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Wireless Communications Systems Performance in Noise and Interference Limited Situations

Part 4: Recommended Methods for Technology- Independent Broadband Performance Modeling

TSB-88.4

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FOREWORD

(This foreword is not part of this bulletin.)

Working Group WG-8.18.4 prepared this document. Subcommittee TR-8.18 of TIA Committee TR-8 approved this document.

Changes in technology to support the public safety nationwide broadband network, plus increased reporting of interference have recently occurred. These events support keeping this document current and that it provide the methodology of modeling the various interference mechanisms to support frequency coordinators in determining the best assignments to be made for the available pool of frequencies and mixtures of technology.

This document, Wireless Communications Systems --- Performance in Noise-and Interference-Limited Situations ---Part 4: Recommended Methods for Technology Independent Broadband Performance Modeling includes 3 informative Annexes A through C.

This is the original release of Part 4 of this Bulletin. Other parts of this Bulletin are titled as follows:

- Part 1: Recommended Methods for Technology Independent Performance Modeling
- Part 2: Propagation and Noise
- Part 3: Performance Methods for Technology Independent Performance Verification
- Part 5: Recommended Methods for Technology Independent Broadband Performance Verification

Patent Identification

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INTRODUCTION

The TSB-88 series of documents is intended to address the following issues:

- Addressing migration and spectrum management issues involved in the transition either to narrowband/bandwidth efficient digital and analog technologies or to broadband technologies. Provide information on new and emerging Land Mobile bands;
- Assessing and quantifying the interference impact between narrowband technologies and broadband technologies;
- Address the methodology of minimizing system interference between current or proposed Noise Limited Systems in spectral and spatial proximity to current or proposed Interference Limited Systems;
- Assessing and quantifying the impact of new narrowband/bandwidth efficient digital and analog technologies on existing analog and digital technologies; Address the methodology to minimize inter-system interference between systems at national boundaries;
- Accommodating the design and frequency coordination of bandwidth-efficient narrowband technologies likely to be deployed as a result of the Federal Communications Commission “Spectrum Refarming” efforts; and
- Accommodating the design and frequency coordination of broadband technologies to be deployed in support of FirstNet’s nationwide interoperable broadband public safety network;

The TSB-88 series of documents was prepared partially in response to specific requests from three particular user organizations: the Association of Public Safety Communications Officials, International (APCO), the Land Mobile Communications Council (LMCC) and the National Coordination Committee (NCC). In 2003, the National Public Safety Telecommunications Council (NPSTC) assumed the responsibilities of NCC. [1]

This document, TSB-88.4, is intended to address performance modeling and the parametric values used to accomplish that modeling within the context described above.

[1] NPSTC's Broadband Requirements Report “Defining Public Safety Grade Systems and Facilities” describes best practices for coverage modeling based on recommendations from TSB-88 [NPSTC 14].

Wireless Communications Systems - Performance in Noise and Interference-Limited Situations

Part 4: Recommended Methods for Broadband Performance Modeling

1. SCOPE

1.1. The TSB-88 Series

The TSB-88 series of bulletins gives guidance on the following areas:

- Establishment of standardized methodology for modeling and simulating either narrowband/bandwidth efficient technologies or broadband technologies;
- Establishment of a standardized methodology for empirically confirming the performance of either narrowband/bandwidth efficient systems or broadband systems;
- Aggregating the modeling, simulation and empirical performance verification reports into a unified “Spectrum Management Tool Kit” which can be employed by frequency coordinators, systems engineers, software developers, and system operators;
- Recommended datasets that are available for improved results from modeling and simulation; and
- Providing current information for new and emerging bands.

The purpose of these documents is to define and advance a scientifically sound standardized methodology for addressing technology compatibility. This document provides formal structure and quantitative technical parameters from which automated design and spectrum management tools can be developed based on proposed configurations that can temporarily exist during a migration process or for longer term solutions for systems that have different technologies.

As wireless communications systems evolve, the complexity in determining compatibility between different types of modulation, different operational geographic areas, and application usage increases.

Spectrum managers, system designers and system maintainers have a common interest in utilizing the most accurate and repeatable modeling and simulation capabilities to determine likely wireless communication system performance. A standardized approach and methodology is needed for the modeling and simulation of wireless communications systems performance, considering both analog and digital practices in all frequency bands of interest.

In addition, subsequent to wireless communications system implementation, validity or acceptance testing is often an issue subject to much debate and uncertainty. Long after a system is in place and optimized, future interference dispute resolution demands application of a unified quantitative methodology for assessing system performance and interference.

These documents also provide a standardized definition and methodology to a process for determining when various wireless communications configurations are compatible. These documents contain performance recommendations for public safety and non-public safety that are recommended for use in the modeling and simulation of these systems. These documents also satisfy the desire for a standardized empirical measurement methodology that is useful for routine proof-of-performance and acceptance testing and in dispute resolution of interference cases.

To provide this utility necessitates that specific manufacturers define various performance criteria for the different capabilities and their specific implementations. Furthermore, sufficient reference information is provided so that software applications can be developed and employed to determine if the desired system performance has been realized.

Wireless system performance can be modeled and simulated with the effects of single or multiple potential distortion sources taken into account. These sources include:

- Performance parameters
- Co-channel users
- Off-channel users
- Internal noise sources
- External noise sources
- Equipment non-linearity
- Transmission path geometry
- Delay spread and differential signal phase
- Over the air and network protocols
- Performance verification methods

Predictions of system performance can then be based on the desired RF carrier versus the combined effects of single or multiple performance degrading sources. Performance is then based on a faded environment to more accurately simulate actual usage and considers both signal magnitude and phase attributes.

It is anticipated that this series of documents will serve as the standard reference for developers and suppliers of land mobile communications system design, modeling, simulation and spectrum management software and automated tools.

1.2. TSB-88.4

This document, TSB-88.4, provides additional guidance for establishing a standardized methodology for simulating and modeling broadband technologies for public safety systems. TSB-88.4 addresses performance modeling and the parametric values used to accomplish that modeling within the context described in §1.1.

System designers and system maintainers have a common interest in utilizing the most accurate and repeatable modeling and simulation capabilities to determine likely broadband system performance. Given the complexity of broadband systems such as LTE and the possibility for numerous modeling approaches, a standardized approach and methodology is needed for the modeling and simulation of these systems, in all frequency bands of interest.

The performance recommendations for modeling in TSB-88.4 cover best effort data systems. The scope might expand in the future to cover other classes of data such as VoLTE and streaming video.

2. REFERENCES

This Telecommunications System Bulletin contains only informative information. There are references to TIA and 3GPP standards which contain normative elements. These references are primarily to indicate the methods contained in those documents. At the time of publication, the edition indications were valid. All standards and bulletins are subject to revision and parties to agreements based on this document are encouraged to investigate the possibility of applying the most recent edition of the standards or bulletins indicated in Section 3. ANSI and TIA maintain registers of currently valid national standards published by them.

3. DEFINTIONS AND ABREVIATIONS

There is a comprehensive Glossary of Terms, Acronyms, and Abbreviations listed in Annex-A of TIA TSB-102. In spite of its size, numerous unforeseen terms still may have to be defined for the Compatibility aspects. Items being specifically defined for the purpose of this document are indicated as (New). All others will be referenced to their source as follows:

3GPP TS-36.101	[101]
3GPP TS-36.104	[104]
3GPP TS-36.133	[133]
3GPP TS-36.214	[214]
ANSI/IEEE 100-2000 Standard Dictionary	[IEEE]
TIA-603-E	[603]
TIA/EIA-102.CAAA-C	[102.CAAA]
Recommendation ITU-R P.1407-4	[ITU3]
Report ITU-R M.2014	[ITU8]
TIA-902.CAAA	[902.CAAA]
TIA-902.CBAA	[902.CBAA]
TSB-88.1-D	[88.1]
TSB-88.2-E	[88.2]
TSB-88.3-D	[88.3]
TSB-88.5	[88.5]
TSB-171	[171]

The preceding documents are referenced in this bulletin. At the time of publication, the editions indicated were valid. All such documents are subject to revision, and parties to agreements based on this document are encouraged to investigate the possibility of applying the most recent editions of the standards indicated above:

3.1. Definitions

For the purposes of this document, the following definitions apply:

16QAM: 16 Quadrature Amplitude Modulation is a digital modulation requiring 4bits/symbol. It uses 16 points on the constellation diagram typically spaced on a rectangular grid with equal separation between points.

64QAM: 64 Quadrature Amplitude Modulation is a digital modulation requiring 6bits/symbol. It uses 64 points on the constellation diagram typically spaced on a rectangular grid with equal separation between points.

Adaptive Modulation and Coding (AMC): Dynamically adapting the modulation and coding scheme based on the channel conditions

Adjacent Channel: The RF channel assigned adjacent to the licensed channel. The difference in the offset frequency is determined by the channel bandwidth.

Adjacent Channel Leakage power Ratio (ACLR): the ratio of the filtered mean power centered on the assigned channel frequency to the filtered mean power centered on an adjacent channel frequency

Adjacent Channel Power Ratio (ACPR): The ratio of the total power of a transmitter under prescribed conditions and modulation, within its maximum authorized bandwidth to that part of the output power which falls within a prescribed bandwidth centered on the nominal offset frequency of the adjacent channel.

Air-Ground-Air (AGA): Providing coverage to airborne devices from ground-based base stations

Application Layer Data Rate: The application layer data rate in units of bits per second is defined as the number of bits received at the application layer in a defined sample duration divided by the sample duration.

Boltzmann's Constant (k): A value 1.3805x 10^{-23} J/K (Joules per Kelvin). Room temperature is 290 K.

BPSK: Binary Phase Shift Keying is a digital modulation used in communications to modulate at 1bit/symbol. It uses two phases separated by 180 degrees. Also called 2-PSK or PRK (Phase Reversal Keying), 2QAM.

Cell: Following 3GPP terminology, a cell is equivalent to a sector in legacy LMR and radio terminology. A broadband base station will typically serve multiple cells (e.g. 3 or 6) via a set of radio units and directional antennas dedicated to each cell.

Cell Edge: The cell edge as applied to broadband coverage modeling coincides with the CPC. The cell edge data rate requirement is the minimum required data rate in units of bits per second to meet the desired application services objectives.

Channel Performance Criterion (CPC): The CPC is the specified design performance level in a faded channel. See §5.2.

Channel Quality Indicator (CQI): CQI is an indicator in LTE that is provided to the network by the UE to indicate the channel quality. It is a 4-bit value, reported periodically or aperiodically, that indicates the MCS and code rate which the UE can support given the current channel conditions.

Co-Channel User: Another user on the same center frequency. In a single reuse communications networks, users in adjacent or neighboring cells are co-channel users. Also, if different systems at geographic borders utilize the same frequency band, users of these systems are co-channel users.

Confidence Interval: A statistical term where a confidence level is stated for the probability of the true value of something being within a given range which is the interval.

Confidence Level: also called Confidence Coefficient or Degree of Confidence, the probability that the true value lies within the Confidence Interval.

Coverage Acceptance Test Plan (CATP): The CATP is a document that defines the method and metric (i.e. DRCPC) that will be used to validate in the field that the predicted service area reliability or covered area reliability has been achieved.

Covered Area Reliability: The Covered Area Reliability is the probability of achieving the desired CPC over the defined covered area. A *tile-based area reliability* (q.v.) that is calculated by averaging the individual tile reliabilities only for those tiles that meet or exceed the minimum desired tile reliability. It can be used as a system acceptance criterion.

CPC Reliability: CPC Reliability is the probability that the prescribed CPC exists at a specified location.

Cyclic Redundancy Check (CRC): A technique utilizing a hash function to detect errors in digital data.

Data Rate Channel Performance Criterion (DRCPC): The DRCPC is the minimum required application layer data rate in a faded channel to meet the broadband data services objectives. See §5.2.

Delay Spread [ITU3]: The power-weighted standard deviation of the excess delays, given by the first moment of the impulse response.

Deployable Aerial Communications Architecture (DACA): A communication system where one or more base stations are airborne, generally serving ground based devices.

Dipole: A half wave dipole is the standard reference for fixed station antennas. The gain is relative to a half wave dipole and is expressed in *dBd*.

Doppler Frequency: The Doppler frequency is given by v/λ where v is the vehicle velocity and λ is the radio carrier wavelength (same units). Frequently this is also referred to as Doppler Shift.

Downlink (DL): From the fixed equipment outward to the "mobile" units. Also referred to as a forward-link.

DRCPC Reliability: The probability that the prescribed DRCPC exists at a specified location.

Evolved or E-UTRAN Node B (eNB): The LTE base station

Extended Pedestrian A (EPA) Channel: The 3GPP Extended Pedestrian A Channel model, defined as a multi-path delay profile in 3GPP TS 36.101 and TS 36.104. It is used to model pedestrian channel scenarios. When followed by a number, this indicates the Doppler shift in Hz.

Equivalent Noise Bandwidth (ENBW): The frequency span of an ideal filter whose area equals the area under the actual power transfer function curve and whose gain equals the peak gain of the actual power transfer function. In many cases, this value could be close to the 3 *dB* bandwidth. However, there exist situations where the use of the 3 *dB* bandwidth can lead to erroneous results. Sometimes ENBW is referred to as Effective Noise Bandwidth.

Extended Typical Urban (ETU) Channel: The 3GPP Extended Typical Urban Channel model, defined as a multi-path delay profile in 3GPP TS 36.101 and TS 36.104. It is used to model typical urban channel scenarios. When followed by a number, this indicates the Doppler shift in Hz.

Extended Vehicular A (EVA) Channel: The 3GPP Extended Vehicular A Channel model, defined as a multi-path delay profile in 3GPP TS 36.101 and TS 36.104. It is used to model vehicular channel scenarios. When followed by a number, this indicates the Doppler shift in Hz.

Frequency Division Duplex (FDD): Indicates a full duplex configuration in which uplink and downlink communications are performed in separate frequency bands.

Frequency and Time-based Interference Coordination: A set of algorithms that endeavor to improve data system performance in terms of coverage and capacity by coordinating transmit frequencies between cells in the case of frequency-based interference coordination and coordinating transmission in time in the case of time-based interference coordination.

Frequency Selective Scheduling (FSS): In a broadband system in which multiple users can be allocated subsets of frequency domain resources at the same time, FSS refers to the scheduling strategy in which resources are opportunistically allocated to simultaneously scheduled users based on the estimated channel conditions for each user.

Height Above Average Terrain (HAAT): A regulatory term describing the height of the radiating antenna center above the average terrain that is determined by averaging equally spaced data points along radials from the site or the tile equivalents. Average only that portion of a radial between 3 and 16 km (2 and 10 miles) inclusive.

Inferred Noise Floor: The noise floor of a receiver calculated when the Reference Sensitivity is reduced by the static S_S/N necessary for the Reference Sensitivity. This is equivalent to kT_0B + Noise Figure of the receiver.

Interference Limited: The case where the CPC is dominated by the Interference component of $S/(I+N)$.

Interference Cancelling Receivers: Advanced receivers capable of suppressing interference in which simultaneous signals are modeled and decoded together rather than treating all but one as random noise. Some use iterative techniques to obtain increased interferer rejection performance.

Isotropic: An isotropic radiator is an idealized model where its energy is uniformly distributed over a sphere.

kT_0B: The receiver thermal noise floor, where k = Boltzmann's constant (1.380622E-23 J/K), T_0 = 290K at the generally defined room temperature, and B is the bandwidth in Hertz. kT_0B = -174 *dBm* with ENBW in Hertz, and kT_0B = -114 *dBm* with the ENBW in MHz

Maximum Transmission Unit (MTU): The largest size packet or frame, specified in octets, that can be sent in a packet based network protocol such as IP.

Measurement Error: The variability of measurements due to the measuring equipment's accuracy and stability.

Modulation and Coding Scheme (MCS): In a data system that supports Adaptive Modulation and Coding, the Modulation and Coding Scheme (MCS) describes the type of modulation used (e.g. BPSK, QPSK, 16QAM, or 64QAM) and the error detection and correction coding rate used with that modulation (e.g. rate ½, rate ¾, etc.).

Multiple Input Multiple Output (MIMO): MIMO utilizes multiple antennas at the transmitter and receiver to improve system performance and spectral efficiency. Transmit diversity and spatial multiplexing are examples of MIMO implementations.

Multi-User MIMO (MU-MIMO): A form of spatial multiplexing MIMO (SM-MIMO) in which multiple spatial streams transmitted by a base station are intended for multiple devices, or multiple devices simultaneously transmit using the same time-frequency resources to the same base station.

Noise Limited: The case where the CPC is dominated by the Noise component of *S/(I+N).*

Noise Rise: In self interfering networks receiver performance is impaired by intra-system interference and is often called noise rise or interference over thermal (IoT). Noise rise is calculated as the ratio of interference plus thermal noise over thermal noise in linear domain and notated (I+N)/N.

