort. Hence, the deduced HPI includes a judicious fusion of MSI and RTPI details yielding eventually an appropriate and meaningful performance metric assessing the relative mobile network operations. The underlying considerations are elaborated in the following subsection:
6.8 Hedonic Approach toward Pricing of Telco Services: Proposed Model

Relevant to the theme of the present study in specifying a hedonic pricing structure to mobile services and derive thereof a performance measure so as to compare relatively, different service operations in a given service area, the existing hedonic pricing strategies advocated in the literature are as follows: Building a hedonic regression model in making direct price adjustments *vis-à-vis* quality changes in the consumer price index for Internet access services (known as “Internet services and electronic information providers,” item index SEEE03) involves the use of the so-called Box-Cox regression as described in [6.25]. Further, hedonic pricing analysis has been indicated for DSL Internet services in order to identify key factors that determine the pricing of DSL service; hence, potential users of DSL services can sort out the maze of pricing practices and the marketers can devise effective pricing strategies [6.26, 6.27, 6.37, 6.10]. Presented below is a pseudocode written to explain the evaluation of HPI in wireless network contexts.

Pseudocode to determine hedonic pricing index (HPI)

```%\% Hedonic pricing model applied to wireless networks supporting smart mobile devices and service

**Initialize**

**Input**

→ Service area: Boston

→ Year (i)

← Starting from: i = 1 ↔ 2010

← Ending in: i = 4 ↔ 2013

→ Service provider (j)

← j = 1 ↔ AT & T

← j = 2 ↔ Verizon

← j = 3 ↔ Sprint

← j = 4 ↔ T-Mobile

→ Type of service (k)

← k = 1 ↔ Pre 4G

← k = 2 ↔ 4G LTE
```
Define/Get Data on

Performance specific indices

→ Mobile speed related performance index/MSI -- Table 6-1
  \((M_{i,j,k})\)

→ Economics-related performance index/ERI -- Table 6-2
  \((E_{i,j,k})\)

→ Productivity-related performance index/PRI -- Table 6-2
  \((X_{i,j,k})\)

Construct

Consumer-preference (consumer “crush”) related performance index/CRI:

\((Y_{i,j,k})\)

→ CRI are listed in -- Table 6-3
→ Data is availed from [6.28-6.30,6.36]

Set-up/Define

→ Hedonic pricing model

\((P_{i,j,k}) = f(M_{i}, E_{i}, X_{i}, Y_{i})_{j,k}\)

→ Real price of the service, (that is, willingness-to-accept (WA) price structure constrained by return-on-investment (RoI); also, known as producer price index/PPI) in the \(i^{th}\) year offered by the \(j^{th}\) service provider for the \(k^{th}\) service type

\(f(M_{i}, E_{i}, X_{i}, Y_{i})_{j,k} = \text{Real price of the service in the } i^{th} \text{ year offered by the } j^{th} \text{ service provider for the } k^{th} \text{ service type}\)

Assign

→ Identify explicitly the constitutive entities of \((M_{i,j,k}), (E_{i,j,k}), (X_{i,j,k}), \text{ and } (Y_{i,j,k})\)

→ Assign (normalized) relative weights to the constitutive entities (vectors) of \((M_{i,j,k}), (E_{i,j,k}), (X_{i,j,k}), \text{ and } (Y_{i,j,k})\)

→ For each of the constitutive vectors of \((M_{i,j,k}), (E_{i,j,k}), (X_{i,j,k}), \text{ and } (Y_{i,j,k})\) designate binary variables, 1 (for available) or 0 (for non-available) state

→ Construct thereof a relevant Table on the vector set \((Y_{i,j,k})\)
  → Table 6-3

Assumptions

→ The constitutive vectors of \((M_{i,j,k}), (E_{i,j,k}), (X_{i,j,k}), \text{ and } (Y_{i,j,k})\) are explanatory variables in hedonic regression context

→ All the entities of the vector sets (itemized in Table 6-1-6.3) are homogeneous variables

→ These variables are building blocks from which the heterogeneous goods and services are realized

→ They are valued by both producers (service providers) as well as consumers (subscribers)

Estimation

→ The objective in hand, is to estimate \(P_{i,j,k}\) denoting the real price index of the service (or PPI) under hedonic perspectives
Relevant estimation is constrained by:

- Willingness-to-accept (WA) by the producer subject to RoI decided by budget-line restrictions
- Willingness-to-pay (WP) by the consumer subject to hedonic criterion

**Model**

The hedonic model (algorithm) to determine \([P_{i,j,k}]\), is as follows:

- It is a constrained optimization problem that can be stated as follows:
  - Maximize: \([P_{i,j,k}]\)
  - Subject to the constraints:
    - \([P_{i,j,k}] \geq \text{WA decided by budget-line restrictions: RoI}\)
    - \([P_{i,j,k}] \leq \text{WP decided by consumers’ choice}\)

**Analysis**

- \([P_{i,j,k}]\) is set by the functional relation: \(f(M_i, E_i, X_i, Y_i)_{i,j,k}\)
- The constraints namely, \([\text{WA and WP}]\) themselves can be expressed as the functional: \(f(M_i, E_i, X_i, Y_i)_{i,j,k}\)

In order to accommodate the constraints on the optimization in question, a penalizing Lagrangian coefficient, \(\lambda\) can be stipulated so that, a solution towards maximizing \(f(.)\) can be found in terms of the Lagrangian, \(L(.)\) given below:

\[
L(M_i, E_i, X_i, Y_i; \lambda_i)_{i,j,k} = f(M_i, E_i, X_i, Y_i)_{i,j,k} + \sum_c [\lambda_i^c \times \phi(M_i, E_i, X_i, Y_i)_{i,j,k}]_{\text{WA, WP}}
\]

Each \(\lambda_c\) gives the price associated with constraint, \(c\).

Suppose stated in a generic format that \(z^* = (z_1^*, z_2^*, \ldots, z_u^*)\) maximizes \([f(z)]_{i,j,k}\) subject to \([f_c(z)]_{i,j,k} = C_c\) for \(c = 1, 2, \ldots, v\). Then, there exists a vector, \(\lambda^* = (\lambda_1^*, \lambda_2^*, \ldots, \lambda_v^*)\) such that \(\nabla L(z^*, \lambda^*) = 0\).

A suboptimal solution for the maximized \([f(z)]_{i,j,k}\) is a logistic function that can be written in a general form as described below:

The resulting logistic function (or logit function), \(P(z)\) conforms to the explanatory variable \(z\) being equal to: \(a_0 + a_1 z_1 + \ldots + a_u z_u\) in \(f(z)\), where \(\{z_1, z_2, \text{etc.}\}\) denote contributory set of predictive regressors and \(\{a_1, a_2, \text{etc.}\}\) are regression coefficients properly assigned to ‘weigh’ the predictive variables. Further, the logistic regression function, \(P(z)\) satisfies the following limiting cases: As \(z \to \infty\), \(P \to 1\) and as \(z \to 0\),
P → 0. That is, the outcome of suboptimal solution sought (in normalized form) is specified between 0 to 1.

In an explicit form, \( p(z) = 1/[1 + \exp(-z)] \equiv (1/2) + (1/2) \times \tanh(z/2) \). In an alternative form, \( p(z) \) can be specified as: \( 1/2 \) + \( (1/2) \times L_Q(z/2) \) where \( L_Q(.) \) is known as Langevin-Bernoulli function [6.31, 6.32] given by:

\[
L_Q(\mu) = (1 + 1/2Q) \times \coth[(1 + 1/2Q) \times \mu] - (1/2Q) \times \coth[(1/2Q) \times \mu]
\]

with \( Q \) depicting the order-parameter implicating the underlying stochastic features. As \( Q \rightarrow \frac{1}{2} \), the function \( L_Q(\mu) \rightarrow \tanh(\mu) \) depicting the upper-bound (UB) meaning totally disordered system; and, when \( Q \rightarrow \infty \), the function \( L_Q(\mu) \rightarrow \left[ \cot(\mu) - 1/\mu \right] \) and it depicts the lower-bound (LB).

**Computation**

→ The solution sought in this study, refers to obtaining a maximized value for the functional relation \( P_{i,j,k} = f(M_i, E_i, X_i, Y_i) \) subject to the constraints stipulated by WA and WP.

← In terms of logistic-function considerations as above, the (sub-optimally) deducible solution for the hedonic pricing structure namely, \( P_{i,j,k} = f(M_i, E_i, X_i, Y_i) \) can be specified as follows:

\[
P_{i,j,k} \leftrightarrow [f(M_i, E_i, X_i, Y_i)]_{WA, WP}\text{constraints}
\]

→ Perform the following computations:

\[
Z_{i,j,k} = \left[ \sum_{\ell} \beta_\ell \times (S_{1,0})_\ell + \sum_m \gamma_m \times (S_{1,0})_m + \sum_n \eta_n \times (S_{1,0})_n + \sum_r \zeta_r \times (S_{1,0})_r \right]_{i,j,k}
\]

→ \( P(z)_{i,j,k} = (1/2) + (1/2) \times \tanh(z/2) \)

→ \([P(z)_{i,j,k}]_{LB, UB} = [(1/2) + (1/2) \times L_Q(z/2)]_{Q=1/2: UB} = [(1/2) + (1/2) \times L_Q(z/2)]_{Q=\infty: LB} \)
Results

← Tabulate the computed data in tabular forms:

→ Table 6-3: Computed data on HPI
→ Table 6-4: Summary of results on MSI, RTPI and HPI
→ Table 6-5: Estimated HPI and relevant service charges enforced by network providers
→ Table 6-6: Summary of details on tariffs and pricing structure in practice

%% Note: Relevant data are retrieved from [6.28-6.30, 6.36].

