LTE Link Budgets

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2.0 Preliminary

2.1 Scope

This document provides the R&D view of the LTE link budget. This document will be continuously updated to reflect the finalizing of the LTE standard, Nortel product and applications. As such, care should be exercised when making conclusions from the material contained herein. This document shall cover all frequency variants, all duplexing schemes, and all architectures for the LTE product portfolio.

2.2 Introduction

LTE (UTRA - Long Term Evolution) is a 4G wireless standard that uses OFDM-MIMO and scalable channel bandwidths to provide high speed wireless packet data. This document derives the LTE link budget. The link budget is of primary importance to an operator as the link budget enables them to make predictions about cell range, perform technology trade-offs, and business case decisions. The link budget is broken into two distinct parts; downlink and uplink (downlink is in the direction of the BS to the UE, uplink is in the direction of the UE to the BS). The link budget calculates the system gain, this is the amount of bulk propagation path loss the system can tolerate. The system gain is specified for a given channel model and error performance or application type. Different channel models cause the PHY layer to perform differently, i.e. different SNRs are required for different channels.

Nortel's solution is designed to meet a specified system gain. However the system gain alone does not determine the cell range. Several margins are required;

- Shadow margin
- Building loss margin
- Interference Margin
- Body Loss Margin

Margins are required for shadowing, typically to guarantee 90% area coverage and to allow for the fact that the propagation path loss model predicts the median path loss vs. range. Shadowing is normally distributed on a log scale and is generally referred to as log-normal shadowing. Typical shadowing standard deviation (sigma) is 8 dB for outdoor mobiles. Shadowing increases with frequency [1].

Building losses need to be taken into account for mobiles located indoors. Building losses depend on the construction/type of the building. Generally building loss is defined per morphology classification such as urban, sub-urban, rural. There may also be a frequency dependency. There is some research material on this but generally limited measurements due to the difficult logistics of entering numerous buildings.

Interference margin is used to account for the co-channel interference increasing the noise floor of the system, and degrading the channel estimation algorithms. Coverage is defined by the SNIR cumulative distribution, which varies according to frequency re-use. It is different for downlink and uplink because the sources of interference are different in the two cases; downlink interfering sources are other base stations transmitting the same carrier frequency, uplink interfering sources are other mobiles (on other cell sites) using the same carrier frequency.

Body loss needs to be accounted for with hand-held UEs placed in close proximity to a body, e.g. a mobile phone held to the ear/head. For devices that are located on desktops the body loss margin may not be appropriate.

The maximum allowable path loss (MAPL) is then the system gain minus all margins. The MAPL is used as an input into a propagation model to predict the range.

Nortel uses generally agreed industry standard practises to determine the margins and calculate the range with a given propagation model. It must be noted however that these margins are considerable, and a change to these margins can dramatically effect the range. Moreover, the propagation model chosen also effects the range prediction dramatically, some propagation models are known to differ from others by as much as 10 dB. Care must be exercised when quoting ranges. Sometimes, especially the large operators, mandate that range predictions are done using a specified propagation model with specified margins, in this way the operator can compare technologies / vendors on a level playing field. After all, Nortel will deliver a solution to be deployed in the real world, we cannot change the laws of physics determining the building loss or propagation loss. We can guarantee the system gain, nothing more. However, we can provide expert opinion on margins and models and even perform propagation model tuning (recommended) as a service.

The propagation models vary with frequency and morphology. Typically they obey a range-to-the-power 3.5 law (r^3.5) i.e. the signal strength decays faster than the line-of-sight inverse square law (r^2). The propagation model usually has terms for the BS and UE antenna heights; the higher the antenna the less the loss.