Number of Test Tiles: The number of uniformly distributed but randomly selected test locations used to measure the CPC. It is calculated using the Estimate of Proportions equation and the specified Area Reliability, Confidence Interval and Sampling Error.

Orthogonal Frequency Division Multiplexing (OFDM): OFDM is a digital modulation method which modulates data on closely spaced multiple orthogonal carrier frequencies.

Orthogonal Frequency Division Multiple Access (OFDMA): A multiple access scheme which uses OFDM technologies.

Open Systems Interconnection (OSI) Model: A conceptual model that standardizes the functions of a telecommunication or computing system without regard of their underlying internal structure and technology.

Out of Band Emissions (OOBE) [ITU8]: Emission on a frequency or frequencies immediately outside the necessary bandwidth, which results from the modulation process, *but excluding spurious emissions.* This definition is restrictive for the purpose of this document.

Path Loss Exponent: The exponent of range (or distance from a signal source) that calculates the decrease in received signal power as a function of distance from a signal source, e.g. the received signal power is proportional to transmitted signal power time r^{-n} where r is the range and n is the path loss exponent.

Physical Uplink Control Channel (PUCCH): The PUCCH is the LTE channel that is used to carry uplink control information from the device to the eNB.

Power Spectral Density (PSD) [IEEE]: The energy, relative to the peak or rms power per Hertz, usually given in dB units. It is also referred to as Spectral Power Density which is utilized in this document.

Propagation Model: A model that predicts path-loss as a function of distance and parameters such as environment, carrier frequency, and antenna height.

Quadrature Phase Shift Key (QPSK): The acronym for the Quadrature Phase Shift Keyed family of compatible modulations. Quadrature Phase Shift Keying is a digital modulation requiring 2 bits/symbol. It uses 4 points on the constellation diagram equally spaced around a circle (90 degree spacing).

Resource Block (RB): The minimum OFDMA allocation that can be scheduled in LTE. An RB is 180 kHz wide in the frequency dimension and 0.5 ms in time.

Received Signal Strength Indicator (RSSI): The measurement of the power in a received communication signal. RSSI includes both signal and noise power in a communication band.

Reference Signal Received Power (RSRP): In LTE, RSRP is defined as the linear average of the power contributions (in Watts) of the resource elements containing cell-specific reference signals within the considered measurement frequency bandwidth.

Reference Signal Received Quality (RSRQ): In LTE, RSRQ is defined as the ratio of RSRP to RSSI, scaled by number of RBs in the system bandwidth.

Real-Time Transport Protocol (RTP): A connectionless IP session layer protocol that specifies a way for programs to manage the real-time transmission of multimedia data over either unicast or multicast network services

Sampling Error: A percentage error; caused by not being able to measure the "true value" obtained by sampling the entire population.

Service Area: The specific user's geographic bounded area of concern. Usually a political boundary such as a city line, county limit or similar definition for the users business. Can be defined relative to site coordinates or an irregular polygon where points are defined by latitude and longitude. In some Public Safety systems the Service Area could be greater than their Jurisdictional Area. This is done to facilitate mutual aid or interference mitigation.

Service Area Reliability: The Service Area Reliability is the probability of achieving the desired CPC over the defined Service Area. A *tile-based area* *reliability* (q.v.) that is calculated by averaging the individual tile reliabilities for all tiles within the service area. It can be used as a system acceptance criterion. If mixed tile sizes are used, the individual tile reliabilities must be weighted or normalized based on their individual tile area.

Short Message Service (SMS): The text messaging service component of mobile communication systems

Signal to Noise plus Interference Ratio (SINR): In broadband air interface technologies the main carrier is normally divided into many different control and payload signals. Each of these signals often use different modulation and coding techniques and have different receiver sensitivity and QoS performance criterion. Therefore it is important to define the quality metric for each as the ratio of the desired signal power to the power of the received noise and interference, notated S/(I+N), typically expressed in units of dB.

Signal to Noise Ratio (SNR): The ratio of the desired signal power to the average noise power within a specified bandwidth, typically expressed in units of dB.

Single Carrier Frequency Division Multiple Access (SC-FDMA): A multiple access scheme, sometimes also known as Discrete Fourier Transform (DFT)-spread OFDM, which is a linearly pre-coded OFDMA scheme with an additional DFT step proceeding the OFDMA processing.

Space Frequency Block Coding (SFBC): A form of transmit diversity where the blocks, e.g. pairs of OFDM symbols in LTE, are coded across the frequency dimension. LTE utilizes this form of transmit diversity by transmitting each orthogonally designed code block on neighboring subcarriers of the same OFDM symbol.

Spatial multiplexing MIMO (SM-MIMO): A MIMO implementation in which independent and separately encoded data signals (or “streams”) are simultaneously transmitted from multiple transmit antennas to enhance spectral efficiency. The SM-MIMO streams can be transmitted from or received by a single user or multiple users, with the latter referred to as multi-user (MU) MIMO.

Symbol Rate: The rate of change of symbols, symbols/sec. Each symbol represents multiple bits of binary information. Each symbol can have multiple states which correspond to the binary value represented by the symbol. The symbol rate is the bit rate divided by the number of bits per symbol.

Time Division Duplex (TDD): Indicates a half duplex configuration in which uplink and downlink communications are performed in the same frequency band.

Tile-based Area Reliability: The mean of the individual tile reliabilities over a predefined area. See §5.3.1.3

Tile Mean Data Rate: The mean data rate measured at the application layer in a Test Tile using UDP at the transport layer. Calculated as the total application layer bits received in the specified time duration divided by the time duration.

Tile Reliability: In a Monte Carlo simulation, multiple data transmission attempts are made at a geographic tile location. The tile reliability is the percentage of transmission attempts that resulted in an achieved data rate that was greater than or equal to the CPC. See §5.3.1.3

Transmit Diversity: A MIMO implementation which utilizes techniques such as varying delay/frequency offsets between the transmit paths or via space-time channel coding or both to provide diversity gains. The transmit diversity mode in LTE utilizes Space-Frequency Block Coding (SFBC).

Transport Layer Data Rate: The transport layer data rate in units of bits per second is defined as the number of bits received at the transport layer in a defined sample duration divided by the sample duration.

Uplink (UL): From the "mobile equipment" inbound to the fixed equipment, also referred to as a reverse-link.

Uplink Power Control (ULPC): ULPC refers to the technique in which the device transmission power is varied. In general, the device transmit power level is adjusted with the goal of meeting a pre-defined target power density (power per unit bandwidth) received by the base station. ULPC can generally have open-loop or closed-loop control or both.

X2 Interface: A logical interface between eNBs in LTE. It includes a user plane that carries end-user packets and a control plane for signaling.

3.2. Abbreviations

16QAM	16 point Quadrature Amplitude Modulation
64QAM	64 point Quadrature Amplitude Modulation
ACK	Acknowledgement
ACLR	Adjacent Channel Power Ratio
ACPR	Adjacent Channel Power Ratio (preferred by FCC)
AGA	Air-Ground-Air
AGC	Automatic Gain Control
AMC	Adaptive Modulation and Coding
ANSI	American National Standards Institute
APCO	Association of Public Safety Communications Officials International, Inc.
BB	Broadband
BPSK	Binary Phase Shift Keying
CATP	Coverage Acceptance Test Plan
CPC	Channel Performance Criterion
CQI	Channel Quality Indicator
CRC	Cyclic Redundancy Check
DACA	Deployable Aerial Communications Architecture

dBd	Decibels relative to a half wave dipole
dBi	Decibels relative to an isotropic radiator
dBm	Power in decibels referenced to 1 milliWatt
DL	Downlink
DRCPC	Data Rate Channel Performance Criteria
EIRP	Effective Isotropic Radiated Power
eNB	Evolved Node B
ENBW	Equivalent Noise Bandwidth
EPA5	Extended Pedestrian A model, 5Hz max Doppler frequency
EVA70	Extended Vehicular A model, 70Hz max Doppler frequency
ERP_d	Effective Radiated Power, relative to a $\lambda/2$ dipole
ETSI	European Telecommunications Standards Institute
ETU300	Extended Typical Urban, 300Hz max Doppler frequency
EVA70	Extended Vehicular A, 70Hz max Doppler frequency
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FSS	Frequency Selective Scheduling
HAAT	Height Above Average Terrain
HTTP	Hypertext Transfer Protocol
IMD	Intermodulation Distortion
ICIC	Inter-Cell Interference Coordination
ICMP	Internet Control Message Protocol
IP	Internet Protocol
IRC	Interference Rejection Combining
ISO	International Organization for Standardization
ITU-R	International Telecommunication Union - Radiocommunication Sector
k	Boltzmann's Constant
LLC	Logical Link Control
LMR	Land Mobile Radio
LTE	Long Term Evolution
MAC	Media Access Control
MCS	Modulation Coding Scheme
MIMO	Multiple-Input Multiple-Output
MRC	Maximum Ratio Combining
MTU	Maximum Transmission Unit
MU-MIMO	Multi-User MIMO
N/A	Not Applicable

NCC	National Coordination Committee
NLCD	National Land Cover Dataset
NPSTC	National Public Safety Telecommunications Council
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OOBE	Out of Band Emissions
OSI	Open Systems Interconnection
PSD	Power Spectral Density
PUCCH	Physical Uplink Control Channel
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
RB	Resource Block
RF	Radio Frequency
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Receiver Signal Strength Indication
RTP	Real-Time Transport Protocol
RTT	Round Trip Time
SAR	Service Area Reliability
SC-FDMA	Single Carrier FDMA
SFBC	Space Frequency Block Coding
SINR	Signal to Interference plus Noise Ratio, same as S/(I+N)
SIP	Session Initiation Protocol
SM-MIMO	Spatial Multiplexing MIMO
SMTP	Simple Mail Transfer Protocol
SMS	Short Message Service
SNR	Signal to Noise Ratio
TBD	To Be Determined
TDD	Time Division Duplex
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
UL	Uplink
ULPC	Uplink Power Control

3.3. Trademarked Names

The purpose of this Bulletin is to provide performance modeling parametric values for different broadband communications systems. Many manufacturers use trademarked names to identify their proprietary offerings. As a result it is difficult to determine the specifics for modeling without knowing the transceiver characteristics. As broadband solutions become available in the public safety market, this section and additional annexes are available to manufacturers to provide data on their trademarked products.

The use of trademarks does not constitute an endorsement of the product or services.

4. TEST METHODS

Test methods listed in this section are either specific to the referenced normative TIA documents or informative recommendations.

Test methods are defined in the following subsections:

- §5.7.1.1 [603]
- §5.7.1.2 [102.CAAA]
- §5.7.1.4 [902.CAAA], [902.CBAA]

5. WIRELESS SYSTEM TECHNICAL PERFORMANCE DEFINITIONS AND CRITERIA

The complete definition of the user needs eventually evolves into the set of conformance criteria. Based on prior knowledge of what the user needs are and how the conformance testing is to be conducted, iterative predictions can be made to arrive at a final design. Due to the complexity of modern broadband systems, an assumption is made in the following that Monte Carlo simulation methods are used to model broadband coverage. The following factors need to be defined before this process can be accomplished.

5.1. Service Area

This is the user's operational area within which the broadband radio system is specified to provide:

- The specified Channel Performance in the defined area for data services
- The specified CPC Reliability in the defined area for data services

The definitions in the following sections build upon the concept of the Service Area, Channel Performance Criterion (CPC), and reliability. It is recommended that the Service Area be defined in geographic terms.

5.2. Data Rate Channel Performance Criterion (DRCPC)

The DRCPC is the specified broadband data services design performance level in a faded channel. It is defined as the minimum required data rate to meet the broadband data services objectives. The DRCPC defines the coverage objective during modeling and is the performance metric measured during broadband data coverage acceptance testing. The data rate being modeled must correspond to data rate measured during acceptance testing. In order to facilitate stable and repeatable field measurements for coverage acceptance testing, it is recommended that the best effort data rate be modeled as the payload of UDP datagrams, where the payload of the UDP datagram contains application data only with no additional application layer headers or overhead. From the coverage acceptance testing perspective, UDP datagrams would be sent containing only data as the payload and the throughput of this payload would be measured. This can be considered measured Transport Layer Throughput or Application Throughput for this special case of an application that consists of data only with no additional headers or overhead. Refer to Annex B Traffic Modeling for a detailed description of the OSI Model layers and associated overheads.

5.3. DRCPC Reliability

CPC Reliability is defined as the probability that the prescribed CPC exists at a specified location. Hence, DRCPC Reliability is the percentage of computed data rate samples from the Monte Carlo simulation at the specified point that are greater than or equal to the data rate defined by the DRCPC.

5.3.1. DRCPC Reliability Design Targets

The reliability of wireless broadband data communications over a prescribed area is often an issue that is misunderstood. Standardized definitions that are universally applicable are necessary and are presented below.

5.3.1.1 Service Area Reliability

The Service Area Reliability (SAR) is the probability of achieving the desired DRCPC over the defined Service Area. It is calculated by averaging the individual Tile Reliabilities for all tiles within the Service Area. Typically tiles are all the same size. If mixed tile sizes are used, the individual tile reliabilities must be weighted or normalized based on their individual tile area.

5.3.1.2 Covered Area Reliability

The Covered Area Reliability is defined as the probability of achieving the desired DRCPC over the defined covered area. It is the average of the individual Tile Reliabilities for only those tiles that meet or exceed the minimum desired Tile Reliability.

5.3.1.3 Tile Reliability

In a Monte Carlo simulation, multiple data transmission attempts are made at a geographic tile location. The Tile Reliability is the percentage of predicted data rate samples at the given geographic tile location that are greater than or equal to the data rate defined by the DRCPC.

5.4. Reference Sensitivity

Broadband communication systems define reference sensitivity in terms of a receiver throughput requirement instead of an SNR value. For example, in [101] and [104], 3GPP defines reference sensitivity as the “minimum mean power received at the antenna connector at which a throughput requirement shall be met for a specified reference measurement channel”. For narrowband systems, [88.1] defines reference sensitivity in terms of a “signal strength value used in receiver C/N calculations”. In [88.1] a given value of Reference Sensitivity doesn’t specifically relate to a defined audio quality or other measurement value.

Broadband communications systems use different mechanisms for allocating resources. WiMAX (802.16) and LTE are scheduler based. WiFi uses a contention mechanism for allocating resources. These mechanisms improve spectral efficiency by allowing allocation of time/frequency resources on smaller time intervals. As the link SINR changes, resources are allocated to match the current conditions. When the SINR is high, higher throughputs can be achieved. However, manufacturers use proprietary methods for allocating resources to improve spectral efficiency. Therefore, defining reference sensitivity in terms of throughput instead of SINR allows measured data rates to be used to easily compare both equipment performance and network performance. This document and the [88.5] document use 3GPP’s throughput based definition of reference sensitivity.

5.5. Device Parametric Values

In this section, device parameters that have significant impact on coverage model estimation are described. General guidance is provided for each parameter. These parameters ought to be specified for each device type for which coverage maps are desired.

Table 1 Device Parameters

Parameter	**Options/Guidance**
Device Type	Portable or handheld, vehicular modem, customer premises (e.g. dongle), shoulder or vehicle mounted video camera, air-ground-air modem
Frequency Band(s) of operation	3GPP Band 14 (758-768MHz DL, 788-798MHz UL) has been allocated for Public Safety use in the United States. The band(s) of operation impact many modeling aspects such as propagation modeling, antenna gains, head and body losses, building and vehicle penetration losses, etc.
Bandwidths for each band	3GPP options are 1.4, 3, 5, 10, 15 and 20MHz
Channel model	Pedestrian, Vehicular, High Speed Train, AGA
Antenna Schemes, # of Tx/Rx antennas for primary band	1x2 MIMO (1 Tx and 2 Rx) is typical for 3GPP R9, R10 LTE devices, optional switched Tx Diversity, Rx Diversity
Antenna Gain	Antenna gain is a function of many factors including type of antenna, whether the antenna is mounted internally or externally, the total number of antennas in the device, frequency of operation and antenna correlation. While many narrowband LMR devices use external antennas to improve coverage performance, broadband smartphone-type devices typically use multiple internal antennas to support Public Safety 4G bands, various consumer bands (2G, 3G, 4G), WiFi and GPS. In the 700-900 MHz bands, current LTE smartphone total antenna efficiencies (radiation efficiency and the effects of mismatch and mutual coupling) range from 30% to 60%, with peak gains in the -4 to -1 dBd[2] range [Wang15] [Wang15b]. Vehicular modems typically utilize external antennas mounted on the roof of the vehicle. In the 800MHz frequency range, taking into account coupling and ground plane effects, the average antenna gain of a roof-mounted quarter-wave dipole is -1 dBd [171].

[2] These values are converted from dBi units used in the cited references.