Plot

← The data on pricing indices (shown in Tables 6.4 – 6.6) are plotted for comparative observation over the service period for each service provider

→ Presented in Figures 6.1 - 6.4 are evaluated performance indices versus the service period (2010-2013) for each service provider in the exemplar service area, Boston, MA

→ The evaluated performance indices indicate the relative performance profiles of the service providers (in the service area), based on their technology resources (MSI), the associated technoeconomics (RTPI) and the hedonic heuristics of customer preferences.

End

-----------------------------------------------------------------------------------------------------------------------------

Table 6-3: Evaluation of hedonic pricing (HPI) examplified with relevant turf data

<table>
<thead>
<tr>
<th>Service area: Boston, MA: USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Service provider: (j)</td>
</tr>
<tr>
<td>Comprehensive field data on the vector sets: ( (V_i)_{jk} ) [6.28-6.30, 6.36]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Service period (i)</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Constitutive variables - Vector sets of:

<table>
<thead>
<tr>
<th>Constitutive variables - Vector sets of:</th>
<th>Service type (k)</th>
<th>Availability status coefficient</th>
<th>([Y_i]_{\text{rel}})</th>
<th>(r)</th>
<th>(\zeta_r)</th>
<th>(\zeta_r)</th>
<th>(\zeta_r)</th>
<th>(\zeta_r)</th>
<th>(\xi)</th>
<th>(\xi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Service type (k)</td>
<td>Pre4G</td>
<td>Pre4G</td>
<td>4G/LTE</td>
<td>4G/LTE</td>
<td>Relative performance coefficient</td>
<td>Yes (1)</td>
<td>No (0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[(Y1)k]r</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consumer preferences on:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Free App-download preference factor: FA</td>
<td>1</td>
<td>0.09</td>
<td>0.15</td>
<td>0.27</td>
<td>0.49</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paid or (WP for) App-download preference factor: PA</td>
<td>2</td>
<td>0.11</td>
<td>0.16</td>
<td>0.28</td>
<td>0.45</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intensity of App usage due to subscribers “Crush”: UA</td>
<td>3</td>
<td>3.16</td>
<td>4.86</td>
<td>6.96</td>
<td>9.25</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>App-category based preference factor: CA</td>
<td>4</td>
<td>0.11</td>
<td>0.20</td>
<td>0.30</td>
<td>0.39</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age-based App-preference factor: AA</td>
<td>5</td>
<td>1.91</td>
<td>2.59</td>
<td>2.94</td>
<td>2.98</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basic essential email and SMS: ES</td>
<td>6</td>
<td>0.52</td>
<td>0.70</td>
<td>0.80</td>
<td>0.81</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Social networking: SN</td>
<td>7</td>
<td>0.40</td>
<td>0.55</td>
<td>0.62</td>
<td>0.81</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Web browsing: WB</td>
<td>8</td>
<td>0.53</td>
<td>0.71</td>
<td>0.81</td>
<td>0.81</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Streaming music and video: MV</td>
<td>9</td>
<td>0.24</td>
<td>0.33</td>
<td>0.38</td>
<td>0.81</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimated HPI (from 2010 to 2013)</td>
<td>0.89</td>
<td>0.90</td>
<td>0.92</td>
<td>0.92</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6-4: Performance Indices: Summary of compiled MSI, RTPI and HPI value across 2010 to 2013: Summary
<table>
<thead>
<tr>
<th>Service provider</th>
<th>2011 Performance indices</th>
<th>2012 Performance indices</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MSI</td>
<td>RTPI</td>
</tr>
<tr>
<td>AT&amp;T</td>
<td>0.56</td>
<td>0.55</td>
</tr>
<tr>
<td>Verizon</td>
<td>0.99</td>
<td>0.73</td>
</tr>
<tr>
<td>T-Mobile</td>
<td>0.63</td>
<td>0.62</td>
</tr>
<tr>
<td>Sprint</td>
<td>0.56</td>
<td>0.51</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Service provider</th>
<th>2013 Performance indices estimated</th>
<th>Monthly price (in US$)</th>
<th>Service area [6.27]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MSI</td>
<td>RTPI</td>
<td>HPI</td>
</tr>
</tbody>
</table>
| AT&T             | 0.95 | 0.76 | 0.92 | 85.00      | -      | Nationwide
|                  |      |      |      | 1 GB       |        | Boston, MA: 50 GB |
| Verizon          | 0.87 | 0.74 | 0.92 | 90.00      | 120.00 | Nationwide:
|                  |      |      |      | 1 GB       |        | Boston
|                  |      |      |      | Unlimited  |        |
| T-Mobile         | 0.54 | 0.53 | 0.92 | 60.00      | 100.00 | Nationwide:
|                  |      |      |      | 2.5 GB     |        | Boston
|                  |      |      |      | Unlimited  |        |
| Sprint           | 0.67 | 0.53 | 0.92 | 70.00      | 100.00 | Nationwide:
|                  |      |      |      | 1 GB       |        | Boston, Unlimited |

Comments: For smart devices, data streaming (in GB) is facilitated by mobile networks on ad hoc basis as shown above consistent with these in service level agreement (SLA). It may vary across the service area of the nation. This study refers exclusively to Boston, MA: USA; however, without any loss of generality, relevant observations and inferences can be made for any specific service area considered.
Table 6-5: Summary - Computed data on HPI of the services *versus* relevant actual prices enforced by the network operators. (The prices are specified as normalized values with respect to the average pricing enforced in the service area)

<table>
<thead>
<tr>
<th>Service area: Boston, MA: USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Service provider</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>AT&amp;T</td>
</tr>
<tr>
<td>Verizon</td>
</tr>
<tr>
<td>T-Mobile</td>
</tr>
<tr>
<td>Sprint</td>
</tr>
</tbody>
</table>

Compiled data on pricing and computed details on HPI

<table>
<thead>
<tr>
<th>Year (i)</th>
<th>Service provider-(j) &amp; Service type-(k)</th>
<th>Actual price ($P_A$): Monthly service charges (in US $ enforced by the operator) and their normalized values ($F$) with respect to the national mean value</th>
<th>Computed lower and upper bounds (LB and UB): of HPI $p_{Comp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>i = 1</td>
<td>k = 1: Pre-4G</td>
<td>$P_A$ (in US $)</td>
<td>LB</td>
</tr>
<tr>
<td></td>
<td>j = 1 AT&amp;T</td>
<td>0.89 1.0 0.945</td>
<td>Note: Precise data on $P_A$ and $F$ for these years are not available</td>
</tr>
<tr>
<td></td>
<td>j = 2 Verizon</td>
<td>0.89 1.0 0.945</td>
<td></td>
</tr>
<tr>
<td></td>
<td>j = 3 T-Mobile</td>
<td>0.89 1.0 0.945</td>
<td></td>
</tr>
<tr>
<td></td>
<td>j = 4 Sprint</td>
<td>0.89 1.0 0.945</td>
<td></td>
</tr>
<tr>
<td>i = 2</td>
<td>k = 1: Pre-4G</td>
<td>Note: Precise data on $P_A$ and $F$ for these years are not available</td>
<td></td>
</tr>
<tr>
<td></td>
<td>j = 1 AT&amp;T</td>
<td>0.90 1.0 0.950</td>
<td></td>
</tr>
<tr>
<td></td>
<td>j = 2 Verizon</td>
<td>0.90 1.0 0.950</td>
<td></td>
</tr>
<tr>
<td></td>
<td>j = 3 T-Mobile</td>
<td>0.91 1.0 0.950</td>
<td></td>
</tr>
<tr>
<td></td>
<td>j = 4 Sprint</td>
<td>0.91 1.0 0.950</td>
<td></td>
</tr>
<tr>
<td>i = 3</td>
<td>k = 2: 4G/LTE</td>
<td>Note: Precise data on $P_A$ and $F$ for these years are not available</td>
<td></td>
</tr>
<tr>
<td></td>
<td>j = 1 AT&amp;T</td>
<td>0.93 1.0 0.965</td>
<td></td>
</tr>
<tr>
<td></td>
<td>j = 2 Verizon</td>
<td>0.93 1.0 0.965</td>
<td></td>
</tr>
<tr>
<td></td>
<td>j = 3 T-Mobile</td>
<td>0.93 1.0 0.965</td>
<td></td>
</tr>
<tr>
<td></td>
<td>j = 4 Sprint</td>
<td>0.92 1.0 0.965</td>
<td></td>
</tr>
<tr>
<td>i = 4</td>
<td>k = 2: 4G/LTE</td>
<td>Note: Precise data on $P_A$ and $F$ for these years are not available</td>
<td></td>
</tr>
<tr>
<td></td>
<td>j = 1 AT&amp;T</td>
<td>0.92 1.0 0.960</td>
<td></td>
</tr>
</tbody>
</table>