LTE uses MIMO technology, this requires a minimum of two transmit antennas at the BS and two receive antennas at the UE. The BS can transmit in one of two modes SM-MIMO (spatial multiplexing) where the data rates are doubled, or SFBC (Space Frequency Block Coding), which is a form of transmit diversity similar to that used in WiMAX (STTD - Space Time Transmit Diversity) based on Alamouti coding. SFBC is used when the SNR is low, e.g. cell edge, or highly shadowed region. For this reason for link budget purposes we will make exclusive use of SFBC, this transmission is sometimes referred to as DL 2x2. On the uplink, the UE (in most cases) has one transmit PA, because of concerns for battery life and also cost, the uplink is then a UL 1x2 system or SIMO system. Because of the limited tx power available at the UE and the increased data rates required by 4G technologies, the uplink can, in most cases, be the limiting link. This can be improved by other architectures such as 4 branch receive at the BS, with the impact being cost and complexity at the BS. This document provides some analysis of the trade-offs of different BS architectures.

Other BS architectures are permissible and include using tower mounted electronics to remove the cable loss from; the uplink using a TTLNA (Tower Top Low Noise Amplifier), or possibly both the uplink and downlink using a RRH (Remote Radio Head).

Link budget data rates are quoted at the PHY layer, however, care must be exercised; the minimum PHY allocation while providing a reasonable PHY data rate does not give much room for higher layer data due to the amount of MAC overhead per TTI interval and per packet. A brief and simplified analysis is included in this document. The recommendation is that for link budget purposes, the minimum RB allocation is two. For VoIP at edge of cell the LTE standards group have proposed a method to reduce the MAC overhead with one RB allocation - TTI bundling. TTI bundling groups several consecutive TTI intervals together and allocates the MAC overhead per TTI bundle, hence improving the MAC layer efficiency and allowing VoIP to work at edge of cell - with one RB allocated. For data services more RBs are required, and so far, with discussion with potential customers, LTE is required to offer competitive data services. Though VoIP is required, it is not the primary motivator for the deployment of new network infrastructure.

SDMA (Spatial Division Multiple Access) is a technique to re-use the time-frequency resources of the OFDM symbols/frame in another region of space, this is done by an antenna array that can form two orthogonal beams, pointing in different azimuth directions. The beams are narrower than a conventional tri-sectored cell site sectored antenna, and hence have more gain, typically 2 dB more, for the same equivalent antenna height of the conventional antenna. The extra gain of course improves the link budget, both downlink and uplink and all control channels experience the same gain. The gain is not dependent on the channel model. The gain does come at a cost however, in that the antenna array is larger, and more BS electronics (radios) are required to feed the additional beams.

Other Channels such as PRACH as well as all the control channels and those required for network entry and handoff need link budget analysis, these channels require their own dedicated simulations, which at the time of writing were not available. A later issue of this document will complete the link budget analysis for all the control channels.

This document also includes a look on how LTE can be used to overlay an already deployed GSM network, or a CDMA/1xEV-DO network.

Finally several example LTE link budgets are presented of the different system configurations.

3.0 LTE Specifics

3.1 Frame Structure

The frame structure of LTE is important to understand. There is a 10 ms radio frame which is broken up into 20 slots, two slots form a sub-frame. Hence there are 10 sub-frames in each radio frame, each sub-frame being 1 ms in duration. A TTI (Transit Time Interval) is also denoted to be a sub-frame. Also note that scheduler resource decisions are taken on a TTI or sub-frame cadence.