Table 1 (*continued*)

Parameter	**Options/Guidance**
Head and body loss	For portable devices, the device location relative to the human body creates loss that ought to be modeled. Loss depends on multiple factors including frequency, location of the device relative to the body, size of the body, and whether or not device is held in the hand or next to the head. For many PS applications, a portable device is mounted in a holster on the officer's body prior to the call and is either held at the head or in front of the head during the call, depending on whether the primary use case is voice or data. Therefore downlink and uplink head and body loss are a function of the use case and are not necessarily the same. Typical head, hand, and body loss for the 700-900 MHz frequency range and various device use cases can be found in [Neilsen12] [Boyle03] [Berg09] [Bahramzy15]. Measured values range from 3-12dB depending on the use case, hand placement, antenna location within the device, etc.
Vehicle Penetration Loss	When modeling coverage of portable devices located inside vehicles, a vehicle penetration loss ought to be modeled. The loss depends on multiple factors including the frequency, vehicle type, and location of device within the vehicle. In the 700-900 MHz range, vehicle penetration losses between 3-24 dB have been measured [Tanghe08] [Virk14] [Hill91].
Building Penetration Loss	When modeling coverage of portable devices located indoors, a building penetration loss ought to be modeled. The loss depends on multiple factors including the frequency, building construction type, and which floor the device is on. Building penetration loss between 16 and 24 dB has been measured for commercial buildings in the 700-900 MHz range for devices on lower floors, with losses generally decreasing for higher floors. [Durante73] [Turkmani88] [Kvicera10] [Davidson97] [Schramm97]. Penetration losses between 3 and 7 dB have been measured for residential structures in the same frequency range [NTIA92] [88.2].

Table 1 (*concluded*)

Parameter	Options/Guidance
Cable Loss	Typical cable loss is 1 to 2dB for vehicular devices depending on frequency, cable type and cable length. For large vehicles such as fire trucks, city buses and trains, locating the modem near the antenna is desirable to reduce cable loss.

Other parameters such as receiver noise figure and RF sensitivity are vendor specific. Values used for modeling ought to reflect the specific products offered by vendors. It is recommended that modelers use the parameter values within the ranges specified in the table above and that modelers justify use of values at the extremes of range or outside the range.

6. WIRELESS SYSTEM PERFORMANCE MODELING METHODOLOGY

The flowchart depicted in Figure 1 illustrates the recommended broadband wireless system performance modeling methodology. The Monte Carlo-based methodology involves several major components including propagation modeling, data application modeling, broadband data transmission modeling, and public safety grade coverage modeling. The coverage modeling is dependent on numerous technology specific broadband data models including broadband carrier bandwidth, subscriber speed, MIMO, receive diversity processing, scheduling of shared resources, uplink power control strategies, interference modeling , modulation and coding rate adaptation, handoff, accounting for air interface overhead such as for control channels and demodulation reference symbols, and control channel coverage modeling.

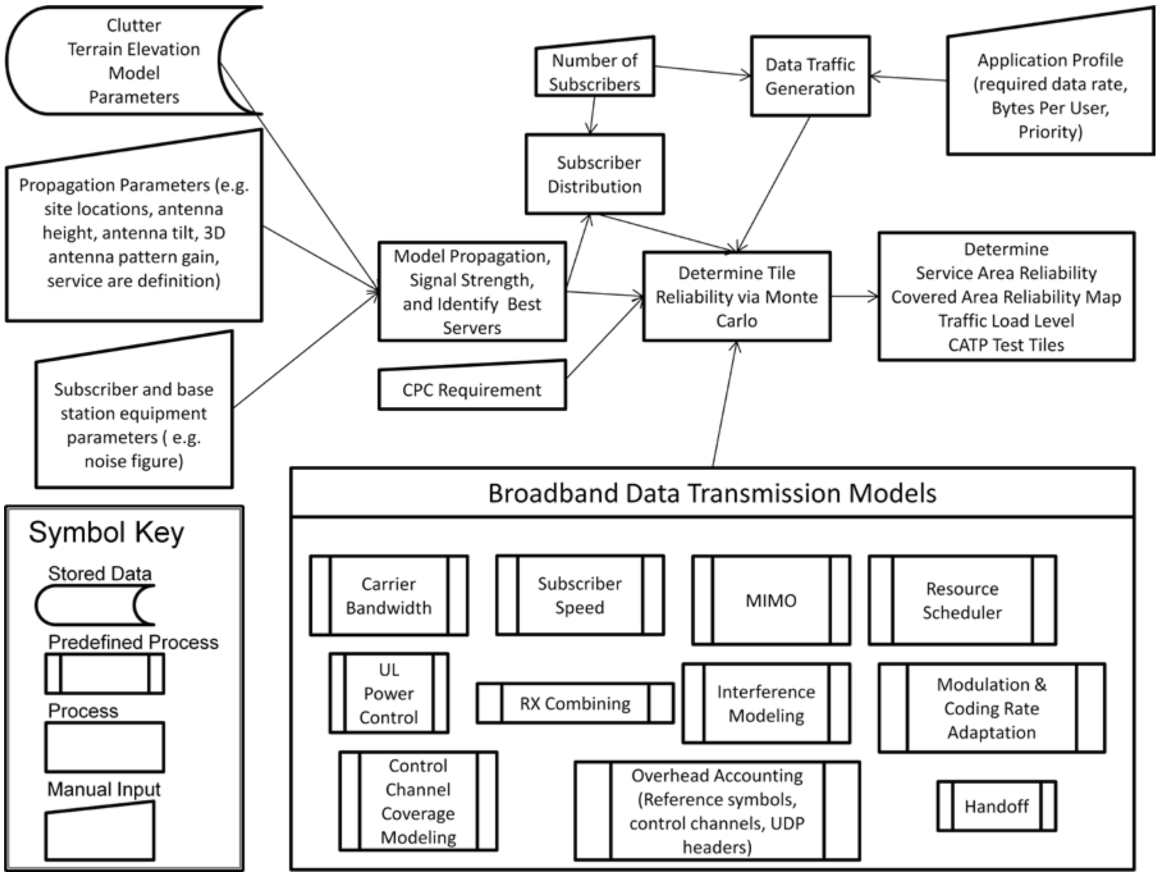

Figure 1 Broadband Model Flowchart

6.1. Propagation and Signal Strength Modeling

The wireless broadband coverage modeling methodology begins with estimating the median propagation path loss between the base stations and tile locations throughout the service area. This median path loss is typically estimated using one of a number of different models and using inputs such as terrain elevation and NLCD databases as further described in [88.2].

These predicted path loss estimates are then used along with other model inputs including transmit power, 3D antenna pattern gains, transmission line losses, and head and body losses to compute uplink and downlink signal strengths. These signal strengths are further employed to determine the best server coverage areas and in calculating SINR. Section 6.3.6 describes methodologies for calculating data and control channel SINR values.

Calculating signal strength is an intermediate step towards computing SINR. It is not recommended to assess broadband coverage based on signal strength maps alone because signal strength does not correlate directly to performance in terms of the achievable data rate. Signal strength by itself does not account for the effects of interference or resource sharing, both of which impact the achievable data rate. However, if for some reason it is desirable to view a broadband signal strength map, it is important to realize that the map can represent various different signals and bandwidths. For example, in an OFDM-based broadband data system, the signal strength represents the power contained in the full transmission bandwidth, a single OFDM subcarrier, or some bandwidth in between, such as one Resource Block (180 kHz) in an LTE system. In LTE the data channel, control channel, synchronization channel, and reference symbols comprise different bandwidths and are often transmitted with different power levels, both in DL and UL. The following provides some LTE-specific signal measurement definitions.

6.1.1. LTE Measurements

[214] defines DL LTE measurements taken by the UE. These are: Reference Signal Received Power (RSRP), Received Signal Strength Indicator (RSSI), and Reference Signal Received Quality (RSRQ). Although SINR is not specifically defined by 3GPP, the Channel Quality Indicator (CQI), a parameter that is fed back from the device to the eNB, is based on a proprietary evaluation of SINR by the device. CQI is defined in [213]. The following sub-sections describe each of these parameters in more detail.

6.1.1.1 RSRP

RSRP is defined as the linear average of the power contributions (in Watts) of the resource elements containing cell-specific reference signals (RS) within the considered measurement frequency bandwidth. It provides signal strength information but does not provide an indication of signal quality and is independent of the traffic loading in the serving cell. It is specified in dBm units.

RSRP is reported in 1 dB steps (98 steps) from -140 dBm to -44 dBm. It provides a reasonable capability of measuring the signal power from a specific cell while potentially eliminating interference and noise power from other cells. The typical usable range is from -75 dBm when close to a cell to -120 dBm when at the edge of a cell.

Note that both the considered measurement bandwidth and the measurement (i.e. averaging) period is left up to the UE implementation, with consideration of the accuracy requirements defined in [133]. The RSRP calculation is based on cell-specific reference symbols transmitted from antenna port 0, or both ports 0 and 1 (refer to [214] for details) of the eNB. RSRP measurements are used in handover, cell selection, and cell re-selection procedures [133].

6.1.1.2 RSSI

RSSI is defined as the linear average of the total received power (in Watts) observed in certain OFDM symbols (typically only those containing reference symbols from eNB antenna port 0) of measurement subframes across the system bandwidth. Like RSRP, RSSI is typically specified in dBm units. This measurement includes all sources of received power, including co-channel serving and non-serving cells, adjacent channel interference, etc. This represents the total received wideband power at the user equipment antenna port, which includes reference signals and traffic from the serving cell.

6.1.1.3 RSRQ

RSRQ is an SINR type of measurement and is defined as the ratio of RSRP to RSSI, scaled by number of RBs in the system bandwidth. Based on the number of resource blocks (N_R) RSRQ is calculated as follows:

$$RSRQ = (N_R \times RSRP) / RSSI \quad (1)$$

The reporting range consists of 35 indications in 0.5 dB steps from -19.5 dB to -3 dB. RSRQ measurements are sometimes used to replace or supplement RSRP measurements for handover and cell re-selection procedures.

6.1.1.3.1 Example RSRQ Calculations

In OFDM symbols containing reference symbol resource elements, there are 2 OFDM sub-carriers with reference symbols out of 12 sub-carriers per resource block. Figure 2 below illustrates an LTE resource block consisting of 7 OFDM symbols in time and 12 subcarriers in frequency, with reference symbol resource elements shown in red.

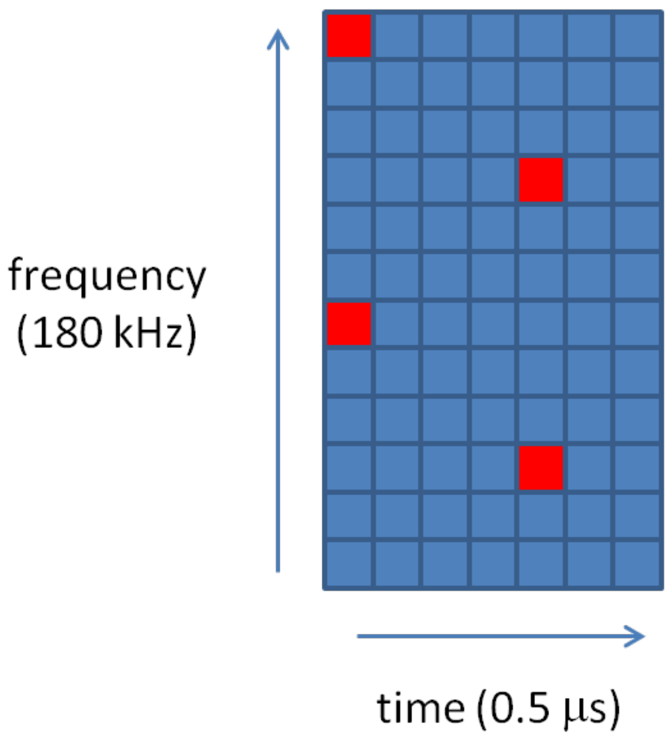

Figure 2 – An LTE Resource Block (RB)

Assume a noise-limited case with no interference from neighbor cells or other sources and no traffic loading in the serving cell. In this unloaded case, only the red reference symbol resource elements contain power. Defining the power per RS to be "P", RSRP is then equal to P while RSSI is N_R x 2P. Then:

$$RSRQ = (N_R \times P) / (N_R \times 2P) = ½ = -3 \text{ dB} \quad (2)$$

Taking the same noise-limited assumption but with full loading in the serving cell, RSSI is then N_R x 12P, and the calculation becomes:

$$RSRQ = (N_R \times P) / (N_R \times 12P) = 1/12 = -10.8 \text{ dB} \quad (3)$$

In these two noise-limited examples, the only power measured in the RSSI is from the serving cell. Neighbor cell transmissions and external interference increase RSSI, which reduces RSRQ.

6.1.1.4 Reference Signal SNR

Assuming P_{RS} is the noise power in a 15 kHz subcarrier that contains a reference symbol, the reference signal SNR is defined as:

$$RS\ SNR = RSRP / P_{RS} \quad (4)$$

Assuming a noise figure of 7 dB and that RSRP contains no interference power, the power in a single subcarrier would be: -174 dBm/Hz + 10log(15000) + 7 dB = -125.2 dBm. Therefore a 0 dB SNR occurs when RSRP = -125.2 dBm.

6.1.1.5 SINR and CQI

SINR is not defined by 3GPP but vendors create their own definition and SINR measurements are often available for recording via drive test tools. While UEs do not explicitly report SINR to the network, they do report CQI, which is an indication of the MCS that the UE can support given the current SINR. CQI is reported periodically via the PUCCH with a period specified by the eNB or aperiodically via the PUCCH or "piggybacked" with UL data transmissions via the PUSCH. CQI is reported as a 4-bit (16-level) value that is mapped into an MCS.

6.1.1.6 Example Ranges of LTE Measurements

The following table illustrates an example mapping between RF conditions and the LTE measurements summarized above:

Table 2 – Example Mapping Between RF Conditions and LTE Measurements

		RSRP (dBm)	RSRQ (dB)	SINR (dB)
RF Conditions	Excellent	≥ -80	≥ -10	≥ 20
	Good	-80 to-90	-10 to -15	13 to 20
	Mid Cell	-90 to -100	-15 to -20	0 to 13
	Cell Edge	≤ -100	< -20	≤ 0

6.2. Traffic Modeling

The coverage performance of broadband data systems described in this document is typically limited by interference for multisite, contiguous coverage deployments. The level of interference in the system is dependent upon the traffic loading. Increased traffic load corresponds to increased interference levels. The traffic load level is dependent upon the data applications being modeled, the number of active users in the system, and the RF conditions for the actively transmitting and receiving users. As such, data application modeling and subscriber unit location are components of the overall broadband coverage modeling approach.

6.2.1. Data Application Modeling

There are a variety of different data applications with different traffic profiles, protocols, periodicities, etc. These characteristics, including protocol and corresponding overheads (see ANNEX - A Communication Protocol Overheads), drive the amount and timing of data transmissions when modeling a specific data application.

6.2.2. Subscriber Location

Subscriber location impacts the RF conditions experienced during data transmission. In the absence of detailed information regarding subscriber location, the recommendation is to distribute subscribers geographically according to a uniform random distribution.

6.2.3. Uniform Resource Utilization Modeling

The data application modeling method described above is based on defining data applications, assigning these data applications to subscriber units, and distributing these subscriber units throughout the service area. An alternative approach for modeling traffic on interfering cells is to define an air interface resource utilization as an input to the model and then enforce this resource utilization in each of the interfering cells being modeled. For example, in an LTE system, if the specified resource utilization is 25% and the maximum number of resource blocks available per cell is 50, then the model would ensure that 50 * 0.25 = 13 resource blocks are continually occupied per interfering cell.

This resource utilization modeling approach is useful when preparing final maps for coverage acceptance testing. Most wide area broadband data systems provide functionality to broadcast in the downlink direction on a user defined percentage of air interface resources per cell, specifically for the purposes of testing coverage under an emulated downlink load.

6.3. Broadband Data Transmission Modeling

As seen in the “Broadband Data Transmission Models” section of Figure 1, there are numerous technologies, processes, and parameters used in broadband data transmission that must be accounted for in the coverage modeling methodology. A brief description of each of the broadband data transmission modeling considerations follows. Detailed modeling methodologies must be developed in coordination with the equipment vendor since the specifics of the implementation and associated performance vary from vendor to vendor and technology to technology.

6.3.1. Carrier Bandwidth

Current broadband radio access technologies such as LTE, WiMax and WiFi each offer a small set of bandwidth configuration options. For 3GPP LTE, bandwidth configurations of 1.4, 3, 5, 10, 15 and 20 MHz are allowed. For the 3 to 20MHz configurations, only the central 90% of the configured LTE bandwidth is occupied by modulated signals. This leaves 5% on each end of the band to act as an internal guard band to reduce interference from adjacent channel leakages. In the 1.4 MHz bandwidth configuration, the central 77% of the bandwidth is occupied by modulated signals with 11.5% on each end serving as guard band. 3GPP supports operation of multiple LTE carriers in a single 3GPP band, but each carrier must use the standard LTE bandwidths above.