159
Table 6-6: Summary of results: Tariff details and pricing structure in practice - A comparison

<table>
<thead>
<tr>
<th>Service provider</th>
<th>Estimated performance Index</th>
<th>Tariff details: Estimated and actual values of <em>per mensum</em> charges (in US $)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>^\text{Average of MSI, RTPI and HPI}</td>
<td>Average nationwide price</td>
</tr>
<tr>
<td></td>
<td>Mean performance Index: MI</td>
<td>Estimated price by the proposed method: [P_{ES}]<em>{USA} = (MI \times [P</em>{av}]_{USA})</td>
</tr>
<tr>
<td></td>
<td>LB UB (LB+UB)/2</td>
<td>Actual nationwide price</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Percentage difference of: {[P_{AC}]<em>{USA} and [P</em>{ES}]<em>{USA}} with respect to [P</em>{av}]_{USA}</td>
</tr>
<tr>
<td>AT&amp;T</td>
<td>0.88 1 0.94</td>
<td><strong>72</strong></td>
</tr>
<tr>
<td>Verizon</td>
<td>0.84 1 0.92</td>
<td><strong>70</strong></td>
</tr>
<tr>
<td>T-Mobile</td>
<td>0.66 1 0.83</td>
<td><strong>63</strong></td>
</tr>
<tr>
<td>Sprint</td>
<td>0.71 1 0.85</td>
<td><strong>65</strong></td>
</tr>
</tbody>
</table>

Mean value: 76.25

<table>
<thead>
<tr>
<th>Year: 2013</th>
<th>Estimated performance Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>j = 2</td>
<td>Verizon 120 1.62 90 1.18 0.92 1.0 0.960</td>
</tr>
<tr>
<td>j = 3</td>
<td>T-Mobile 100 1.35 60 0.79 0.92 1.0 0.960</td>
</tr>
<tr>
<td>j = 4</td>
<td>Sprint 100 1.35 70 0.92 0.92 1.0 0.960</td>
</tr>
</tbody>
</table>
Figure 6.1: Performance indices versus the service period (2010-2013) for AT & T in the service area, Boston, MA

Figure 6.2: Performance indices versus the service period (2010-2013) Verizon in the service area, Boston, MA
Figure 6.3: Performance indices versus the service period (2010-2013) for T-Mobile in the service area, Boston, MA

Figure 6.4: Performance indices versus the service period (2010-2013) for Sprint in the service area, Boston, MA
6.9 Discussions and Inferential Remarks

Commensurate with the objective of this study, the analysis pursued and results obtained can be viewed in two perspectives: (i) How the mobile network operators who render data services to App-intense smart devices, perform relatively when compared in terms of technology and economics-based considerations; and, (ii) how such performance characteristics are influenced by subscriber-liking (that is, hedonic trend of the customers) vis-à-vis their preferential choice of services offered. Accordingly, this study provides an assortment of indices pertinent to performance based on technology-specific parameters, economic-related issues and customers’ choice decided by hedonic heuristics. Hence, three relevant measures of performance, namely MSI, RTPI and HPI are prescribed respectively.

The *modus operandi* of deducing these three indices can be summarized as follows:

- Considering nationwide mobile network operations, a select service area (for example, Boston, MA) is first chosen for the study. (However, without any loss of generality, any other service area can be addressed in the same way as the done in this study)
- MSI for each operator in the test service area is determined using the technology pertinent details as indentified by PCMag in [6.1-6.6].
- Corresponding RTPI values are obtained by overlaying technoeconomic details on MSI.
- Lastly, using the algorithmic approach proposed in this study, the HPI values (evaluated over a period of interest such as (2010 through 2013) for each operator in that service area are obtained using pertinent data on customer performances vis-à-vis hedonic traits.

Hence, the comprehensive sets of information as presented in Tables 6.1 to 6.4 are compiled; and, graphical details thereof are presented as illustrated in Figures 6.1 - 6.4.
In terms of these results, the following inferences are made:

- The mobile-speed considerations (MSI) are resource attributes (indexed as, \( \lambda \) in Table 6-1) dictated by technology options of the network operators; and, they may widely differ depending on the service type (k) rendered to customers as per the SLA.

- Corresponding to MSI values observed in the service area, the performance attributes of the network operators would change when due considerations are given to the associated economics details (indexed as m) and productivity enhancements (indexed as n) experienced as a result of using mobile units in work environment. Hence, the RTPI results are deduced as present in Table 6-2.

- In addition to MSI and RTPI results on mobile network performance, elucidated are tariff-based pricing indices (HPI) consistent with hedonic concepts. Relevant results on HPI are shown in Table 6-3.

- The results presented in Figures 6.1 - 6.4 illustrate the aforesaid performance indices of four incumbent service providers in the service area considered over the period 2010 through 2013.

From the results indicated above, the following observations can be made:

I. The MSI exhibits dominate variations in all network operations (over the service period) due to the reason that newer technology options are invariably introduced on year-to-year basis to cope with customer demands on service types

II. The profile of RTPI tends to follow the MSI variations inasmuch as the economic factors (such as, service salability and RoI) are tied to demand-based service-provisioning \emph{vis-à-vis} technology deployed in the turf of the service area

III. In contrast, the HPI is almost steady and poses the largest extent of performance index (close to 1). In other word, the tariff decisions by the network operators and pricing of the services are aimed at customer satisfaction \emph{versus} customers' liking or hedonic feeling for the desired services. The pricing is thus decided overwhelmingly thereof.
In all, the network operations incline to have almost the same tariff structure (in the designated market) regardless of MSI and RTPI performances. As a result of invariancy in tariff structure indicated above, the nationwide pricing remains competitively similar across all operators as reported in Table 6-4. However, service providers who improvised better technology (as evinced by their MSI and RTPI values) tend to be at the higher end of pricing 17% or 26% (in the example cases of Table 6-4) than the national level so as to balance their underlying expenses (CAPEX and OPEX) resulting from adopting better technology options. Low MSI and/or RTPI profiled operators tend to charge the customers almost close to the national coverage (4% and 7% in Table 6-4).

6.10 Closure

In closure, this chapter offers a neoteric approach to view the performance of competitive mobile network operations in the complex system framework of App-intense, smart mobile devices being adopted by subscribers. though addressed here are related technoeconomic and hedonic considerations focused on mobile services, the pedagogy of this work can be applied to any similar telco operations. the present study indicates that, concomitant to differential performance attributes versus types of services offered of mobile network operators, the associated price or tariff structure adopted (by the operators) may be competitively set by the hedonic preferences of the subscribers.

To conclude, this study demonstrates how the relative performance of mobile network operators is implicated by hedonic preferences of the customers towards their service options, especially in the modern context of facilitated triple services. Specifically, such service options and related hedonic perspective hold water in the case of customer usage of smart devices (mobile and/or fixed) supporting intense Apps. In such cases, this
study reveals that the relative performance of mobile service operators is dictated largely by the underlying, competitively close, traffic structure imposed meeting the demand versus hedonic preferences of services; and, this consideration overrides the MSI and RTPI dictated evaluations of incumbent operators.

Notwithstanding the effort of comparing mobile operators in terms of HPI considerations (and MSI/RTPI issues) as outlined in this study, the eventual pricing economics of mobile traffic and relative performance of mobile operators may be influenced by the speed-specific payment contract that prevails between the content-providers and Internet service providers (ISPs). That is, in the existing practice, the tiered Internet is geared towards faster or slower data transmissions - (a process called “throttling” or such transits are even blocked) depending on the fees paid by the content-providers to ISPs. in other words, the subscribers are taxed implicitly for their hedonic mind set when they opt for high-speed/large bandwidth data, typically needed in App usage. Hence, the government/FCC is considering new regulations on ISPs insisting that, as regard to all legal contents accessible on the Internet, no such content should be provided at faster or slower speeds than the rest. It means that, a “net neutrality” is to be maintained. That is, net neutrality implies that Internet providers should not block, slow or manipulate data moving across their network (unless such data are like pirated music or those prohibited by law).

Correspondingly, radical changes are being sought (in the US) for Internet services supporting DDA in order to address the issue of slower downloads and higher costs. The FCC is being instructed by the US Presidential Office to heavily regulate Internet providers and treat broadband much as it would any other public utility; that is, the FCC is expected to prohibit explicitly the Internet providers from charging data hogs extra to move their content more quickly. Relevant issue is being contemplated (notwithstanding possible legal
implications) by FCC whether broadband providers should be allowed to cut deals with the content providers as a regulatory provision. This "tectonic shift in national policy, should it be adopted" is viewed currently by certain groups culminating in devastating results. However, the other viewpoint is that "consumers should pick winners and losers on the Internet, not broadband gate keeper". In other words, the hedonic choice of subscribers (implicated by the traffic speeds of DDA) should not be hampered.