6.3.2. MIMO Transmission

Current broadband radio access technologies such as LTE, WiMax, and WiFi utilize multiple-input multiple-output (MIMO) radio technology. By utilizing multiple antennas and transceivers at the base station and device, MIMO can multiply channel capacity via spatial multiplexing (SM-MIMO) or utilize diversity gains via transmit diversity. Multi-user (MU) MIMO is another form of SM-MIMO where multiple streams are transmitted to or from different devices. MU-MIMO does not provide per-radio-link throughput gains as SM-MIMO does, but can theoretically improve system capacity and spectral efficiency.

6.3.2.1 MIMO Notation

In MIMO notation, the “input” and “output” terms are typically defined from the perspective of the radio channel. So in an “MxN” MIMO configuration, the transmitter transmits from M antennas (*into* the radio channel) to a receiver with N antennas (the *output* of the radio channel). For example, a device transmitting from a single antenna to a base station receiving from 2 antennas is a 1x2 MIMO configuration. If in the same example the base station receives from 4 antennas, then this would be a 1x4 MIMO configuration.

It is also often useful to characterize the MIMO configuration of the equipment itself. In this case, the MIMO notation indicates the number of antennas the base station or device transmits and receives from. To differentiate between MIMO notation from the radio channel perspective vs. the equipment perspective, it is recommended to use the “MxN” notation for the former and “M Tx / N Rx” notation for the latter, and to clearly reference the equipment in the latter case. For example, a base station with 2 transmit and 4 receive antennas is a “2 Tx / 4 Rx” base station. Similarly, a device with 1 transmit and 2 receive branches is described as a “1 Tx / 2 Rx” device. SM-MIMO

The number of spatial streams that can be supported in SM-MIMO is limited by the minimum of the number of transmit branches from the transmitting equipment and receive branches at the receiving equipment. For example, when a 4 transmit-antenna base station transmits to a device with 2 receive-antennas, 2 streams can be supported.

SM-MIMO can be implemented in open or closed loop fashion, where the latter utilizes pre-coding with the goal of “orthogonalizing” (or beamforming) the transmission for the given channel conditions to improve channel capacity. This requires knowledge of the channel state at the receiver, which in FDD systems must be fed back from the receiver to the transmitter. This adds overhead to the reverse path, and the rate of feedback must increase with the rate of change of the channel conditions (i.e. device speed). For these reasons, the practical benefits of closed loop SM-MIMO are often limited.

6.3.2.2 Transmit Diversity

Transmit diversity is a candidate configuration when the transmit side of the radio link is configured with multiple antennas, regardless of the number of antennas at the receiving end of the link. Transmit diversity utilizes space-time or space-frequency coding that produces equivalent diversity gains to receiver diversity. When transmit and receive diversity are simultaneously implemented, diversity benefits are realized at both ends of the radio link.

6.3.2.3 MIMO Mode Selection

MIMO performance is influenced by factors such as SINR and correlation between the multiple antennas at each end of the link. Generally speaking, transmit diversity produces better link performance at lower SINR and higher receive antenna correlation operating points, while SM-MIMO yields higher channel capacity at higher SINR and lower receive antenna correlation levels. In broadband systems such as LTE, MIMO mode selection behavior and implementation is highly proprietary and varies among base station and device manufacturers. For this reason, it is important that system simulation link performance is modeled based on the behavior of the actual equipment utilized in the broadband system.

6.3.3. Receiver Signal Combining

Just as in narrowband technologies, various receiver diversity combining techniques are leveraged to achieve diversity gains in multi-antenna broadband devices and base stations. These include Maximum Ratio Combining (MRC), where the branch weighting aims to maximize received signal strength, and interference rejection combining (IRC), where the branch weighting aims to maximize the signal to interference plus noise ratio.

6.3.4. Resource Scheduler

In broadband systems such as LTE, the base station is responsible for scheduling uplink and downlink traffic across the available resources in both time and frequency. Examples of scheduling strategies include round robin, resource fair, and proportional fair.

In round robin scheduling, the traffic flows are scheduled sequentially in time, in a circular order. It is usually assumed that all resources in the frequency domain are assigned to a single traffic flow in each transmission time.

With resource fair scheduling, the goal is to provide an equal share of the system capacity to each traffic flow, for example by allocating the same number of bits to each data flow scheduled per transmission time. In broadband systems with link adaptation, such as LTE, bits per unit bandwidth (spectral efficiency) is proportional to the SINR of the link, with dependence also on channel conditions such as Doppler and delay spread. So resource fair scheduling can be achieved by allocating frequency resources in inverse ratio to the SINR for each data flow in each transmission time. While this does, indeed provide fairness between users, overall system capacity is reduced due to users in poor SINR conditions.

Proportional fair scheduling aims to compromise between fairness and system capacity. This can be achieved, somewhat counter intuitively, by assigning the same fraction of frequency resources to each data flow when scheduling each transmission time. In this way, data flows delivered to/from devices in better channel conditions achieve higher throughput, improving system capacity, while data flows to/from devices in poorer channel conditions are still supported, though at lower throughput.

Another scheduling consideration in frequency domain multiple access broadband systems such as LTE is the time-varying channel response (SINR vs. frequency) of each base station – device link. Frequency Selective Scheduling (FSS) is a means for multi-user, frequency-domain allocation in a broadband system where scheduling decisions are based on frequency-dependent channel knowledge. The frequency awareness introduced in FSS allows the scheduler to prioritize which users are scheduled during a certain time interval and to decide which spectrum resources are allocated to each of these users, to maximize the spectral efficiency of the allocations. Both time and frequency dimensions can be taken into account when resource allocation decisions are made. This opportunistic scheduling approach improves spectral efficiency, and hence system capacity.

The above scheduler examples and descriptions are meant to provide an overview on this topic. Actual base station scheduler implementations and strategies are vendor-specific and are often configurable. It is therefore recommended to consider the scheduler implementation of the actual equipment being used when modeling this behaviour in the coverage modeling tool.

6.3.5. Uplink Power Control

Broadband systems will often utilize uplink power control to minimize interference and power consumption of portable devices. Both open and closed-loop power control are typically implemented. For example, in LTE open-loop power control, the eNB broadcasts power spectral density (power per unit bandwidth) targets for each logical uplink channel, and the devices adjust their transmit power accordingly. For the LTE example where the measurement is a power spectral density, frequency resource allocation is taken into account. In addition, LTE closed-loop power control uses uplink power control commands from the base station to the UE to account for errors in path-loss estimation and transmit power calibration at the UE as well as slow fading.

6.3.6. SINR Calculation

As broadband systems tend to have low frequency reuse factors or, most often, single-frequency reuse, it is important to correctly account for self-interference when calculating signal to interference plus noise ratio (SINR). In this section, a recommended methodology for modeling and calculating self-interference, which contributes to the SINR calculation, is presented. Refer to Section 8 for discussion about external interference analysis.

6.3.6.1 Downlink Data Channel SINR

Downlink self-interference to a device originates from co-channel neighbor cells, which can be co-located with the device's serving cell or located at different sites. In broadband systems such as LTE, downlink and uplink frequency domain resources are allocated in discrete units. Since the allocation (i.e. scheduling) of these resources can vary in each transmission time interval, it is important to consider the actual frequency domain resource allocation of each neighbor cell when calculating the self-interference level. For a given transmission time interval and Monte Carlo draw, the self-interference to a given device can be calculated via the following steps:

1. Consider a downlink discrete frequency domain scheduling resource (e.g. a resource block, or RB in LTE) allocated to that device in the current transmission time
2. Identify the co-channel cells that are transmitting in the same frequency domain resource in the current transmission time
3. Sum the received power from all of the identified co-channel cells by applying the appropriate propagation model from [88.2]. This is the total interference level for the downlink frequency domain resource. Note that the interference to the downlink data channel comes from co-channel data or control channels, depending on the network synchronization configuration.
4. Divide the desired signal power in the frequency domain resource by the sum of the interference calculated in step 3 and the noise floor for that resource to determine SINR of the frequency domain resource
5. Repeat steps 1-4 for each downlink frequency domain resource allocated to the device in the current transmission time

When this process is completed, the SINR of each downlink frequency domain scheduling resource allocated to the user is known.

6.3.6.2 Uplink Data Channel SINR

Uplink SINR is calculated in a similar manner as in the downlink. In this case the self-interference to a cell originates from co-channel devices transmitting to neighbor cells. For a given transmission time interval and Monte Carlo draw, the uplink self-interference to each allocated uplink discrete frequency domain scheduling resource (allocated to one or more devices) can be calculated via the following steps:

1. Consider an allocated uplink discrete frequency domain scheduling resource (e.g. a resource block, or RB in LTE) in the current transmission time
2. Identify the co-channel devices that are transmitting in the same frequency domain resource in the current transmission time
3. Sum the received power from all of the identified co-channel devices by applying the appropriate propagation model from [88.2]. This is the total interference level for the uplink frequency domain resource.
4. Divide the desired signal power in the frequency domain resource by the sum of the interference calculated in step 3 and the noise floor for that resource to determine SINR of the frequency domain resource
5. Repeat steps 1-4 for each allocated uplink frequency domain resource in the current transmission time

When this process is completed, the SINR of each allocated uplink frequency domain scheduling resource is known.

6.3.6.3 Control Channel SINR

Similar methodologies as those described above ought to be utilized to calculate SINR of downlink and uplink control channels. Note that the interference to the downlink control channel comes from co-channel data or control channels, depending on the network synchronization configuration. The same steps can then be followed to determine the downlink and uplink control channel SINR in each transmission time.

6.3.7. Modulation and Coding Rate Adaptation

Modulation and coding schemes (MCS) are widely used in modern wireless systems. Typical modulation schemes for a broadband wireless system include BPSK, QPSK, 16QAM, 64QAM, 256QAM. Higher order modulations carry more bits per symbol. Channel coding schemes are used to improve bit error rate over noisy communication channels. The main idea of channel coding is to use redundant bits to provide error resilience. The channel coding rate depends on how much redundancy is added to the transmitted block. Higher rate code means less error resilient capability, but it has better efficiency. Typical coding schemes include Convolutional codes, Turbo codes, Low Density Parity Check (LDPC) codes etc.

In broadband wireless system, modulation and coding schemes are usually assigned dynamically according to channel conditions. This is also called Adaptive Modulation and Coding scheme (AMC). Transmitters can choose various MCS based on estimation of channel conditions, which is usually provided by feedback from receivers. AMC allows efficient use of radio resources and improves channel capacity.

6.3.8. Control Channel Modeling

Control channels in broadband systems are typically designed with better sensitivity than their data channel counterparts. This advantage can be offset due to high interference on the control channels. This can be caused in scenarios with higher loading of control channel resources relative to the corresponding data channel resources, for example in traffic profiles with a high number of users all transmitting at low data rates. When this occurs, downlink or uplink cell coverage may be limited by the control channel rather than the data channel because the higher self-interference level on the control channel more than offsets its sensitivity advantage over the data channel. As such, it is recommended to model control channel coverage. Section 6.3.6.3 presents a methodology for calculating control channel SINR that can be used together with control channel link curves to model control channel coverage.

In addition, it is possible in scenarios such as those described above that control channel capacity is exhausted before all data channel resources are allocated. Modeling of control channel capacity captures this aspect of system performance.

6.3.9. Interference Coordination

In broadband systems with low or single-frequency reuse, self-interference can contribute up to 10 dB or more noise rise on the uplink, and up to 20 dB or more on the downlink, depending on factors such as deployment topology, system configuration, and environment. That being said, broadband technologies such as LTE are designed to operate at very low SINR levels. LTE achieves this through the use of low rate channel coding, retransmission schemes, and robust designs for the broadcast and control channels. Frequency and time based resource partitioning strategies, such as Inter-Cell Interference Coordination (ICIC) in LTE, are well-known interference mitigation solutions that trade off available bandwidth or time resources for SINR. Analysis considering both Shannon capacity theorem and specific broadband link performance of broadband technologies generally demonstrates that at full system loading, both cell edge and cell average throughput are higher without any interference coordination strategies employed. But in cases with low system loading or when interference degrades SINR levels below device or base station sensitivity levels, interference coordination strategies are potentially beneficial. The following provides insights into different LTE ICIC approaches.

Static ICIC solutions improve cell-edge SINR by restricting radio resource availability in frequency or time domains or both for the entire cell or just the cell-edge users. So spectral efficiency is typically improved, especially at the cell-edge, but with fewer radio resources available, cell-edge data rates often do not improve. In other words, whether the spectral efficiency increase offsets the reduction in usable bandwidth or time is a function of many variables including loading and network topology. Static ICIC imposes an artificial reduction in average cell capacity as well. Another cost inherent to static ICIC is the need for time-consuming manual coordination and maintenance updates within and between networks. This can be especially disruptive to networks that are already in service.

Dynamic approaches may, for example, randomize the starting index for resource block allocation. They can be implemented autonomously or coordinated across neighbor sites. Autonomous ICIC approaches in LTE are implemented within each eNB, independent of neighboring eNB's. Coordinated approaches between eNBs utilize inter-site communication to exchange loading and interference statistics and the schedulers utilize this information with the goal of scheduling resource allocations in orthogonal time and frequency resources, thereby reducing interference. The inter-site communications are exchanged via the X2 interface between eNBs.

Compared to approaches with static allocation, dynamic allocation provides improved frequency diversity and does not require any manual planning. In light to medium loading scenarios, dynamic allocation provides a more distributed utilization of resource blocks between neighboring cells, which reduces interference in the utilized resources and enhances capacity. At high loading, all resources are utilized, resulting in higher full-load system capacity than provided by ICIC solutions with static “hard” fractional frequency re-use strategies. Dynamic autonomous approaches can also provide significant cell edge data rate gains under lower system loading while avoiding the complexity and implementation issues of the static and coordinated dynamic schemes.

It is worth noting that while LTE ICIC implementations partition the shared data resources, neither the uplink nor downlink control channels are partitioned. Hence, inter-cell interference between control channels is not mitigated by ICIC solutions. As the control channels have more robust coding than the shared data channels, they are more able to tolerate the interference. That said, inter-cell control channel interference can limit the performance benefits realized via ICIC.

Broadband standards such as 3GPP provide mechanisms for enabling interference coordination, but leave specific details to infrastructure manufacturers to implement. As a result there are a wide variety of interference coordination solutions available in the industry. Modelers are encouraged to work with the infrastructure manufacturers to select the appropriate algorithm to use with their modeling tool.

6.3.10. Link Curve Modeling

When data rate is used as the broadband Channel Performance Criterion (CPC), a methodology is needed to map data channel SINR to data rate. However, as broadband data systems have characteristics such as flexible and dynamic resource allocation (scheduling), adaptive modulation and MIMO mode / MIMO configurations, and other variable factors as described above, it is recommended to map SINR to spectral efficiency (e.g. SINR vs. bps/Hz). Link curves defined in this way can flexibly take into account all of these factors and may be applied to an arbitrary resource allocation to determine instantaneous per device throughput for each transmission time interval. It is preferable that the curves be fitted to the actual broadband equipment performance. Examples of per-vendor factors include:

- Scheduler implementation and configuration
- Adaptive modulation and MIMO mode selection implementations
- UE and eNB receiver implementations

Empirical, parametric curves can be defined and tuned for the specific base station and device equipment being modeled. [Mogensen07], for example, models LTE capacity by defining a modified version of the Shannon capacity formula with parameters for bandwidth efficiency, SNR efficiency, and a correction factor. Different sets of parameters may be defined for different configurations, considering factors such as scheduler implementation, MIMO mode, channel type (i.e. delay profile, velocity), etc. Refer to ANNEX - C for an overview of the [Mogensen07] reference and example LTE link curves that map

SNR to spectral efficiency (defined in bits per resource block) using the formula proposed in the reference.

6.3.11. Cell Selection

In a broadband data system, serving cell selection for a device is typically based on criteria such as downlink signal strength or signal quality. In LTE, for example, cell selection is based on RSRP and RSRQ measurements, as defined in Section 6.1. The best cell as determined by these criteria may not be the nearest cell due to the propagation environment, terrain, and lognormal shadowing. The propagation and terrain factors will typically be modeled in a system simulation (Section 7), and a lognormal draw is associated with each tile and Monte Carlo draw. These factors can then be considered in the calculation of the cell selection criterion.

In addition, real-world effects from factors such as measurement errors and “stale” measurements (i.e. due to fading channel changes since the last measurement) can impact correct cell selection. These factors may also be modeled if it is desired to capture their impact on coverage reliability.

6.3.12. Carrier Aggregation

Carrier Aggregation, a 3GPP LTE feature first offered in Release 10, allows aggregation of LTE signals, effectively increasing maximum throughput. The R10 feature was for downlink CA. Uplink CA was added in R11 and R12. Each unique combination of CA frequencies must be analyzed and approved by 3GPP. As part of the approval process, 3GPP requires an interference assessment to determine impact of aggregating the specific band proposals on the neighboring bands. Once approved, chip set manufacturers may implement the new CA band combinations. As of 3GPP Release 12, Band 14 has not been approved for use with CA and no CA related work items have been submitted to 3GPP Release 13 for Band 14 CA. Details of the carrier aggregation specifications are in [101].

6.4. Broadband Coverage Modeling

All of the steps described thus far in this section lead to computing tile and area reliabilities using Monte Carlo simulation. The overall Monte Carlo simulation methodology used to arrive at the final coverage estimate is described as follows.

6.4.1. Tile Reliability

DRCPC Reliability for a given tile is computed using Monte Carlo simulation methods by:

- Defining the coverage design criterion, which is the required data rate (DRCPC).

- Calculating propagation path loss, signal strengths, and best server coverage areas.
- Dropping a prescribed number of subscriber units within the service area according to a defined subscriber distribution such as a random uniform distribution.
    - o The coverage results are highly dependent on the subscriber locations for an interference limited system. For example, if subscribers are located near base stations, signal conditions may be good. Under good signal conditions, higher order modulation such as 64QAM can be used to transmit at increased data rates thereby satisfying the users' data transmission requests with fewer air interface resources. In this subscriber distribution scenario, air interface utilization is lower, which means that the overall interference level in the system will be lower and S/(I+N) levels are higher. Higher S/(I+N) translates into improved coverage.
- Initiating data transmission requests in the uplink and downlink directions according to traffic profiles for the subscribers being modeled. The traffic profiles are defined using parameters such as the required data rate, bytes per user in the busy hour, and application priority.
- Using a technology-appropriate resource sharing algorithm such as a resource scheduler to share broadband resources amongst the users requesting to transmit data on the system. Consult with the equipment vendor on specific resource sharing approaches.
- Applying technology appropriate power control to base station and subscriber equipment in the uplink and downlink directions.
- Predicting the S/(I+N) ratio at the tile being modeled. S/(I+N) is calculated by adding separate random log-normal components to the best serving signal level (S) and interfering signals (I) and taking the ratio of S/(I +N).
    - o The best serving signal is identified after considering non-ideal handover with hysteresis between cells for broadband technologies using handover. Consult with the equipment vendor on specific handover approaches and parameters.
- Predicting the data rate for the given Monte Carlo throw using the computed S/(I+N) to index into the performance tables as described in Section 6.3.10 and considering the assigned broadband resources.
- Checking that data channel coverage is adequate to support reception of required control and signaling information as appropriate for the broadband technology being modeled.
- The result of a given Monte Carlo throw for the specified location is considered to be a success if the computed data rate for the data channel is greater than or equal to the DRCPC.

- The Tile Reliability is computed as the ratio of the number of Monte Carlo throws where the achieved data rate for the data channel is greater than or equal to the DRCPC to the total number of Monte Carlo throws.

6.4.2. Area Reliability

The Tile-Based Area Reliability is the average of the individual Tile Reliabilities over a predefined area. It can be used as a system acceptance criterion. In the Broadband Data Service, it is used in the following two forms:

Service Area Reliability is defined as the probability of achieving the desired DRCPC over the defined Service Area. It is calculated by averaging the individual Tile Reliabilities for all tiles within the Service Area.

Covered Area Reliability is defined as the probability of achieving the desired DRCPC over the defined covered area. It is the average of the individual Tile Reliabilities for only those tiles that meet or exceed the minimum desired Tile Reliability.

7. SYSTEM MODELING

7.1. Terrestrial System Modeling

Terrestrial operation provides broadband coverage to earthbound devices from ground-based base stations. Special considerations for Air-Ground-Air devices will be covered in section 7.2. In the present section, key Terrestrial coverage modeling considerations are discussed.

7.1.1. Propagation Models

Propagation modeling accounts for the losses between the transmitting radio antenna and the receiving radio antenna. As such, this modeling would include losses due to terrain shadowing, environmental losses, and losses due to propagation through air. These topics are covered in detail in [88.2].

7.1.2. Antenna models

Modeling of directional fixed station base antennas is best achieved by a 3D antenna model. A 3D model allows for modeling of both the directional aspect of the antenna along the horizon, and the vertical component required to model the down-tilt that is often used to mitigate interference between cells. Vendor supplied antenna patterns are recommended over the generic 3GPP antenna patterns. Vendors typically define their antenna patterns in a number of standard formats, such as TIA-804.

Non-fixed subscriber antennas, on the other hand, are recommended to be modeled as 2D omni-directional antennas because of their frequent change in orientation. As a subscriber changes bearing, any gain attributed to a directional lobe changes. In a similar manner, as the subscriber ascends and descends hilly terrain the vertical pattern changes. In such cases, use of a 2D omni-directional model with a gain representing the average radiated power is warranted.

When modeling fixed subscriber antennas where the pattern is available and direction and tilt is known, the 3D model is recommended. The 2D model is recommended when the direction and tilt of the fixed subscriber is unknown.

7.1.3. Link performance models

RF links are modeled as faded channels. Fading is caused by multipath propagation and shadowing and can be characterized as fast fading and slow fading. These inconsistencies in signal quality ought to be accounted for in the system model.

Performance of a radio channel is dependent on the speed at which the subscriber moves through areas of fading. This is typically modeled using the Raleigh fading model (or Rician where appropriate) with a suitable Doppler shift for the speed being modeled. Multipath can be considered by accounting for the effects of delay spread appropriate for the frequency and environment. Detailed coverage of these topics can be found in [88.2] and the link curves used in modeling (see Section 6.3.10) ought to consider these effects.

7.2. Air-Ground-Air System Modeling

Air-Ground-Air (AGA) operation provides broadband coverage to airborne devices from ground-based base stations. AGA coverage can be modeled in a similar manner as terrestrial coverage, but some differences ought to be considered. In this section, key AGA coverage modeling considerations are discussed.

7.2.1. Propagation Models

AGA-specific propagation models are needed for air-to-ground links. These models typically assume close to square law propagation and also capture effects due to the curvature of the earth and diffraction from terrain as a function of distance and HAAT of the base station and device. Since ground to air propagation is primarily line-of-sight, interference between airborne devices and neighbor cells using the same time/frequency resources is typically much greater than for terrestrial coverage. An example airborne propagation model is EPM73 [Lustgarten73]. Sample curves from this recommendation are shown in Figure 3 below with free space path-loss plotted for reference (Assumptions: Base Station antenna height is 30m for EPM73 and HATA City, and 60m for HATA Rural; Device height is 1.5m for HATA City and Rural, and as noted in the legend for EPM73). For more detail refer to [88.2].

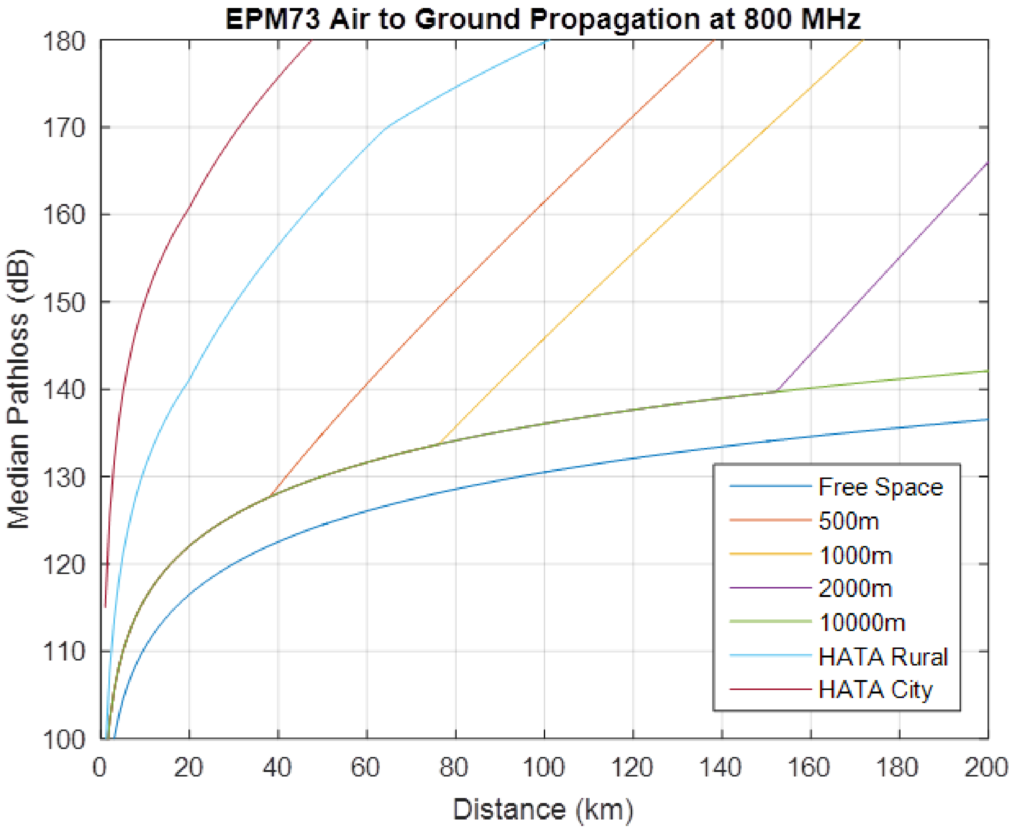

Figure 3 – Sample AGA Pathloss Curves

7.2.2. Antenna models

For AGA modeling, it is very important to correctly model the antenna pattern and orientation for both the terrestrial and airborne systems. While rotorcraft and other stationary airborne platforms can assume a static link configuration relative to the ground, system modeling with fixed wing aircraft ought to account for the angle-of-attack and roll angle during loiter maneuvering. Omni-directional antennas may be used to support wide area applications, such as broadcast, multicast, and point-to-multipoint operations. For these systems, the operational range is typically maximized by using rotationally-symmetric antennas with gain pattern main lobes near the horizon. This could be achieved with upward-tilted antennas at the base station and downward-tilted antennas on the aircraft. Directional antennas, such as beam-forming arrays, may be considered to mitigate interference, improve SINR, and expand system capacity. While 2D antenna models may suffice for many omni-directional antennas, 3D antenna models are especially important for AGA modeling of directional antennas, which is consistent with the recommendations for terrestrial coverage modeling (see Section 7.1.2). Regardless of the antenna types in use, accurate modeling of the link configuration, to include respective antenna orientations, is essential for AGA system modeling.

7.2.3. Link performance models

The impact of AGA channel conditions on link performance ought to be modeled appropriately. Depending on the design criteria, the AGA channel may have high Doppler frequency (due to high speed aircraft operation) but low delay spread (due to the strong line-of-sight signal component). Such channel conditions are very different than those for terrestrial links and may not map to existing channel model definitions, for example 3GPP pedestrian (EPA5) or vehicular (EVA70) channels. Even the 3GPP ETU300 channel model, which is intended for high-speed channels (e.g. high-speed train), may have lower Doppler frequency and higher delay spread than the actual AGA channel. Since link curve performance is closely tied to channel conditions, it may be beneficial to model the AGA link performance to match the specific AGA channel.

7.2.4. Interference Considerations

While an AGA system can be deployed in the same spectrum as a terrestrial system, high levels of interference between the systems can greatly compromise performance. For this reason, dedicated AGA spectrum is highly recommended [3GPP15a][CEPT14]. Even when deployed in dedicated spectrum, AGA deployments suffer from increased noise rise compared with terrestrial systems. Hence, interference mitigation and suppression techniques, while often not needed in terrestrial systems (see Section 6.3.9), are more important and impactful for AGA whether deployed in dedicated or shared spectrum. Such techniques may be needed to meet system performance criteria, especially in shared spectrum deployments. It is therefore recommended that the performance benefits of any interference mitigation solutions be abstracted and accounted for in the link performance and SINR calculations (see Section 6.3.6).

7.2.5. Spectrum Allocation

High frequency bands are well suited for AGA systems as the line-of-sight propagation typical of AGA links tends to offset the poorer propagation characteristics as frequency increases. However, propagation characteristics as well as tolerance for large Doppler shifts (a function of the aircraft speed and carrier frequency) do result in a practical upper frequency limit on spectrum appropriate for broadband AGA. In [AGA10], for example, it was concluded that spectrum above 6 GHz is not suitable for LTE AGA applications.

TDD configurations are also suitable for AGA, especially if beam-forming antenna arrays are utilized for interference mitigation. This is the case because configuration of antenna weighting in transmitter beam-forming requires knowledge of the channel state from the perspective of the receiver. As this is a function of the frequency band of the channel, this requires channel state feedback in FDD configurations, which adds overhead and provides limited performance benefits when the channel is rapidly varying (as in high-speed AGA scenarios). TDD configurations naturally lend themselves to transmit beam-forming implementations because transmission and reception occur in the same band, which provides channel reciprocity (assuming calibration of the transmitter and receiver RF chains). Hence if TDD broadband spectrum is available, AGA deployment in a TDD band may be desirable even if the terrestrial broadband system is FDD. One consideration, however, is that a switching time between transmission directions is required in TDD, and this overhead increases with the large cells that are typical for AGA.

Finally, it is noted that whatever spectrum and duplex mode of operation (TDD or FDD) is utilized for AGA operation, transmit power and altitude restrictions for that band must be considered. For example, Title 47 Part 90 (Section 90.423) of the Electronic Code of Federal Regulations restricts aircraft operation of mobile stations to below 1 mile above the earth's surface and output power to less than 10 Watts.

7.2.6. Deployable Aerial Communications Architecture (DACA)

In DACA systems one or more base stations are airborne, e.g. on a drone or balloon, and generally serve ground based devices [FCC11]. This architecture is similar to AGA and hence can be modeled similarly as well. The current section focuses on the aspects of DACA coverage modeling that are different than for AGA.

7.2.6.1 Interference

In the previous section, interference between AGA and terrestrial systems (using the same or separate spectrum) was discussed. In the case of DACA, the potential for interference can be more severe as the airborne base stations in DACA solutions will often have higher transmit power, higher gain antennas, and will often be positioned at higher altitudes than aircraft-mounted mobile stations in AGA. For this reason, frequency reuse between DACA and terrestrial systems located in the same geographic area is not recommended.

AGA propagation models [88.2] can be used to estimate appropriate separation between DACA and terrestrial systems using the same spectrum. Figure 3 illustrates example path-loss vs. distance curves for the EPM73 AGA model for a few different assumptions.

7.3. Building Penetration into High Rises

Modeling propagation to devices located inside tall buildings requires the use of path loss models that are tuned for the corresponding device heights and account for building penetration loss. [3GPP15b] presents path loss models for high rise scenarios for carrier frequencies above 2GHz. AGA propagation models [88.2] with additional building penetration loss may also be suitable in some cases.

8. INTERFERENCE ANALYSIS METHODS

The goal of this section is to present methods to model and analyze interference into broadband communication systems. A high level method for interference analysis can be found in [ATIS/TIA]. This white paper provides methods for interference analysis for scenarios with coexistence of 700MHz public safety communications and cellular communications systems. General descriptions of interference mechanism and basic analysis for intermodulation products are provided. The basic model presented in [ATIS/TIA] shows how to add internal and external interference sources into a coverage modeling tool. This method was described in Section 6.3.6 for modeling the impact of intra-band interference. The present section describes how external sources are added to the coverage model and provide analysis methods useful for estimating the impact of external interference on broadband communications.

This section introduces analysis methods for scenarios when external interference sources are present in a broadband communications network. General guidance on interference sources and methods for interference analysis can be found in [88.1] [88.2] [ATIS/TIA]. These references describe sources of external interference that may impact performance of a communication network including environmental noise (cosmic and atmospheric) and intentional and unintentional man-made emitters.

The focus in this section will be on interference analysis that is unique to broadband networks employing single frequency reuse such as LTE. Analysis and examples will be provided for the case where the broadband system is the victim of man-made noise from external communication systems. For cases where a broadband communication system is the aggressor and a narrowband LMR communication system is the victim, the minimum required transmitter specifications for that broadband technology (e.g. for LTE these are defined in [101] for devices and [104] for base stations) may be used in conjunction with the tools and information provided in [88.1] and [88.3] to estimate the impact of new broadband communications on existing LMR voice and data systems.