Whether the US Presidential direction to FCC on net neutrality (namely, the broadband information loaded at one side should be streamed at the same speed like any other similarly sized data elsewhere implying the broadband services to carry the same obligation like other vital services so as to ensure, "the network works for everyone -not just one or two companies") will impact the global telco business is yet to be seen [6.33-6.35]. So, to conclude, it can be anticipated in the near future, the emergence of yet another performance measure to compare mobile services in vogue based on net neutrality heuristics subduing MSI, RTPI and/or HPI evaluations.
CHAPTER VII
RESULT AND DISCUSSIONS

7.1 General

This chapter is written to outline the summary of the research addressed as deliberated in this dissertation. Consistent with the title of the research, the study carried out is mainly concerned with determining the performance aspects of smart wireless devices and related services. Within the scope of this topic, the efforts are performed in two major suites, indicated: Part A: Device level performance issues; and, Part B: Business level performance issues of mobile network services. The following sections briefly summarize the objectives, tasks preformed, results obtained and concluding remarks relevant to each part.

7.2 Device Level Performance: Part A

Under this part, three major issues are considered: (i) The time internal error (TIE) performance of signal transports at the baseband level in the PCB having densely-packed traces in the audio/video sections of smart wireless devices: (ii) Crosstalk performance issues across random traces of audio/video sections; and, (iii) EMP-EMI specific performance issues at the RF section of smart wireless devices. Relevant to these three topics studied, the results obtained and concluding details are as follows:
7.2.1 Performance of Baseband Infrastructure: TIE Considerations in Smart Wireless Devices

In the context of the state-of-the-art smartphones and other mobile/handheld/wearable devices, the bit-rates of the data adopted at baseband levels could be significantly high (~ 500 Mbps); and, such streams of high-speed bits are invariably transferred between chips and/or various circuit nodes during baseband signal-processing, for example, between an image-sensor and an image sensor processor (ISP). To negotiate such transfers, numerous copper-traces are used at the board-level formed either on a single surface or in multiple board/flex stacks. Normally, such trace-lines are of different lengths so as to accommodate ad hoc interconnections and digital transits between the pins across any two devices and/or components placed at distinct locations on the board. Further, several of these lines may run almost parallel to each other with jagged tracks. An example of such a track is illustrated in Figure 2.1. As a result of varying physical lengths of such traces, the digital bits transported from any node on any given trace will arrive at the pin of signal destination (terminated on the chips in question) with a specific extent of transmission-line dependent delay. However, this delay could be distinctly variable in each of the traces due to varying path-lengths involved and different bit-rates of information transmitted. That is, the observed delay is specific to each line-length as defined by the associated line-parameters namely, the inductance and the capacitance per unit length and the digital signature of the information communicated. The resulting data dependent jitter (DDJ) [2.1] introduces time interval error (TIE) (also known as phase jitter) perceived invariably on the bits.

Given the spatial features (length etc.) of the high-speed line (transmission topology) and the associated data transceived, the DDJ and the associated TIE can be viewed as a class of deterministic timing jitter. It is an undesired artifact and may cause flicker in displays (or
the camera view finders etc.). It would also affect the performance of the digital processors at large. Hence, the data pulses received with varying delays traversing different parallel-lines may become unusable for applications and digital-processing efforts at the receiving devices due to the associated randomness of delay variations tied to the TIE. Therefore in practice, delay-lines are introduced in each trace to compensate for the transit-delay so that the digital data supported are displaced in time on *ad hoc* basis and get synchronized at the receiving end as needed minimizing the influence of TIE.

Traditionally, placed at circuit-board level are physical inductors in solenoidal forms, designed, trimmed and incorporated on traces so as to offer a desired inductance value (especially at the RF sections) [2.2]. However, such a conventional (solenoidal) inductor element on a circuit-board implies the task of complex component-accommodation due to bulky, three-dimensional geometry of the solenoid designed. Therefore, such an option is not conducive for applications in systems like smartphones and other handheld devices encountering restricted size and space. Alternative to bulk solenoidal inductors, advocated in practice for space-constrained circuit-board applications is planar geometry of copper-traces (such as spiral traces) designed to emulate the desired inductance values [2.3][2.4].

Yet, considering the specific needs of modern smartphones or similar handheld gizmos *vis-à-vis* emulating tailor-made extents of delays compatible for high-density traces (at baseband levels), a novel design is proposed in this study toward synthesizing a new class of planar inductors using fractal geometry. Shown in Figure 2.2 is the geometry of a conceivable module of distributed delay-line (DDL) based on spiral circular or square-loop geometry conforming to a fractal structure. Shown in Figure 2.3 is the photograph of the circular-spiral fractal inductance adopted in the present study.
It is surmised in this study that the fractal planar inductors can be designed to facilitate a desired delay-time in a constrained on-board area. Apart from spiral, other options such as meander line, Hilbert structure, Minkowski curve, Koch’s curve etc. can be adopted in making fractal geometry. Conceived thereof in practice, are structures to optimize the delay-line performance versus space-filling considerations as warranted in baseband, high-speed operations of smartphones and/or similar devices. Associated higher order fractal curves enable design options with good space-filling properties. Most of such fractal structures have been conceived in the contexts of antenna designs and related RF units as reported in [2.3-2.11]. The underlying considerations are however, can be borrowed in making fractal inductance as time-delay lines.

This research describes a test study on a proto-type of fractal inductor geometry illustrated in Figure 2.2(a) and Figure 2.3, which is commensurate with practical aspects of its implementation as a delay-line in high-speed digital transports at baseband operations in the infrastructure of smartphones (and/or similar handheld/fixed/wearable devices). Experimental results obtained from the test module are presented to illustrate the efficacy of the module and realizable delay performance vis-à-vis the digital transports of interest. Thus, the scope of this study in essence is evolved to provide an overview of general details on digital information transmission/processing at baseband levels of modern smartphones and similar gadgets of different technologies; hence, indicated is the conceived fractal geometry as a plausible delay-line structure for combating the TIE. The physically transmitted baseband signal represents a ‘digital-over-digital’ transmission of pulse trains. In modern context of 3G through 4G considerations and associated LTE implications, the baseband data handled in the infrastructures of smartphones (and similar devices) is used at specific versions of processors with chip-designs and system-on-chips (SoCs) that accommodate generous audio, and video
digital signal processing. Such processors are required to meet multi-standard integration, reduced power dissipation and facilitate extra key functions for next-generation smart, handheld devices. Relevantly, baseband processors provide efficient operations with cost-effective multimedia application-specific processing for entry-level 3G as well as next-generation/evolving 4G systems. Further, in such complex baseband chip-specific operations, the underlying applications invariably dictate the use of high-speed bit rates.

Considering for example video-processing support for 10/12 Mixels imaging and 720p video-playback plus accelerated 2D/3D graphics, operational needs push the processor speeds up to 1GHz or even higher. Concurrently, related transmissions point out the gravity of multiple high-speed transports on the limited-space circuit-board (and/or flexible-board) layouts. Together with the packaging designs of the components and chips on the board, the interconnections that support the said digital transports are crowded and routed haphazardly. Hence, the transmission-lines (traces) envisaged are high in density (per unit area) and of varying lengths. Therefore, the digital transports end up in TIE-related issues that call for effective counter designs. the present study proposes thereof using delay compensation via planar inductors of fractal geometry.

7.2.2 EMI/Crosstalk Performance across Multiple Traces in the Baseband Infrastructure of Smart Wireless Devices

As described in the previous sections, in the state-of-the-art devices, a dense layout of copper traces on the associated printed circuit boards (PCBs), single and/or multi-layered is inevitable. Relevantly, considering the baseband level of audio and/or multimedia sections in smart handheld devices, ad hoc routing of traces in a zigzag pattern may prevail and a unique modeling strategy to address the extent of crosstalk victimization of such trace-lines caused by proximally located, aggressing signal path is required.
In view of statistically-specified, routing geometry of the trace layout, the resulting near- and far-end crosstalk (NEXT and FEXT) parameters would warrant a random-theoretic approach for their meaningful evaluations. Further, for a given layout of the traces, the resulting crosstalk effects are decided by the associated electromagnetic (EM) coupling between the lines.

Hence, the relevant study addressed in this research is exclusively devised to evaluate the performance integrity of a smart devices with a PCB infested with a random cluster of traces and the associated high-speed signal-processing culminates in causing unwanted crosstalks across certain victim traces. In short, the probabilistic attributes of randomly-dispersed trace pattern on a PCB invoking nondeterministic values of crosstalk are considered; and, corresponding crosstalk estimation that would lead to compatible suggestions on mitigating pursuits relevant to baseband sections supporting high-speed transports is carried out.

From the results obtained, the following inferences can be made:

- *In lieu* of the traditional method of using LC parameters to assess NEXT and FEXT values in a PCB supporting multiple traces intended for the transport of high-speed pulses, an alternative, implicit technique as proposed here based on evaluating the inter-trace coupling caused by \( E \)- and \( H \)-field components of the EMI involved
- Further, the proposed method is comprehensive to include the statistical aspects of high-density traces laid out with random routings on the PCB. Such configuration of traces are common in the baseband sections of modern handheld wireless devices
- Considering three attributes of the associated EMI phenomenon, namely, (i) EM field, (ii) statistical aspects of the physical PCB constituents and (iii) the transit delay issues of the signal pulse propagation on the traces, a pair of closed-form algorithms are derived (equations 3.15(a) and 3.15(b)) to deduce approximate values of the NEXT and the FEXT on a test PCB. Using the details and data as required, relevant
computations of NEXT and FEXT are done via simple computational efforts. This is viably demonstrated with reference to a test PCB.