Three interference mechanisms account for man-made noise from external communication systems: (1) out-of-band emissions (OOBE) (2) intermodulation distortion (IMD) and (3) in-band blocking. OOBE occurs when an external transmitter operating outside the broadband receiver band creates noise in the BB receiver band. IMD occurs when two or more signals combine in a non-linear mixing element to create intermodulation products that fall into the BB receiver band. In-band blocking occurs when an external signal passes through the broadband receiver front end filters and causes the automatic gain control (AGC) circuits to increase front end attenuation in order to protect the receiver. The increased attenuation causes a decrease in the desired signal power relative to the receiver noise floor reducing SNR. Conventional techniques described in [88.1], [88.2] and [ATIS/TIA] can be used to estimate impact of these three mechanisms on broadband communications. The sections that follow provide analysis and examples to supplement the conventional techniques. Analysis is provided for co-channel and adjacent channel external interference into broadband receivers.

8.1. Co-Channel

Co-channel interference may occur when another system is using the same spectrum as the broadband receiver. Co-channel interferers reduce the in-band signal-to-interference-plus-noise (SINR) ratio. When accounting for external interference from broadband or narrowband sources operating in the same band, the following recommendations are provided:

- Model relevant details of the co-channel interference, such as the interference source location, transmit power, frequency, bandwidth and modulation.
- Use appropriate propagation models from [88.2] for the external interferers
- If desired, computational complexity may be reduced by considering only the N strongest interferers. "N" may be set based on the desired tradeoff between model fidelity and simulation runtime.
- Model proprietary interference rejection or beam-forming features (Section 6.3.3) implemented in the devices and infrastructure. For LTE, interference rejection combining (IRC) features may be available from infrastructure and device vendors. Work with manufacturers to ensure appropriate interference models and analysis methods are used.
- Frequency selective scheduling (Section 6.3.4) may be modeled if available from the manufacturer.
- In the scenario where the source of the co-channel interference is another broadband system using the same radio access technology, frequency-reuse coordination between the systems may be considered and modeled accordingly. In the case of LTE, with single-frequency reuse for example, ICIC (Section 6.3.9) may be used.
- In the scenario where the co-channel interference comes from a narrowband source, any frequency or time based resource partitioning strategies (Section 6.3.9) deployed by the broadband system ought to be accounted for. Static vs. dynamic partitioning strategies, such as ICIC in LTE, will result in static or varying interference between the systems, and the interference impact ought to be modeled accordingly.

8.2. Adjacent Channel

Adjacent-channel interference may occur when an external signal is using spectrum adjacent to the broadband receiver's licensed channel. Adjacent channel bandwidth is defined to be the same as that for the desired broadband signal. Adjacent Channel interference analysis for broadband generally follows the interference analysis processes described in [88.1], with updated recommendations for assessing ACLR of broadband signals (defined in a similar manner as ACPR for narrowband signals). Minimum ACLR requirements for LTE are given in [101] for the device and [104] for the eNB. Actual ACLR performance is available via lab measurements or from the device or base station vendor.

Adjacent channel interferers may cause OOBE, IMD or in-band blocking. OOBE, IMD and RF Blocking may impact a broadband base station or device operating in close proximity to a base station or device belonging to a different communications system. Since broadband channels are so much larger than narrowband channels, it is possible for many narrowband channels to fall within the adjacent band of a broadband receiver.

Analysis of interference due to a signal from an adjacent band (resulting in OOBE into the desired band) is performed in a similar manner as ACPR analysis with narrowband signals described in [88.1]. In the broadband case, minimum data rate is used as the channel performance criterion. Recommended guidelines for adjacent channel interference analysis are listed below.

- Obtain a calculated value of the ACLR for each adjacent channel transmitter within the adjacent band of the broadband system's channel. The calculated ACLR value is based on the receiver characteristics of the victim receiver and the specific interferer's modulation. Use each ACLR value to reduce the ERP_d of its respective transmitter, or alternatively change the calculated field strength value.
- In the scenario where the adjacent channel interference comes from a narrowband source, any frequency or time based resource partitioning strategies (Section 6.3.9) deployed by the broadband system ought to be accounted for. Static vs. dynamic partitioning strategies, such as ICIC in LTE, will result in static or varying interference between the systems, and the interference impact ought to be modeled accordingly.
- Use the appropriate propagation model to calculate the various signal levels. For adjacent channel(s) use their modified transmitter ERP_d.
- If desired, computational complexity may be reduced by considering only the N strongest interferers. “N” may be set based on the desired tradeoff between model fidelity and simulation runtime.
- Sum the adjusted adjacent channel signal powers and add to other noise power as determined in Section 6.3.6 (SINR Calculation) to determine in the level of interference plus noise power to be overcome by the received power of the desired signal. The received power of the desired signal is determined by using the propagation model and the ERP_d of the desired transmitter.
- Numerically subtract the interference power level in dBm from the desired signal power in dBm to determine the signal to interference plus noise ratio. Compare the resulting value to the value necessary for the desired minimum data rate channel performance criterion (DRCPC).

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ANNEX - A Communications Protocol Overheads (Informative)

The OSI Model is a conceptual model that standardizes the functions of a telecommunication or computing system without regard of their underlying internal structure and technology. Its goal is the interoperability of diverse communication systems with standard protocols. The model is a product of the Open Systems Interconnection project at the International Organization for Standardization (ISO), maintained by the identification ISO/IEC 7498-1. The model partitions a communication system into seven abstraction layers. Protocols enable an entity in one host to interact with a corresponding entity at the same layer in another host. Service definitions abstractly described the functionality provided to an (N)-layer by an (N-1) layer, where N is one of the seven layers of protocols operating in the local host. The following table shows the OSI layers and their attributes.

Table A1 – OSI Layers and Attributes

OSI Layer	OSI Name	Units	Implementation	Description
7	Application	Data	Application Nodes	Network services such as file, print, messaging, database services
6	Presentation	Data	Application Nodes	Standard interface to data for the application layer. Data encoding & encryption, formatting, compression
5	Session	Data	Application Nodes	Establishes, manages and terminates connections between host applications
4	Transport	Segments	Application Nodes	End-to-end connectivity and reliability. Segmentation & reassembly of data in proper sequence. Flow control
3	Network	Packets	Network Routers	Logical addressing and routing. Reporting delivery errors.
2	Data Link	Frames	Network Switches	Physical addressing and access to media. Two sublayers: Logical Link Control (LLC) and Media Access Control (MAC)
1	Physical	Bits	Network Transceivers	Binary transmission signals and encoding. Layout of pins, voltages, cable specifications, modulation

The Internet or TCP/IP communications model has only four layers and these layers can essentially be mapped to OSI layers. The TCP/IP application layer merges OSI layer 5 – 7, the transport layer is synonymous, the TCP/IP internet layer maps to the OSI network layer, and the TCP/IP network access layer covers the OSI Data Link and Physical layers. While all protocol layers interact and combine to determine the overall end to end user experience, the physical and transport layers have the most impact to the network performance.

Each of the protocol layers can add networking overheads in terms of bits or bytes for headers, padding, and cyclic redundancy checks (CRCs). The following figure shows the size of an application layer packet as it progresses down the stack through the various protocol layers. The actual size of the final physical layer packet depends both on the protocols and optional features enabled in the protocols.

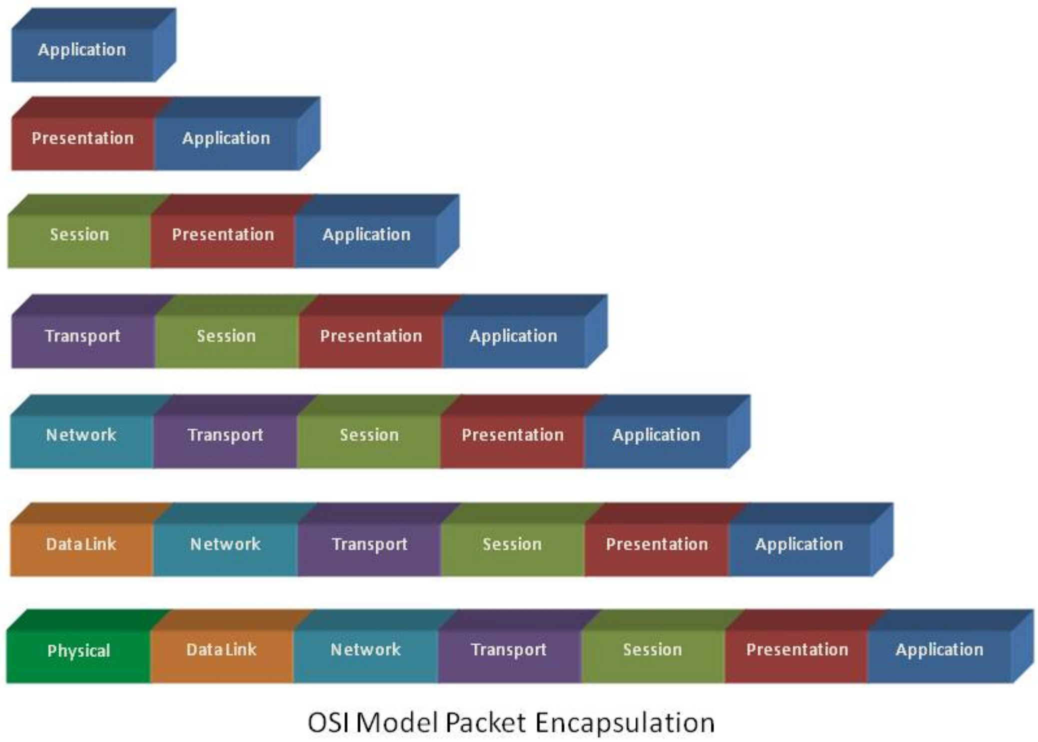

Figure A1 – OSI Model Packet Encapsulation

Prevalent Communications Protocols

Internet Protocol (IP)

IP is a network layer protocol by which data is sent from one computer to another on the Internet. Each computer (known as a host) on the Internet has at least one IP address that uniquely identifies it from all other computers on the Internet. The most widely used version of IP today is Internet Protocol Version 4 (IPv4). However, IP Version 6 (IPv6) is also beginning to be supported. IPv4 / IPv6 headers have a minimal length of 20/40 octets of overhead and permit options that can increase the overheads. A maximum transmission unit (MTU) is the largest size packet or frame, specified in octets, that can be sent in a packet based network protocol such as IP. The Internet de facto standard MTU is 576, but service providers often suggest using a value in the 1400 – 1500 range. The optimum value depends on the underlying link layer network capabilities. For most modern computing devices, the operating system is able to select the appropriate MTU for the connection.

Internet Control Message Protocol (ICMP)
ICMP is an error-reporting network layer protocol that routers and hosts use to generate error messages to the source IP address when network problems prevent delivery of IP packets. ICMP creates and sends messages to the source IP address indicating that a router, service or host cannot be reached for packet delivery. Any IP network device has the capability to send, receive or process ICMP messages. PING is actually an ICMP echo request/response message type that measures round trip time statistics and reports errors and packet loss. The default packet size is 8 bytes on top of the standard IPv4/IPv6 header and can optionally contain additional payload data.

Transmission Control Protocol (TCP)
TCP is a connection-oriented transport layer protocol, which means a connection is established and maintained until the application programs at each end have finished exchanging messages. Most Internet traffic is TCP based, but streaming multimedia flows utilizing UDP are ramping up and decreasing the TCP/UDP traffic ratios. It determines how to break application data into packets that networks can deliver, sends packets to and accepts packets from the network layer, manages flow control, and because it is meant to provide error-free data transmission, it handles retransmission of dropped or garbled packets as well as acknowledgement of all packets that arrive. Retransmissions and the need to reorder packets after they arrive can introduce latency in a TCP stream. TCP segment headers are 20 octets and TCP acknowledgements (ACKS) are 20 octets of overhead.

A fundamental assumption in TCP's design for wireline networks is that packet loss is caused by congestion, which is not typically true in wireless networks. The TCP slow-start algorithm is part of congestion control in TCP that tries to avoid sending more data than the network is capable of transmitting. There are also variations to the slow-start algorithm known as fast recovery functions that are typically vendor specific. The TCP flow control and segment transmission and retransmission algorithms are somewhat vendor specific and furthermore some clients even permit parameter tuning for the deployment network.

The performance optimization of TCP over lossy wireless networks has been the topic of many studies (e.g. [Park11], [Garcia14]) because of the wide variance in end user performance. Such studies have found various inefficiencies in TCP over LTE such as undesired slow start, and that on average TCP actually used bandwidth is less than 50% of the available bandwidth. They found that the under-utilization can be caused by both application behavior and TCP parameter setting. They also observed other troubling TCP behaviors, such as not updating round trip time (RTT) estimation using duplicate ACKs which can cause severe performance issues in LTE networks upon a single packet loss. Since the available bandwidth for LTE networks has high variation, TCP is not able to fully utilize the bandwidth as the congestion window cannot adapt fast enough, especially when RTT is large. The limited TCP receive window size throttles the performance for over 50% of the downlink flows. Researchers have also identified that large delays associated with handovers in cellular environment lead to TCP performance degradation and proposed some optimizations to reduce handover-related delay.

User Datagram Protocol (UDP)
UDP is a connectionless transport layer protocol that, like TCP, runs on top of IP networks. Unlike TCP/IP, UDP/IP provides very few error recovery services, offering instead a direct way to send and receive datagrams over an IP network. It's used primarily for broadcasting or streaming media over a network. Highly time-sensitive applications like voice over IP (VoIP) and streaming video generally rely on an unreliable transport like User Datagram Protocol (UDP) that reduces latency and jitter by not worrying about reordering packets or getting missing data retransmitted. UDP segment headers are 8 octets of overhead.

Real-Time Transport Protocol (RTP)
RTP is a connectionless session layer protocol that specifies a way for programs to manage the real-time transmission of multimedia data over either unicast or multicast network services. RTP is commonly used in telephony and streaming multimedia applications. RTP does not in itself guarantee real-time delivery of multimedia data it does, however, provide the wherewithal to manage the data as it arrives to best effect. RTP combines its data transport with a control protocol (RTCP), which makes it possible to monitor data delivery for large multicast networks. Monitoring allows the receiver to detect if there is any packet loss and to compensate for any delay jitter. Both protocols work independently of the underlying protocols. Information in the RTP header tells the receiver how to reconstruct the data and describes how the codec bit streams are packetized. As a rule, RTP runs on top of the User Datagram Protocol (UDP), although it can use other transport protocols. RTP headers have a minimal length of 12 octets of overhead and permit options that can increase the overheads.

Session Initiation Protocol (SIP)
SIP is a connection-oriented application layer protocol for initiating an interactive user session that involves multimedia elements such as video, voice, chat, gaming, and virtual reality. Like Hypertext Transfer Protocol (HTTP) or SMTP (Simple Mail Transfer Protocol), SIP works in the Application layer of the Open Systems Interconnection (OSI) communications model. The Application layer is the level responsible for ensuring that communication is possible. SIP can establish multimedia sessions or Internet and wireless broadband IMS based telephony calls, and modify, or terminate them. The protocol can also invite participants to unicast or multicast sessions that do not necessarily involve the initiator. SIP is a request-response protocol, dealing with requests from clients and responses from servers. Requests can be sent through any transport

protocol, such as UDP or TCP. SIP determines the end system to be used for the session, the communication media and media parameters, and the called party's desire to engage in the communication. Once these are assured, SIP establishes call parameters at either end of the communication, and handles call transfer and termination. SIP control packet and header overheads are variable and specific for the application and service deployed.

Example Packet Overhead Calculations
The following table shows an example IPv4 packet overhead calculation given a comparison of SMS and full network MTUs.

Table A2 – IPv4 Packet Overhead Calculation

OSI Layer	TCP Ack	Small SMS	Large SMS	Small MTUs	Large MTUs
Application	0	10	100	436	1360
Presentation	0	14	14	40	40
Session	0	40	40	40	40
Transport	20	8	8	40	40
Network	20	20	20	20	20
Link	4	4	7	7	7
Physical	4	4	4	4	4
IP MTU	40	92	182	576	1500
Total	48	100	193	587	1511
Efficiency	0%	10%	52%	74%	90%

The following table shows an example IPv6 packet overhead calculation given a comparison of SMS and full network MTUs.

Table A3 – IPv6 Packet Overhead Calculation

OSI Layer	TCP Ack	Small SMS	Large SMS	Small MTUs	Large MTUs
Application	0	10	100	416	1340
Presentation	0	14	14	40	40
Session	0	40	40	40	40
Transport	20	8	8	40	40
Network	40	40	40	40	40
Link	4	4	7	7	7
Physical	4	4	4	4	4
IP MTU	60	112	202	576	1500
Total	68	120	213	587	1511
Efficiency	0%	8%	47%	71%	89%

The following figure shows the range of application layer data transport efficiencies for our example IPv4 and IPv6 based applications.

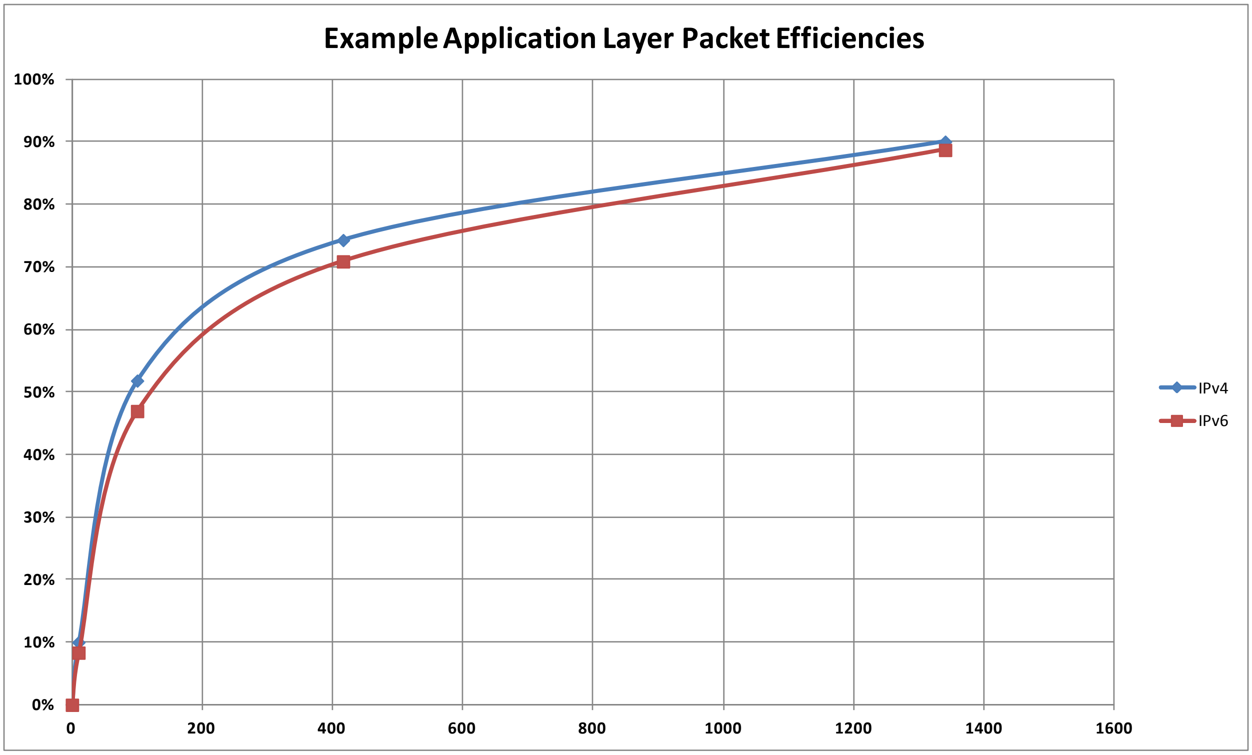

Figure A2 – Example Application Layer Packet Efficiencies

The following text and chart from [www.isoc.org] shows a recent packet trace on the Internet over a 24 hour period.

"The figure shows the distribution of packet sizes from a 24-hour time period on both directions of the measured trunk. As with graphs from previous years, this figure illustrates the predominance of small packets, with peaks at the common sizes of 44, 552, 576, and 1500 bytes. The small packets, 40-44 bytes in length, include TCP acknowledgment segments, TCP control segments such as SYN, FIN, and RST packets, and telnet packets carrying single characters (keystrokes of a telnet session). Many TCP implementations that do not implement Path MTU Discovery use either 512 or 536 bytes as the default Maximum Segment Size (MSS) for nonlocal IP destinations, yielding a 552-byte or 576-byte packet size. A Maximum Transmission Unit (MTU) size of 1500 bytes is characteristic of Ethernet-attached hosts."

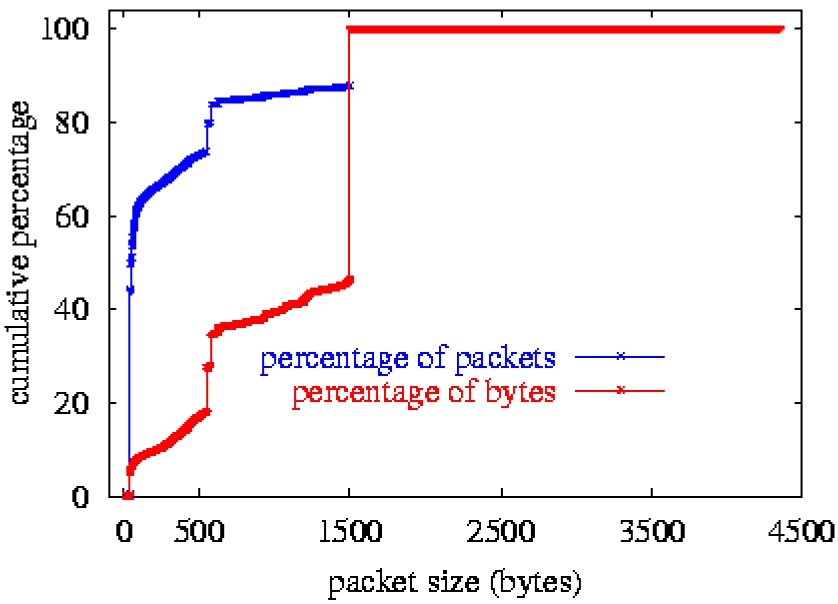

Figure A3 – Example Internet Packet Size Distribution

What this means to actual deployments is that broadband network performance is highly dependent on the actual application traffic model.

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ANNEX - B LTE Link Budget Examples (Informative)

A link budget can be a useful tool to estimate maximum allowable path-loss and coverage range in wireless systems. Typically a separate link budget is generated for the DL (forward) and UL (reverse) directions, and the coverage range is often limited by one of the directions.

In broadband systems, a minimum cell edge throughput is often used to define the cell edge, although cell coverage at lower throughput may extend beyond this point. The UL and DL cell edge criteria, which are often different, then drive the required UL and DL SINR, which is the key parameter in any link budget. In broadband systems such as LTE, these values depend on assumptions regarding resource allocation (scheduling) as well as transmission and reception operating modes, all of which vary dynamically in time.

In addition, broadband systems such as LTE are typically deployed in single-frequency reuse configurations. The result is very high self-interference margins, especially in the DL, and these margins also vary dynamically with loading vs. time. Self-interference margin can be estimated through analytical means, but this margin can only be considered a rough prediction at best.

So while broadband link budgets can provide rough coverage estimates and can be a useful tool for understanding relative impact of parameter changes, it is especially important to rely on Monte Carlo system simulation for modeling of broadband coverage.

Table B1 describes four example link budgets included in this annex along with the calculated maximum allowed pathloss in dB (column 6). For each example the limiting (lowest allowed) pathloss (UL or DL) is selected and noted in parenthesis next to the value. The first two examples cover high power and low power vehicular modem use cases respectively. Examples 3 and 4 cover handheld pedestrian use cases. Each example assumes 2x2 MIMO for downlink, 1x2 MIMO for uplink and 10MHz channel bandwidth. An 8.9dB lognormal fade margin is assumed for each example.

Table B1 – Link Budget Use Cases

Example #	UE	Channel Model	Edge Bit Rate	Loading	Maximum Allowed Pathloss (Relative to Isotropic) (dB)
1	High-Power Vehicular Modem	EVA70	Low (Rural)	Low	149.6 (DL)
2	Vehicular Modem	EVA70	Low (Rural)	Low	142.5 (UL)
3	Handheld on the Street	EPA5	High (Urban)	High	117.6 (DL)
4	Handheld in-Building	EPA5	High (Urban)	Medium	103.6 (DL)

Interference margins increase from Example 1 to 2 and from Example 3 to 4 illustrating the correlation between self-interference and cell size. Note that even though Example 3 has higher loading than Example 4, the cell size decrease (needed to overcome the building penetration loss) in Example 4 results in higher self-interference.

Note that for frequencies below 1 GHz (e.g. B14), TIA 88-series TSBs and FCC rules traditionally use dBd (relative to a dipole antenna) and effective radiated power (ERP_d) units (also relative to a dipole). However, as broadband is deployed in many different bands, both above and below 1 GHz, the antenna gains in the link budget examples presented here are defined in dBi units (relative to an isotropic radiator). Hence, transmitted power (EIRP) and maximum allowed pathloss are also relative to isotropic.

Table B2 and Table B3 provide descriptions of rows in the DL and UL link budgets respectively. Table B4 through Table B11 show detailed calculations for each example. Equations used to calculate link budgets are shown in the last column of each table.

Table B2 – Downlink Link Budget Parameters

Row	Parameter Description
a	Data Rate is a function of factors such as MIMO mode, SINR, UE category, and number of RBs assigned in time and frequency. For a downlink LTE link budget, transmit diversity MIMO mode is typically assumed given the low SINR (cell edge) channel conditions.
b	Resource Blocks: There are 6, 15, 25, 50, 75, and 100 RBs available in 1.4, 3, 5, 10, 15, and 20MHz LTE bandwidth configurations, respectively. In the downlink, a UE may be assigned from 1 to the maximum per sub-frame. Downlink LTE link budgets often assume full RB allocation to a single user.
c	Occupied Bandwidth: Each RB is 180kHz wide
d	Total Transmit Power: Macro eNBs are typically 4-40W or 36 to 49dBm per transmit branch, at the radio unit antenna connector. This field reflects the total combined transmit power in all MIMO transmit branches per cell. In these examples there are two transmit branches, with 43 or 46dBm per branch, so the total transmit power is 46 or 49dBm, respectively. From the eNB, the transmit power per RB is fixed, with total transmit power corresponding to full RB allocation.
e	Transmit Antenna Gain: Sectored antennas are most commonly used in LTE. The peak gain is used in link budgets and is a function of the horizontal and vertical beamwidths, the height of the antenna, and the frequency band. Three dimensional antenna patterns are recommended for system simulations to more accurately model the actual antenna gain given the relative positions of the eNB and UE antennas.
f	eNB Feeder Cable Loss: Captures feeder cable losses between the antenna connector on the radio unit to each antenna.
g	Effective Isotropic Radiated Power: Calculated from d, e, and f
h	UE Noise Figure is typically in the 7-9 dB range
i	Thermal Noise: Calculated from Boltzmann’s constant in the occupied bandwidth at room temperature (27 degrees Celsius)
j	Receiver Inferred Noise Floor is calculated from thermal noise and noise figure
k	Required SNR is a function of the MIMO mode, modulation and coding scheme, and other factors such as receiver implementation. Fast fading and implementation margins can be incorporated into this value, as in these examples, or broken out as a separate margin. The required SINR ought to take into account all overheads associated with the OSI Model layer at which the data rate is measured.
l	Receiver Sensitivity (for the selected MIMO mode and modulation and coding scheme) is calculated from the noise floor and required SNR
m	Self-Interference Margin: LTE is typically deployed in a single frequency reuse configuration, and as a result is typically self-interference limited, especially in the downlink and at high loading levels. This term attempts to capture this effect in the downlink and can be estimated analytically based on factors such as transmit power, loading, and path-loss to the cell edge. Note that this estimated value is a rough, averaged approximation, and that Monte-Carlo system simulation is needed to more accurately capture this effect by modeling the actual traffic and propagation environment of the system.
n	Receiver Antenna Gain: UE antenna gains vary, mainly based on form factor (e.g. smart-phone, CPE, or vehicular modem). This term captures the isotropic gain of the device antennas.
o	UE Body or Cable Loss: This factor represents any head, hand, and body losses associated with the specific use case for handheld devices, or cable losses between a vehicular modem and the antennas

Table B2 (*concluded*)

Row	Parameter Description
p	Lognormal Fade Margin is the additional link margin needed to overcome slow or shadow fading with some reliability. Various references, including [Jakes74], describe the methodology for determining lognormal fade margin as a function of the assumed lognormal standard deviation and path-loss exponent for the environment, as well as the desired area or edge coverage reliability.
q	Penetration Loss is the additional link margin needed to overcome penetration loss into a vehicle or building. It's a function of frequency and material / construction type.
r	Maximum Allowed Pathloss is the output of the link budget. If so desired, this result can be translated to a cell range or radius using a propagation model and environment assumption.

Table B3 – Uplink Link Budget Parameters

Row	Parameter Description
a	Data Rate is a function of factors such as SINR, UE category, and number of RBs assigned in time and frequency.
b	Resource Blocks: There are 6, 15, 25, 50, 75, and 100 RBs available in 1.4, 3, 5, 10, 15, and 20MHz LTE bandwidth configurations, respectively. In the uplink, a UE may be assigned from 1 to the maximum per sub-frame, minus at least 2 RBs reserved for the uplink control channel (PUCCH). A UE at the cell edge is typically assumed to be power-limited, i.e. transmitting at full power in a relatively small number of resource blocks.
c	Occupied Bandwidth: Refer to downlink comments for this parameter
d	Max Transmit Power: Power class 3 UEs can transmit up to 23dBm while (Band 14) power class 1 UEs can transmit up to 31dBm. Pre-LTE-A UEs transmit from a single branch. In LTE, uplink power control varies the UE transmit power (between -40dBm and the max power of the device) based on the path-loss to the eNB and the desired target power spectral density. As the UE reaches the cell edge, it is typically needs to transmit at full power and in fewer than the maximum number of RBs in order to “close” the uplink link budget.
e	Transmit Antenna Gain: The UE antenna gain. Refer to downlink comments for row n
f	UE Body or Cable Loss: Refer to downlink comments for row o
g	Effective Isotropic Radiated Power: Calculated from d, e, and f
h	eNB Noise Figure is typically in the 2-4 dB range
i	Thermal Noise: Refer to downlink comments for this parameter
j	Receiver Inferred Noise Floor: Refer to downlink comments for this parameter
k	Required SNR is a function of the modulation and coding scheme and other factors such as receiver implementation. Fast fading and implementation margins can be incorporated into this value, as in these examples, or broken out as a separate margin. The required SINR ought to take into account all overheads associated with the OSI Model layer at which the data rate is measured.
l	Receiver Sensitivity: Refer to downlink comments for this parameter
m	Self-Interference Margin: LTE is typically deployed in a single frequency reuse configuration, and as a result is very self-interference limited, especially at high loading levels. This term attempts to capture this effect in the uplink and can be estimated analytically based on factors such as uplink power density target (for power control), loading, and path-loss to the cell edge. Note that this estimated value is a rough, averaged approximation, and that Monte-Carlo system simulation is needed to more accurately capture this effect by modeling the actual traffic and propagation environment of the system.
n	Receiver Antenna Gain: The eNB antenna gain. Refer to downlink comments for row e
o	eNB Feeder Cable Loss: Refer to downlink comments for row f
p	Lognormal Fade Margin: Refer to downlink comments for this parameter
q	Penetration Loss: Refer to downlink comments for this parameter
r	Maximum Allowed Pathloss: Refer to downlink comments for this parameter

Table B4 Example 1 – DL Link Budget for 31dBm Vehicular Modem

	Transmitter - eNB	Value	Typical Range	Calculation
a	Data Rate (kbps)	1800	10 to 300000 kbps (depends on BW, device category, MIMO configuration)	
b	Resource Blocks	50	1 to 100 (depends on BW)	
c	Occupied Bandwidth (MHz)	9.00	N/A	b x 180,000
d	Total Transmit Power (dBm)	49.0	36 to 49 dBm per branch for macro eNB	
e	Transmit Antenna Gain (dBi)	16.0	14 to 18 dBi (typical range for 60-90 degree beamwidth panel antennas)	
f	eNB Feeder Cable Loss (dB)	2.0	1 to 3 dB	
g	EIRP (dBm)	63.0	N/A	d + e - f
	Receiver - UE			
h	Noise Figure (dB)	7.0	3GPP assumes 9 dB	
i	Thermal Noise (dBm)	-104.5	N/A	-174 + 10log10(c*10^6)
j	Receiver Inferred Noise Floor (dBm)	-97.5	N/A	i + h
k	Required SNR (dB)	-2.0	-6 to +25 dB	
l	Receiver Sensitivity (dBm)	-99.5	N/A	j + k
m	Self-Interference Margin (dB)	3.0	0 to 30 dB	
n	Receiver Antenna Gain (dBi)	0.0	1 dBi [171]	
o	UE Cable Loss (dB)	1.0	1 to 2 dB	
	System Margins			
p	Lognormal Fade margin (dB)	8.9	3 to 12 dB	
q	Penetration Loss (dB)	0.0	0 dB (assumes vehicle on-street)	
r	Maximum Allowed Pathloss (dB) (Relative to Isotropic)	**149.6**	N/A	g - l - m + n - o - p - q