- The efficacy of the algorithms proposed is ascertained by cross-validating the computed details vis-à-vis measured data on a test PCB. The results presented in Table 3-1 and in Figures 3.15 and 3.16 thereof indicate that the estimation procedure on NEXT and FEXT as advocated in this study favorably yields results (specified within the binding upper- and lower-limits) close to the measured data.

- In essence, the study performed is a motivated effort to alleviate the non-prevailing status of a comprehensive method available to determine the NEXT and FEXT coefficients pertinent to the test PCB described infested with a random layout of traces. That is, with the advent of PCBs required to possess a high-density of traces with random signal transit paths as well as supporting high-speed pulses of DDA category (as warranted in modern wireless handheld devices), estimating the associated inter-trace EMI coupling and crosstalk efforts is imminent; however, no straightforward theoretical and/or computational strategy appears to be in vogue (to the best of authors’ knowledge).

Conclusively, the study performed also provides some observations as regard to EMI and crosstalk infestation in the class test PCB described. Typically, the following are identified:

- The crosstalk values (NEXT and/or FEXT) are decided not only by the traditionally known mutual proximity of the victims (as well as with respect to the aggressor) but also implicated by the number of turning points on each trace. Such turning points depict discontinuities on the transmission-line with corresponding distorted E- and H-field distributions pervasively coupling onto the nearby lines.

- The victim trace closest to the aggressor may suffer crosstalk effects intensely.

- Not only the geometry of the trace-routes, the mutual disposition of turning-point nodes in the adjacent traces would decide the NEXT and FEXT level (Figures 3.3 and 3.7).

- The net effect of crosstalk is decided by the following: (i) Pervasion of E- and H-fields across the random traces; (ii) randomness of the geometrical layout of traces and (iii) signal pulse characteristics.
Thus considering the studies on the practical issues in high-speed PCB designs [3.2] [3.4], objectives of the present study culminates in deducing tangible solution towards EMI suppression and formulating EM compatibility (EMC) considerations toward crosstalk minimization [3.6-3.9, 3.12, 3.15, 3.16, 3.25, 3.26]. Hence, the following are suggested toward possible crosstalk mitigation efforts:

- Design the PCB layout with optimally separated traces
- Minimize the number of turning-points nodes on the traces
- If a directional change is inevitable for a trace, possibly make the associated turn smooth, rather being abrupt
- Crosstalk mitigation efforts should also be done concurrently with minimizing the TIA considerations elaborated in [3.17].

In closure, the topic addressed is a novel concept of deducing the EMI/crosstalk performance of PCB level, especially when the board is infested with a random cluster of traces supporting high-speed digital transports. To the best of author's knowledge no such similar effort is available in open-literature. Further, the underlying analysis can be extended to any other clustered transmission-line infrastructure, such as in the back-plane section of large-frame computers, servers, etc. without any loss of generality.

7.2.3 EMI-EMP Effects at RF Sections of Wireless Devices

This aspect of study offers a review on possible EMP-EMI threats specific to wireless devices (portable/fixed and wearable) operated under E3 ambient. Considering the practical aspects of the infrastructure of those devices, the extent of EMP-EMI susceptibility at RF-sections is estimated *via* Monte Carlo simulation exercised using an appropriate algorithm derived thereof. This simulation duly accounts for random attributes of the geometrical parameters at the PCB level and includes the characteristics of the EMP impressed on the unit.
That is, random attributes of the parameters involved are superimposed on the corresponding nominal (deterministic) values pertinent to a given device; hence, the simulated results represent a cluster of ensemble data on probabilistically estimated EMP-EMI susceptibility, namely, $|K(\cdot)|$ versus rise-time, $t_r$ of the test structure exposed to $E_3$.

In summary, as shown in Figure 4.4, the proposed algorithms yield results relevant to the following: (i) $|K(\cdot)|$ versus rise-time ($t_r$) deduced using the nominal (deterministic) values of the PCB-unit under test plus deterministic EMP features adopted in the computations. (ii) Corresponding limits of upper- and lower-bounds (UB and LB) of the results in (i) are also estimated; and, (iii) an ensemble of clustered data is obtained via Monte Carlo simulations incorporating random perturbations on the test PCB and EMP parameters.

From these results, the following inferential observations are made:

- For a given RF-section with PCB details known \textit{a priori}, relevant deterministic computations of equation (4.3) enable deducing $|K(\cdot)|$ versus rise-time ($t_r$) characteristics with an upper-bound (UB) tending to 1; and, relevant lower-bound (LB) tends to 0.5 for the limiting case of $t_r \rightarrow 0$, (meaning ideal delta-Dirac EMP) as evinced in Figure 4.4

- However, considering the Monte Carlo simulations on the same RF-section with PCB details set randomly (perturbing the nominal values), relevant computations of equation (4.3) enable deducing an ensemble of (random) data on $|K(\cdot)|$ versus rise-time ($t_r$) characteristics as shown in Figure 4.4. These simulated results show their lower limit closer to the deterministic LB (tending to 0.5) of $|K(\cdot)|$ regardless of the values, $t_r \rightarrow $ (high or low); on the other hand, the simulated results overshoots the UB for small values of $t_r \rightarrow 0$. It implies the criticality of EMP-EMI influence on the test unit when the EMP conforms to impulsive attributes with sharp rise-time characteristics (akin to a delta-Dirac function).

- Another observable, interesting feature of $|K(\cdot)|$ versus rise-time ($t_r$) characteristics is that, around a specific value of $t_r$, the profile of $|K(\cdot)|$ shows a transition from the LB
towards the UB. For example, as marked in Figure 4.4, this transition is close to, $t_{rx} = 10^{-9}$ s and it represents approximately the resonance at, $\omega_c \approx 2\pi \times (1/t_{rx})$ shown in Figure 4.2. That is, the estimated value of $f_x$ (as adopted in the computations) is 1000 MHz ($= 1/t_{rx}$). Further, the stretch of $t_r$ approximately, from $10^{-13}$ to $10^{-9}$ s denotes the implied transition towards the severity of threats due to narrow EMPs. This stretch of time-domain values transform to depict in the frequency domain (Figure 4.2) characteristics with the slope changing from $-20$ to $-60$ dB/decade.

- Relevant to simulated details for a given test unit on $|K(.)|$ versus rise-time ($t_r$) characteristics and estimating the value of $f_x$, the present study proposes an EMP protection scheme as illustrated in Figure 4.6 compatible for RF pass-band applications. EMP protection has been a topic of utmost importance in the decades of the past and studied comprehensively in both civilian and military contexts. However, the vulnerability of modern wireless devices (such as smart fixed/mobile and wearable units) to E3 is even more severe. Relevant threat due to EMP-EMI could be devastating as rightly pointed out by Kyle in [4.3].

- Wrist-top and other wearable wireless devices (WWD) with densely-packed and compactly designed infrastructure enabling smart and sophisticated functionality are gizmos of reality for state-of-the-art civilian users of IoTs. Before long, (if not already) such devices would also find inevitable usage and prolific penetration in military scenario involving system-on-person (SoP) operational applications. Then such military operations will be at stake with the imposed vulnerability to failures thanks to SoP exposure to E3 and the associated EMP-EMI [4.24]. Therefore, relevant proactive EMC measures warrant exclusive EMP hardening as well as built-in protections in the aforesaid devices, specifically at the PCB sites of RF-section naked to E3 exposures. The present study can serve as an overview on such EMP-EMI issues and related protection pursuits.

In all, smart and sophisticated wireless devices find immense proliferation in defense and war-zone applications with inevitable possible exposure to E3; and. it is a recognized fact that the associated EMP-threat is a reality of grave concern [4.25-4.26]. So, a focused and exclusive study relevant EMP-EMI and EMC issues concerning mobile/fixed and wearable wireless
devices with IoT connectivity is obviously imminent and strategically important. The present work is indicated as a prelude thereof.


Under this part, three major issues are discussed as regard to performance evaluation of wireless networks operation supporting smart-devices. These are as follows: (i) Technocentric performance based on mobile speed offered, (ii) economics-based service operation plus corresponding performance details; and (iii) performance of the mobile network operations in terms of hedonic tariff structure on wireless services. The following subsections briefly outline the summary of each topic addressed.

7.3.1 Mobile Speed Index and Relative Technoeconomic Performance Index

Commensurate with the scope of this study, the efforts exercised mainly refer to elucidating relative performance (R) details of mobile systems supporting assorted platforms in catering services for the smart as well as feature devices at the subscriber end. Relevant heuristics cohesively include both technological aspects of the service networks as well as economics factors associated with the service areas. The present study is a sequel to the tasks of PCMag.com reported in [5.1]-[5.6], where the relative performance comparisons are restricted to outcomes based purely on technological data. On the contrary, it is surmised in this study that relevant conclusions on R should be based on both technological and economics-related details of the services analyzed. As such, proposed in this study are necessary algorithmic considerations to cohesively formulate the technoeconomics based assertions on R. Hence, the PCMag.com specific performance is specified by a mobile speed indicator (MSI) and relevant economics-constrained factor is marked as economics-related indicator (ERI) values; Thus, the net performance characterization of the mobile services
considered and analyzed is expressed in terms of a relative performance indicator (RTPI) obtained using MSI and ERI details computed to portray the overall technoeconomics-based service performance of the test wireless networks.

In addition, the statistical features of the parameters deduced are explicitly obtained and expressed with upper- and lower-bounds on MSI and RTPI values. Such limiting bounds duly account for the underlying stochastic variations. That is, the data and details adopted in ascertaining the performance indicators should not be treated as deterministic entities. Due to random nature of operational and technical features as well as the fluctuations in the economics base of the service area, an error-bar should be specified on the values of MSI and/or RTPI. However, no such bounds are indicated in the study by PCMag.com; and, as such, the present study is evolved with more comprehensive objective to accommodate (i) economics-related issues and (ii) incorporate statistical bounds on the performance pertinent to such cohesively fused technical and economic considerations in the analyses, some example comparisons are done on the original PCMag.com data versus currently deduced information on MSI plus RTPI considerations. Tabulated in Table A-III of the Appendix are example values presented to show the efficacy of the study pursued. Again, the results tabulated correspond to the graphical details of Figure 5.1.

Notwithstanding observed conclusions by PCMag.com based on MSI values alone, the present study attempts to make a more realistic comparison across the tested networks considered on technoeconomics-based parameters. Subjectively, the underlying tasks considered enable the following inferences:

- The metric of performance comparison is specified in terms of both technology and economics factors [5.17] [5.19]
- The comparison data computed outlines and verifies whether the technology features alone can be used (in all fairness) to declare the network being the "best"
• The technoeconomics-based comparison advocated can help the future market structure of the mobile networks in terms of their relative performance and on possible designs for future pricing the wireless services supporting heavy-duty profiles of smart devices.

• It is queried in this study whether particular mobile services will perform and beat challenges of deregulated market competition be decided just by looking at a measure decided by technological factors. It is opined that due considerations on related site-specific economics should also be duly taken into consideration in deducing the performance metric. Lest, a true deposition on the comparative study becomes questionable for example, as presented in Table 5-7 are computed data on RTPI (versus MSI) values of incumbent mobile services in Boston in 2010 through 2013. The results of Table 5-7 indicate that MSI details are optimistic: that is, the technologic-alone based indices lagged on 'fastness' of information flow (in bps) in the service rendered, may one judge the performance. In reality, however the combined technology and economics-based index (RTPI) details show the subdued values with a statistical variability so that a prudent judgment on the performance of the services can be made. Relevant considerations are however absent in the studies due to PCMag.com. Shown in Table 5-8 are details concerning the statistical error-bar limits (in percentage) of the RTPI values deduced in the same service premises of Boston during 2010 though 2013.

The present study paves the way for future marketing (pricing and tariff) issues vis-à-vis competitive performance of service providers. Especially, it is summarized here that the present pricing structure mostly "same-for-all" namely same data plan pricing for both smart device users and others. Taking into considerations that Smartphone users' demand resources being heavy, but these users pay a like others (who exercise less burden on the network), there is an inevitable "tragedy-of-commons". As such, the mobile service providers may revise their
pricing structure to be dichotomous, one for smart-device users and the other for dumb and feature devices using possibly, the technoeconomic performance indicator (such as RTPI).

7.3.2 Wireless Network Performance: Price Worthiness Heuristics

Commensurate with the objective of this study, another analysis pursued and results obtained refers to two perspectives of wireless network business: (i) How the mobile network operators who render data services to App-intense smart devices, perform relatively when compared in terms of technology and economics-based considerations; and, (ii) how such performance characteristics are influenced by subscriber-liking (that is, hedonic trend of the customers) vis-à-vis their preferential choice of services offered. Accordingly, this study provides an assortment of indices pertinent to performance based on: (a) Technology-specific parameters, (b) economic-related issues and (c) customers’ choice decided by hedonic heuristics. Hence, three relevant measures of performance, namely MSI, RTPI and HPI are prescribed respectively. The modus operandi of deducing these three indices is summarized below:

- Considering nationwide mobile network operations, a select service area (for example, Boston, MA) is first chosen for the study. (However, without any loss of generality, any other service area can be addressed in the same way as the done in this study)
- MSI for each operator in the test service area is determined using the technology pertinent details as indentified by PCMag in [6.1-6.6].
- Corresponding RTPI values are obtained by overlaying technoeconomic details on MSI
- Lastly, using the algorithmic approach proposed in this study, the HPI values (evaluated over a period of interest such as (2010 through 2013) for each operator in that service area are obtained using pertinent data on customer performances vis-à-vis hedonic traits.
Hence, the comprehensive sets of information as presented in Tables 6-1 to 6-4 are compiled; and, resulting graphical details are presented as illustrated in Figures 6.1 - 6.4.

In terms of these results, the following inferences are made:

- The mobile-speed considerations (MSI) are resource attributes (indexed as, $\lambda$ in Table 6-1) dictated by technology options of the network operators; and, they may widely differ depending on the service type ($k$) rendered to customers as per the SLA.
- Corresponding to MSI values observed in the service area, the performance attributes of the network operators would change when due considerations are given to the associated economics details (indexed as $m$) and productivity enhancements (indexed as $n$) experienced as a result of using mobile units in work environment. Hence, the RTPI results are deduced as present in Table 6-2.
- In addition to MSI and RTPI results on mobile network performance, elucidated are tariff-based pricing indices (HPI) consistent with hedonic concepts. Relevant results on HPI are shown in Table 6-3.
- The results presented in Figures 6.1 - 6.4 illustrate the aforesaid performance indices of four incumbent service providers in the service area considered over the period 2010 through 2013.

From the results indicated above, the following inferential observations can be made:

I. The MSI exhibits dominate variations in all network operations (over the service period) due to the reason that newer technology options are invariably introduced on year-to-year basis to cope with customer demands on service types
II. The profile of RTPI tends to follow the MSI variations inasmuch as the economic factors (such as, service salability and RoI) are tied to demand-based service-provisioning vis-à-vis technology deployed in the turf of the service area
III. In contrast, the HPI is almost steady and poses the largest extent of performance index (close to 1). In other word, the tariff decisions by the network operators and pricing of the services are aimed at customer satisfaction versus customers' liking or hedonic feeling for the desired services. The pricing is thus decided overwhelmingly thereof.
In all, the network operations incline to have almost the same tariff structure (in the designated market) regardless of MSI and RTPI performances. As a result of invariancy in tariff structure indicated above, the nationwide pricing remains competitively similar across all operators as reported in Table 6-4. However, service providers who improvised better technology (as evinced by their MSI and RTPI values) tend to be at the higher end of pricing 17% or 26% (in the example cases of Table 6-4) than the national level so as to balance their underlying expenses (CAPEX and OPEX) resulting from adopting better technology options. Low MSI and/or RTPI profiled operators tend to charge the customers almost close to the national coverage (4% and 7% in Table 6-4).

Thus, this study offers a neoteric approach to view the performance of competitive mobile network operations in the complex system framework of App-intense, smart mobile devices being adopted by subscribers. though addressed here are related technoeconomic and hedonic considerations focused on mobile services, the pedagogy of this work can be applied to any similar telco operations. the present study indicates that, concomitant to differential performance attributes versus types of services offered of mobile network operators, the associated price or tariff structure adopted (by the operators) may be competitively set by the hedonic preferences of the subscribers.

7.4 Closure

Notwithstanding the effort of comparing mobile operators in terms of HPI considerations (and MSI/RTPI issues) as outlined in this study, the eventual pricing economics of mobile traffic and relative performance of mobile operators may be influenced by the speed-specific payment contract that prevails between the content-providers and Internet service providers (ISPs). That is, in the existing practice, the tiered Internet is geared towards
faster or slower data transmissions - (a process called “throttling” or such transits are even blocked) depending on the fees paid by the content-providers to ISPs. In other words, the subscribers are taxed implicitly for their hedonic mind set when they opt for high-speed/large bandwidth data, typically needed in App usage. Hence, the government/FCC is considering new regulations on ISPs insisting that, as regard to all legal contents accessible on the Internet, no such content should be provided at faster or slower speeds than the rest. It means that, a “net neutrality” is to be maintained. That is, net neutrality implies that Internet providers should not block, slow or manipulate data moving across their network (unless such data are like pirated music or those prohibited by law).