Table B5 Example 1 – UL Link Budget for 31dBm Vehicular Modem

	Transmitter - UE	Value	Typical Range	Calculation
a	Data Rate (kbps)	100	10 to 75000 kbps (depends on BW, device category, MIMO configuration)	
b	Resource Blocks	2	1 to 98 (depends on BW and PUCCH configuration)	
c	Occupied Bandwidth (MHz)	0.36	N/A	b x 180,000
d	Max Transmit Power (dBm)	31.0	23 to 31 dBm (depends on device power class)	
e	Transmit Antenna Gain (dBi)	0.0	1 dBi [171]	
f	UE Cable Loss (dB)	1.0	1 to 2 dB	
g	EIRP (dBm)	30.0	N/A	d + e - f
	Receiver - eNB			
h	Noise Figure (dB)	3.0	2 to 4 dB	
i	Thermal Noise (dBm)	-118.4	N/A	-174 + 10log10(c*10^6)
j	Receiver Inferred Noise Floor (dBm)	-115.4	N/A	i + h
k	Required SNR (dB)	-1.0	-6 to +20 dB	
l	Receiver Sensitivity (dBm)	-116.4	N/A	j + k
m	Self-Interference Margin (dB)	0.5	0 to 15 dB	
n	Receiver Antenna Gain (dBi)	16.0	14 to 18 dBi (typical range for 60-90 degree beamwidth panel antennas)	
o	eNB Feeder Cable Loss (dB)	2.0	1 to 3 dB	
	System Margins			
p	Lognormal Fade margin (dB)	8.9	3 to 12 dB	
q	Penetration Loss (dB)	0.0	0 dB (assumes vehicle on-street)	
r	Maximum Allowed Pathloss (dB) (Relative to Isotropic)	**151.0**	N/A	g - l - m + n - o - p - q

Table B6 Example 2 – DL Link Budget for 23dBm Vehicular Modem

	Transmitter - eNB	Value	Typical Range	Calculation
a	Data Rate (kbps)	1800	10 to 300000 kbps (depends on BW, device category, MIMO configuration)	
b	Resource Blocks	50	1 to 100 (depends on BW)	
c	Occupied Bandwidth (MHz)	9.00	N/A	b x 180,000
d	Total Transmit Power (dBm)	49.0	36 to 49 dBm per branch for macro eNB	
e	Transmit Antenna Gain (dBi)	16.0	14 to 18 dBi	
f	eNB Feeder Cable Loss (dB)	2.0	1 to 3 dB	
g	EIRP (dBm)	63.0	N/A	d + e - f
	Receiver - UE			
h	Noise Figure (dB)	7.0	3GPP assumes 9 dB	
i	Thermal Noise (dBm)	-104.5	N/A	-174 + 10log10(c*10^6)
j	Receiver Inferred Noise Floor (dBm)	-97.5	N/A	i + h
k	Required SNR (dB)	-2.0	-6 to +25 dB	
l	Receiver Sensitivity (dBm)	-99.5	N/A	j + k
m	Self-Interference Margin (dB)	3.0	0 to 30 dB	
n	Receiver Antenna Gain (dBi)	0.0	1 dBi [171]	
o	UE Cable Loss (dB)	1.0	1 to 2 dB	
	System Margins			
p	Lognormal Fade margin (dB)	8.9	3 to 12 dB	
q	Penetration Loss (dB)	0.0	0 to 20 dB	
r	Maximum Allowed Pathloss (dB) (Relative to Isotropic)	**149.6**	N/A	g - l - m + n - o - p - q

Table B7 Example 2 – UL Link Budget for 23dBm Vehicular Modem

	Transmitter - UE	Value	Typical Range	Calculation
a	Data Rate (kbps)	100	10 to 75000 kbps (depends on BW, device category, MIMO configuration)	
b	Resource Blocks	2	1 to 98 (depends on BW and PUCCH configuration)	
c	Occupied Bandwidth (MHz)	0.36	N/A	b x 180,000
d	Max Transmit Power (dBm)	23.0	23 to 31 dBm (depends on device power class)	
e	Transmit Antenna Gain (dBi)	0.0	1 dBi [171]	
f	UE Cable Loss (dB)	1.0	1 to 2 dB	
g	EIRP (dBm)	22.0	N/A	d + e - f
	Receiver - eNB			
h	Noise Figure (dB)	3.0	2 to 4 dB	
i	Thermal Noise (dBm)	-118.4	N/A	-174 + 10log10(c*10^6)
j	Receiver Inferred Noise Floor (dBm)	-115.4	N/A	i + h
k	Required SNR (dB)	-1.0	-6 to +20 dB	
l	Receiver Sensitivity (dBm)	-116.4	N/A	j + k
m	Self-Interference Margin (dB)	1.0	0 to 15 dB	
n	Receiver Antenna Gain (dBi)	16.0	14 to 18 dBi	
o	eNB Feeder Cable Loss (dB)	2.0	1 to 3 dB	
	System Margins			
p	Lognormal Fade margin (dB)	8.9	3 to 12 dB	
q	Penetration Loss (dB)	0.0	0 dB	
r	Maximum Allowed Pathloss (dB) (Relative to Isotropic)	**142.5**	N/A	g - l - m + n - o - p - q

Table B8 Example 3 – DL Link Budget for Handheld on the Street

	Transmitter - eNB	Value	Typical Range	Calculation
a	Data Rate (kbps)	4200	10 to 300000 kbps (depends on BW, device category, MIMO configuration)	
b	Resource Blocks	50	1 to 100 (depends on BW)	
c	Occupied Bandwidth (MHz)	9.00	N/A	b x 180,000
d	Total Transmit Power (dBm)	46.0	36 to 49 dBm per branch for macro eNB	
e	Transmit Antenna Gain (dBi)	16.0	14 to 18 dBi	
f	eNB Feeder Cable Loss (dB)	2.0	1 to 3 dB	
g	EIRP (dBm)	60.0	N/A	d + e - f
	Receiver - UE			
h	Noise Figure (dB)	7.0	3GPP assumes 9 dB	
i	Thermal Noise (dBm)	-104.5	N/A	-174 + 10log10(c*10^6)
j	Receiver Inferred Noise Floor (dBm)	-97.5	N/A	i + h
k	Required SNR (dB)	2.0	-6 to +25 dB	
l	Receiver Sensitivity (dBm)	-95.5	N/A	j + k
m	Self-Interference Margin (dB)	23.0	0 to 30 dB	
n	Receiver Antenna Gain (dBi)	-2.0	-2 to +1 dBi [Wang15] [Wang15b]	
o	UE Body Loss (dB)	4.0	3 to 12 dB [Neilsen12] [Boyle03] [Berg09] [Bahramzy15]	
	System Margins			
p	Lognormal Fade margin (dB)	8.9	3 to 12 dB	
q	Penetration Loss (dB)	0.0	0 dB (device is on-street)	
r	Maximum Allowed Pathloss (dB) (Relative to Isotropic)	**117.6**	N/A	g - l - m + n - o - p - q

Table B9 Example 3 – UL Link Budget for Handheld on the Street

	Transmitter - UE	Value	Typical Range	Calculation
a	Data Rate (kbps)	536	10 to 75000 kbps (depends on BW, device category, MIMO configuration)	
b	Resource Blocks	4	1 to 98 (depends on BW and PUCCH configuration)	
c	Occupied Bandwidth (MHz)	0.72	N/A	b x 180,000
d	Max Transmit Power (dBm)	23.0	23 to 31 dBm (depends on device power class)	
e	Transmit Antenna Gain (dBi)	-2.0	-2 to +1 dBi [Wang15] [Wang15b]	
f	UE Body Loss (dB)	4.0	3 to 12 dB [Neilsen12] [Boyle03] [Berg09] [Bahramzy15]	
g	EIRP (dBm)	17.0	N/A	d + e - f
	Receiver - eNB			
h	Noise Figure (dB)	3.0	2 to 4 dB	
i	Thermal Noise (dBm)	-115.4	N/A	-174 + 10log10(c*10^6)
j	Receiver Inferred Noise Floor (dBm)	-112.4	N/A	i + h
k	Required SNR (dB)	4.0	-6 to +20 dB	
l	Receiver Sensitivity (dBm)	-108.4	N/A	j + k
m	Self-Interference Margin (dB)	7.0	0 to 15 dB	
n	Receiver Antenna Gain (dBi)	16.0	14 to 18 dBi	
o	eNB Feeder Cable Loss (dB)	2.0	1 to 3 dB	
	System Margins			
p	Lognormal Fade margin (dB)	8.9	3 to 12 dB	
q	Penetration Loss (dB)	0.0	0 dB (device is on-street)	
r	Maximum Allowed Pathloss (dB) (Relative to Isotropic)	**123.5**	N/A	g - l - m + n - o - p - q

Table B10 Example 4 – DL Link Budget for Handheld in-Building

	Transmitter - eNB	**Value**	**Typical Range**	**Calculation**
a	Data Rate (kbps)	4200	10 to 300000 kbps (depends on BW, device category, MIMO configuration)	
b	Resource Blocks	50	1 to 100 (depends on BW)	
c	Occupied Bandwidth (MHz)	9.00	N/A	b x 180,000
d	Total Transmit Power (dBm)	46.0	36 to 49 dBm per branch for macro eNB	
e	Transmit Antenna Gain (dBi)	16.0	14 to 18 dBi	
f	eNB Feeder Cable Loss (dB)	2.0	1 to 3 dB	
g	EIRP (dBm)	60.0	N/A	d + e - f
	Receiver - UE			
h	Noise Figure (dB)	7.0	3GPP assumes 9 dB	
i	Thermal Noise (dBm)	-104.5	N/A	-174 +10log10(c*10^6)
j	Receiver Inferred Noise Floor (dBm)	-97.5	N/A	i + h
k	Required SNR (dB)	2.0	-6 to +25 dB	
l	Receiver Sensitivity (dBm)	-95.5	N/A	j + k
m	Self-Interference Margin (dB)	27.0	0 to 30 dB	
n	Receiver Antenna Gain (dBi)	-2.0	-2 to +1 dBi [Wang15] [Wang15b]	
o	UE Body Loss (dB)	4.0	3 to 12 dB [Neilsen12] [Boyle03] [Berg09] [Bahramzy15]	
	System Margins			
p	Lognormal Fade margin (dB)	8.9	3 to 12 dB	
q	Penetration Loss (dB)	10.0	3 to 24 dB [Durante73] [Turkmani88] [Kvicera10] [NTIA92] [Davidson97] [Schramm97]	
r	Maximum Allowed Pathloss (dB) (Relative to Isotropic)	**103.6**	N/A	g - l - m + n - o - p - q

Table B11 Example 4 – UL Link Budget for Handheld in-Building

	Transmitter - UE	**Value**	**Typical Range**	**Calculation**
a	Data Rate (kbps)	536	10 to 75000 kbps (depends on BW, device category, MIMO configuration)	
b	Resource Blocks	4	1 to 98 (depends on BW and PUCCH configuration)	
c	Occupied Bandwidth (MHz)	0.72	N/A	b x 180,000
d	Max Transmit Power (dBm)	23.0	23 to 31 dBm (depends on device power class)	
e	Transmit Antenna Gain (dBi)	-2.0	-2 to +1 dBi [Wang15] [Wang15b]	
f	UE Body Loss (dB)	4.0	3 to 12 dB [Neilsen12] [Boyle03] [Berg09] [Bahramzy15]	
g	EIRP (dBm)	17.0	N/A	d + e - f
	Receiver - eNB			
h	Noise Figure (dB)	3.0	2 to 4 dB	
i	Thermal Noise (dBm)	-115.4	N/A	-174+ 10log10(c*10^6)
j	Receiver Inferred Noise Floor (dBm)	-112.4	N/A	i + h
k	Required SNR (dB)	4.0	-6 to +20 dB	
l	Receiver Sensitivity (dBm)	-108.4	N/A	j + k
m	Self-Interference Margin (dB)	9.0	0 to 15 dB	
n	Receiver Antenna Gain (dBi)	16.0	14 to 18 dBi	
o	eNB Feeder Cable Loss (dB)	2.0	1 to 3 dB	
	System Margins			
p	Lognormal Fade margin (dB)	8.9	3 to 12 dB	
q	Penetration Loss (dB)	10.0	3 to 24 dB [Durante73] [Turkmani88] [Kvicera10] [NTIA92] [Davidson97] [Schramm97]	
r	Maximum Allowed Pathloss (dB) (Relative to Isotropic)	**111.5**	N/A	g - l - m + n - o - p - q

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ANNEX - C LTE Link Curve Examples (Informative)

The [Mogensen07] reference proposes a "*modification to Shannon capacity bound in order to facilitate accurate benchmarking of UTRAN Long Term Evolution (LTE)*". The following summarizes the approach proposed in this reference.

Shannon capacity formula bounds single-stream spectral efficiency:

- S (bits/s/Hz) = log2(1 + SNR_{linear})

Proposed modified formula:

- S (bits/s/Hz) = $BW\_eff * \eta *$ log2(1 + $SNR_{\text{linear}} / SNR\_eff$)
  - *BW_eff* adjusts for system bandwidth efficiency
    - Depends on factors such as bandwidth occupancy and physical layer overheads (e.g. reference symbols and control channels)
  - *SNR_eff* adjusts for the SNR implementation efficiency
    - Depends on factors such as finite code block length, link and MIMO mode adaptation, scheduling, and receiver algorithm implementations
  - η is a correction factor
- S has an upper limit according to the hard spectral efficiency given by the max MCS and fixed overheads

The table below summarizes the parameters proposed in this reference for LTE downlink assuming Transmit Diversity on Typical Urban Channel at 10km/hr. [BW_eff * η , SNR_eff] is shown for Round Robin and Frequency Selective scheduler implementations. Note that these values are a function of the specific eNB and device hardware and system configuration and ought to be tuned accordingly based on lab measurements or vendor data or both.

Table C1 – Example LTE Scheduler Configurations

LTE Configuration	Round Robin Scheduler	Frequency Selective Scheduler
2Tx SFBC (Tx Div)	[0.62, 1.4] [BW_eff*η,SNR_eff]	[0.65, 0.95] [BW_eff*η,SNR_eff]

The figure below shows how the example parameters proposed above would map to spectral efficiency, defined as bits per RB.

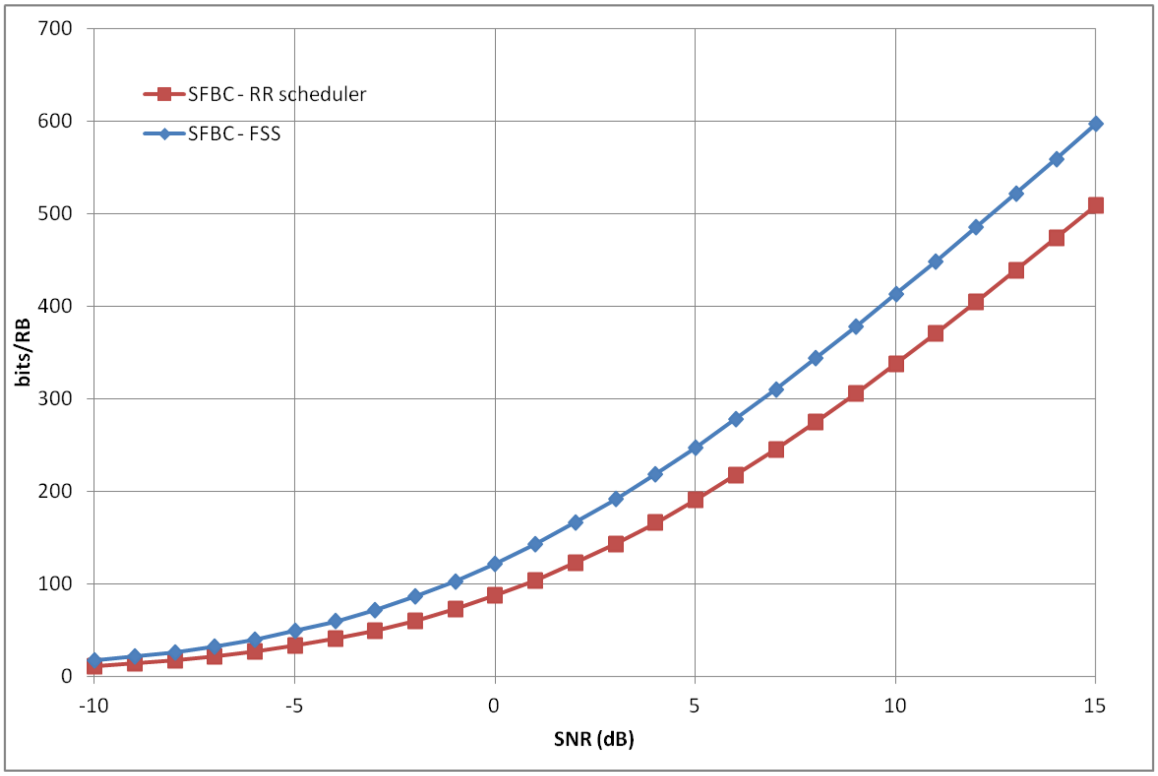

Figure C1 – Example LTE Link Curves

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