Correspondingly, radical changes are being sought (in the US) for Internet services supporting DDA in order to address the issue of slower downloads and higher costs. The FCC is being instructed by the US Presidential Office to heavily regulate Internet providers and treat broadband much as it would any other public utility; that is, the FCC is expected to prohibit explicitly the Internet providers from charging data hogs extra to move their content more quickly. Relevant issue is being contemplated (notwithstanding possible legal implications) by FCC whether broadband providers should be allowed to cut deals with the content providers as a regulatory provision. This “tectonic shift in national policy, should it be adopted” is viewed currently by certain groups culminating in devastating results. However, the other viewpoint is that “consumers should pick winners and losers on the Internet, not broadband gate keeper”. In other words, the hedonic choice of subscribers (implicated by the traffic speeds of DDA) should not be hampered.

Whether the US Presidential direction to FCC on net neutrality (namely, the broadband information loaded at one side should be streamed at the same speed like any other similarly sized data elsewhere implying the broadband services to carry the same obligation like other
vital services so as to ensure, "the network works for everyone -not just one or two companies") will impact the global telco business is yet to be seen [6.33-6.35]. So, to conclude, it can be anticipated in the near future, the emergence of yet another performance measure to compare mobile services in vogue based on net neutrality heuristics subduing MSI, RTPI and/or HPI evaluations. Correspondingly, there will be a shift in the paradigm of arbitrage.
CHAPTER VIII

SUMMARY OF THE RESEARCH STUDY AND OPEN-QUESTIONS FOR FUTURE STUDIES

8.1 General

A cursory look at the efforts performed and results obtained as regard to this research as discussed in the previous chapter indicates the following major topics objectively addressed towards the research endeavor undertaken:

Part A of the present study focuses on performance details relevant to signal-transport features at (i) the baseband/peripheral and display sections and (ii) at the RF-section. Hence, the following three major issues are addressed concerning relevant hardware performance decisions:

- Time-interval error (TIE) perceived on PCB traces due to uneven signal transport delays encountered in the baseband section: Remedial pursuit via delay compensation techniques using fractal inductors (on the PCB traces) is suggested
- Crosstalk effects across the crowded and randomly patterned PCB traces at the baseband section: Relevant analysis and mitigation considerations are indicated
- Non-catastrophic EMI-EMP effects at the RF-section of smart handheld devices and related electromagnetic environmental effects (E3): Analysis and mitigation suggestions are presented.

Part B of the research addressed is concerned with mobile network performance operations; and relevant technoeconomics and business related performance issues are elaborated. In essence, relevant efforts refer to a devoted study on the technoeconomic performance
considerations pertinent to mobile network operations and services rendered. Hence, two performance indications are proposed and appropriate indices are derived as enumerated below:

- By cohesively considering the mobile-speed technology details and relative technoeconomics of the service area, a comprehensive technoeconomics-based performance index (RTPI) is derived using available field data. This measure is more comprehensive than the mobile speed index proposed by PCMag.com [1.2-1.7]
- Based on customer-liking (hedonic-feeling), the pricing structure adopted by various network operators is used prescribed as yet another as a relative performance index. Relevant hedonic concept is explained in terms of turf details and pricing strategies on mobile services adopted across the nation.

8.2 Scope for Future Research

Related to the subject-matter studied, there exists an ample scope to expand the relevant topics to cover more objectives as enumerated below:

- Performance of smart wireless devices in terms of the associated power saving and battery conservation issues: Context aware mobile power management performance [8.1]
- Taming the vicious cycle of power consumption in smart phones and related devices
- Future wireless devices with Apps inclusions toward 4.5/5G LTE consideration: Performance issues and prescribing metrics on performance
- EMI/crosstalk and EMP performance issues in the overall structure of smart wireless devices considering RF, baseband as well as mixed signal platforms.
- Searching for a better technoeconomics-based business performance models: Dynamic market derived capital pricing and Paris Metro schemes [8.2]
- Software performance of wireless devices with open source OS for the internet such as Avatar [8.3]
- Service/network performance of wireless devices exclusively operating with comprehensively enforced Internet of Everything (IoE)
8.3 Concluding Remarks

This study is a maiden attempt to identify explicitly certain performance issues evolving appropriate metrics to assess them in the context of modern wireless devices and mobile network operations. In view of the future research topics identified above, there is however, an ample scope exists to enhance this study in wider perspectives and deeper considerations.
### APPENDIX

Table A-I List of mobile speed parameters adopted in evaluating the MSI by PCMag.com [5.25]-[5.30]: Example details with respect to the service area, Boston Metro, USA, 2010 through 2013

<table>
<thead>
<tr>
<th>Year</th>
<th>Mobile carriers and services</th>
<th>PCMag index (in %)</th>
<th>Down-load speed (DLS) (Mbps)</th>
<th>Up-load speed (ULS) (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>avg (DLS)</td>
<td>max (DLS)</td>
</tr>
<tr>
<td></td>
<td>AT&amp;T</td>
<td>76</td>
<td>1.18</td>
<td>2.54</td>
</tr>
<tr>
<td>2010</td>
<td>Sprint 3G</td>
<td>96</td>
<td>1.24</td>
<td>2.07</td>
</tr>
<tr>
<td></td>
<td>T-Mobile</td>
<td>69</td>
<td>0.76</td>
<td>2.35</td>
</tr>
<tr>
<td></td>
<td>Verizon</td>
<td>69</td>
<td>0.85</td>
<td>1.98</td>
</tr>
<tr>
<td></td>
<td>AT&amp;T 3G</td>
<td>56</td>
<td>2.26</td>
<td>8.01</td>
</tr>
<tr>
<td></td>
<td>Metro PCS</td>
<td>41</td>
<td>1.00</td>
<td>2.54</td>
</tr>
<tr>
<td></td>
<td>Sprint 3G</td>
<td>42</td>
<td>0.58</td>
<td>1.77</td>
</tr>
<tr>
<td></td>
<td>Sprint 4G</td>
<td>56</td>
<td>3.23</td>
<td>9.54</td>
</tr>
<tr>
<td></td>
<td>T-Mobile</td>
<td>63</td>
<td>2.78</td>
<td>10.82</td>
</tr>
<tr>
<td></td>
<td>Verizon 3G</td>
<td>50</td>
<td>0.81</td>
<td>2.22</td>
</tr>
<tr>
<td></td>
<td>Verizon 4G</td>
<td>99</td>
<td>9.41</td>
<td>15.34</td>
</tr>
<tr>
<td></td>
<td>AT&amp;T 3G</td>
<td>41</td>
<td>2.35</td>
<td>3.04</td>
</tr>
<tr>
<td></td>
<td>AT&amp;T 4G</td>
<td>92</td>
<td>21.64</td>
<td>45.71</td>
</tr>
<tr>
<td></td>
<td>Metro PCS</td>
<td>31</td>
<td>1.13</td>
<td>2.72</td>
</tr>
<tr>
<td></td>
<td>Sprint 3G</td>
<td>27</td>
<td>0.44</td>
<td>1.33</td>
</tr>
<tr>
<td>2012</td>
<td>Sprint 4G</td>
<td>45</td>
<td>4.65</td>
<td>11.98</td>
</tr>
<tr>
<td></td>
<td>T-Mobile</td>
<td>53</td>
<td>8.45</td>
<td>22.71</td>
</tr>
<tr>
<td></td>
<td>Verizon 3G</td>
<td>40</td>
<td>0.80</td>
<td>2.30</td>
</tr>
<tr>
<td>Mobile carriers/services</td>
<td>Probability of success of UDP stream transport (P-UDPS) (in %)</td>
<td>Probability of success of HTTP down-load transport (P-HTTP: DL) (in %)</td>
<td>Proportion of unspecified down-loads at link speed &gt; 144 kbps (P-UBR) (in %)</td>
<td>(Mean) time-to-first byte: (TFB) (in seconds)</td>
</tr>
<tr>
<td>-------------------------</td>
<td>---------------------------------------------------------------</td>
<td>---------------------------------------------------------------</td>
<td>---------------------------------------------------------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>Voice/ music</td>
<td>Video</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AT&amp;T</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>2.08</td>
</tr>
<tr>
<td>Sprint 3G</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.44</td>
</tr>
<tr>
<td>T-Mobile</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.76</td>
</tr>
<tr>
<td>Verizon</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.08</td>
</tr>
<tr>
<td>Verizon 4G LTE</td>
<td>72</td>
<td>7.98</td>
<td>19.42</td>
<td>5.51</td>
</tr>
<tr>
<td>AT&amp;T HSPA</td>
<td>39</td>
<td>4.87</td>
<td>12.79</td>
<td>0.82</td>
</tr>
<tr>
<td>AT&amp;T LTE</td>
<td>95</td>
<td>17.34</td>
<td>58.25</td>
<td>6.51</td>
</tr>
<tr>
<td>Sprint 3G</td>
<td>30</td>
<td>1.03</td>
<td>2.39</td>
<td>0.35</td>
</tr>
<tr>
<td>Sprint LTE</td>
<td>67</td>
<td>7.24</td>
<td>27.02</td>
<td>3.90</td>
</tr>
<tr>
<td>T-Mobile HSPA</td>
<td>54</td>
<td>8.97</td>
<td>15.74</td>
<td>1.42</td>
</tr>
<tr>
<td>Verizon 3G</td>
<td>33</td>
<td>0.62</td>
<td>2.55</td>
<td>0.59</td>
</tr>
<tr>
<td>Verizon LTE</td>
<td>87</td>
<td>13.66</td>
<td>51.08</td>
<td>4.52</td>
</tr>
</tbody>
</table>

Table A-II List of additional mobile service parameters considered in evaluating the MSI by PCMag.com [5.25]-[5.30]: Example details with respect to the service area, Boston Metro (MA), USA, 2010 through 2013
<table>
<thead>
<tr>
<th>Service</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average web down-load speed (WDLS in(Mbps))</td>
<td>500 kbps streaming success (P-500: SS) (in %)</td>
</tr>
<tr>
<td>Sprint 3G</td>
<td>73.98</td>
<td>0.78</td>
</tr>
<tr>
<td>Sprint 4G</td>
<td>51.56</td>
<td>1.83</td>
</tr>
<tr>
<td>T-Mobile</td>
<td>87.07</td>
<td>3.04</td>
</tr>
<tr>
<td>Verizon 3G</td>
<td>95.10</td>
<td>67.92</td>
</tr>
<tr>
<td>Verizon 4G</td>
<td>92.08</td>
<td>92.67</td>
</tr>
</tbody>
</table>

Table A- III An example set of MSI values indicated by PCMag.com [5.25]-[5.30] and corresponding upper- and lower-bounds obtained by the present method:

Service areas – Dallas, Boston, Miami, San Francisco, New York and Charlotte, NC

MSI: Mobile speed index – PCMag.com: $\zeta_{\text{year}} = [\text{MSI}]_{\text{year}}$

UB-MSI and LB-MSI: Statistical upper- and lower bounds on MSI:

UB-MSI: $g(\zeta)(0 \text{ to } 1)|_{UB} = [\text{MSI}]_{\text{year}}|_{UB}$ denoting the upper-bound (UB) value with $q = 0.5$

LB-MSI: $g(\zeta)(0 \text{ to } 1)|_{LB} = [\text{MSI}]_{\text{year}}|_{LB}$ denoting the lower-bound (LB) value with $q = \infty$

$g(\zeta)|_{UB \text{ or } LB} = [(1/2) + (1/2) \times L_q(\zeta/2)]$

<table>
<thead>
<tr>
<th>Mobile network service</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MSI</td>
<td>UB-MSI</td>
<td>LB-MSI</td>
<td>MSI</td>
</tr>
<tr>
<td>AT &amp; T</td>
<td>0.82</td>
<td>0.79</td>
<td>0.64</td>
<td>0.55</td>
</tr>
<tr>
<td>AT &amp; T 3G</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AT &amp; T 4G/3G</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AT &amp; T HSPA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprint 3G</td>
<td>0.73</td>
<td>0.59</td>
<td>0.44</td>
<td>0.35</td>
</tr>
<tr>
<td>Sprint 4G/LTE</td>
<td>0.76</td>
<td>0.73</td>
<td>0.57</td>
<td>0.47</td>
</tr>
<tr>
<td>T-Mobile</td>
<td>0.94</td>
<td>0.90</td>
<td>0.74</td>
<td>0.68</td>
</tr>
<tr>
<td>T-Mobile HSPA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Verizon</td>
<td>0.78</td>
<td>0.59</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td>Verizon 3G</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Verizon LTE/4G</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metro PCS</td>
<td>0.67</td>
<td>0.72</td>
<td>0.58</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Service area
Location: Dallas, TX

Service area
Location: Miami, FL
<table>
<thead>
<tr>
<th></th>
<th>Location: San Francisco, CA</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AT &amp; T</td>
<td>0.87</td>
<td>0.82</td>
<td>0.66</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>AT &amp; T 3G</td>
<td></td>
<td></td>
<td></td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>AT &amp; T 4G</td>
<td></td>
<td></td>
<td></td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>AT &amp; T HSPA</td>
<td></td>
<td></td>
<td></td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>Sprint 3G</td>
<td>0.64</td>
<td>0.73</td>
<td>0.57</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>Sprint 4G/LTE</td>
<td></td>
<td></td>
<td></td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>T-Mobile</td>
<td>0.67</td>
<td>0.71</td>
<td>0.55</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>T-Mobile HSPA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Verizon</td>
<td>0.77</td>
<td>0.63</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Verizon 3G</td>
<td></td>
<td></td>
<td></td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>Verizon LTE/4G</td>
<td>0.99</td>
<td>0.96</td>
<td>0.82</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>Metro PCS</td>
<td>0.58</td>
<td>0.62</td>
<td>0.49</td>
<td>0.37</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Location: New York, NY</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AT &amp; T</td>
<td>0.86</td>
<td>0.63</td>
<td>0.48</td>
<td>0.40</td>
<td>0.43</td>
<td>0.31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>AT &amp; T 3G</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.34</td>
<td>0.38</td>
<td>0.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>AT &amp; T 4G</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.90</td>
<td>0.84</td>
<td>0.72</td>
<td>0.96</td>
<td>0.83</td>
</tr>
<tr>
<td>Service area</td>
<td>Location: Charlotte NC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AT &amp; T</td>
<td>0.76 0.69 0.53 0.55 0.62 0.49</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AT &amp; T 3G</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.52 0.57 0.46</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AT &amp; T 4G LTE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.92 0.85 0.73 0.98 0.86 0.72</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AT &amp; T HSPA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.49 0.41 0.30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprint 3G</td>
<td>0.56 0.53 0.39 0.27 0.27 0.19 0.19 0.19 0.13 0.31 0.29 0.20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprint 4G/LTE</td>
<td>0.90 0.84 0.68 0.52 0.56 0.43 0.52 0.54 0.42 0.67 0.59 0.46</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T-Mobile</td>
<td>0.86 0.78 0.62 0.71 0.75 0.61 0.81 0.74 0.62</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T-Mobile HSPA</td>
<td>0.50 0.59 0.46</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Verizon</td>
<td>0.58 0.57 0.43</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Verizon 3G</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.42 0.46 0.34 0.40 0.47 0.35 0.24 0.20 0.14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Verizon LTE/4G</td>
<td>1.00 1.00 0.85 0.79 0.88 0.76 0.86 0.73 0.59</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metro PCS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cricket</td>
<td>0.53 0.61 0.46 0.45 0.48 0.36</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table A-IV Summary of computations on MSI [5.25]-[5.30] and RTPI values of incumbent mobile carriers (Site: Boston, MA: USA – 2010 through 2013)

a: MSI – PCMag.com index (Technology-specified)
b: RTPI – Statistically estimated relative performance index (Present method)
c: RTPI-UB – Upper-bound (UB) of (b)
d: RTPI-LB – Lower-bound (UB) of (b)

<p>| BOSTON Metro | Service period | Years | | |
|-------------|----------------|-------|---|---|---|---|</p>
<table>
<thead>
<tr>
<th>Carrier</th>
<th>RPI</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AT &amp; T</td>
<td>a 0.76</td>
<td>0.56</td>
<td>0.92</td>
<td>0.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>b 0.68</td>
<td>0.55</td>
<td>0.71</td>
<td>0.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>c 1.32</td>
<td>1.12</td>
<td>1.49</td>
<td>1.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>d 0.32</td>
<td>0.28</td>
<td>0.35</td>
<td>0.36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Verizon</td>
<td>a 0.69</td>
<td>0.99</td>
<td>0.72</td>
<td>0.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>b 0.66</td>
<td>0.73</td>
<td>0.69</td>
<td>0.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>c 1.25</td>
<td>1.56</td>
<td>1.29</td>
<td>1.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>d 0.31</td>
<td>0.36</td>
<td>0.32</td>
<td>0.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprint</td>
<td>a 0.96</td>
<td>0.56</td>
<td>0.45</td>
<td>0.67</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>b 0.65</td>
<td>0.51</td>
<td>0.47</td>
<td>0.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>c 1.52</td>
<td>1.13</td>
<td>1.02</td>
<td>1.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>d 0.36</td>
<td>0.28</td>
<td>0.25</td>
<td>0.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T-mobile</td>
<td>a 0.69</td>
<td>0.63</td>
<td>0.53</td>
<td>0.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>b 0.72</td>
<td>0.62</td>
<td>0.59</td>
<td>0.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>c 1.25</td>
<td>1.20</td>
<td>1.10</td>
<td>1.17</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>d 0.31</td>
<td>0.30</td>
<td>0.27</td>
<td>0.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metro PCS</td>
<td>a 0.41</td>
<td>0.31</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>b 0.61</td>
<td>0.45</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>c 0.97</td>
<td>0.88</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>d 0.24</td>
<td>0.20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
REFERENCES


P. S. Neelakanta and W. Deecharoenkul, A complex system characterization of modern telecommunication services, *Complex Systems*, 2000, vol. 12, pp. 31-69


D. Varoutas, C. Michalakelis, A. Vavoulas and K. Deligiorgi, Diffusion forecasting and price evolution of broadband telecommunication services in Europe, Chapter XLV in IGI Global, Online available: http://www.igi-global.com/chapter/diffusion-forecasting-price-evolution-broadband/20472


[8.3] Avatar, A free and open-source operating system for the internet with privacy built-in, Online available: http://sneakpeek.avatar.ai/