Figure 1 - FDD Frame Structure

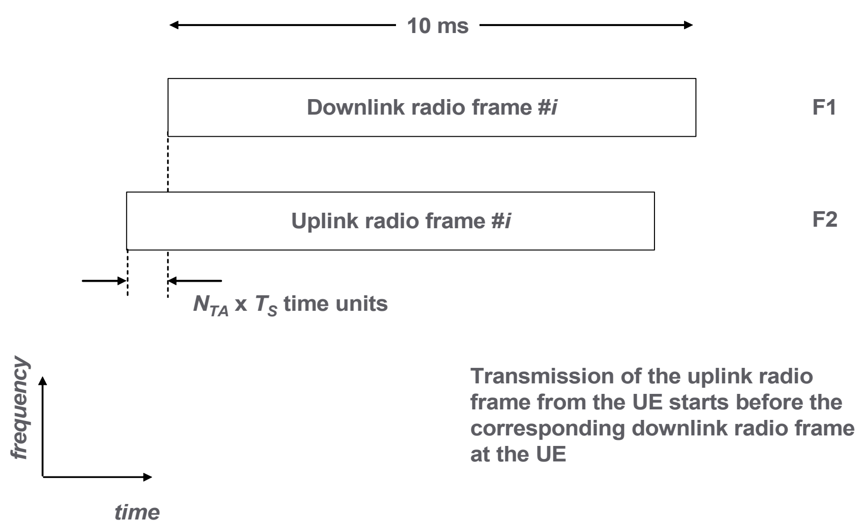
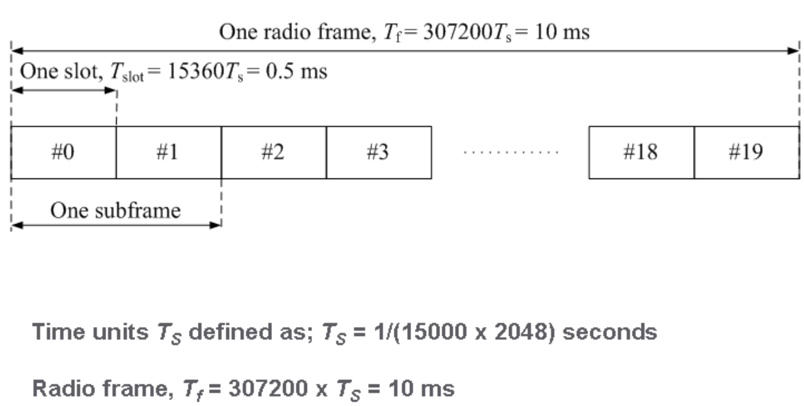


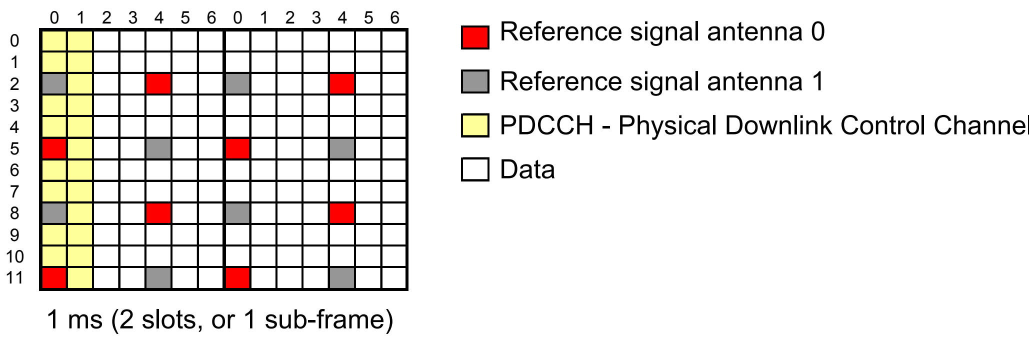
Figure 2 - Sub-Frame Time



LTE has three duplexing modes, FDD, TDD and H-FDD. This first version focusses on FDD.

The downlink frame consists of 50 (assuming a 10 MHz channel bandwidth) Resource Blocks (RB), a RB is 12 carriers or OFDM tones, by 14 symbols. Some of the tones or Resource Elements (REs) are dedicated to Reference Symbols (RS) (to help with channel estimation / demodulation) or other channels. The remaining REs can be used for data transmission. The data carrying REs are modulated with either QPSK, 16-QAM or 64-QAM with a selection of coding rates available. By counting the REs, the efficiency of the modulation and the number of REs per frame we can easily calculate the PHY data rate for the number for RBs allocated. The data rate can then be changed by either increasing or decreasing the allocated number of RBs or by changing the modulation efficiency (MCS - Modulation Code Set).

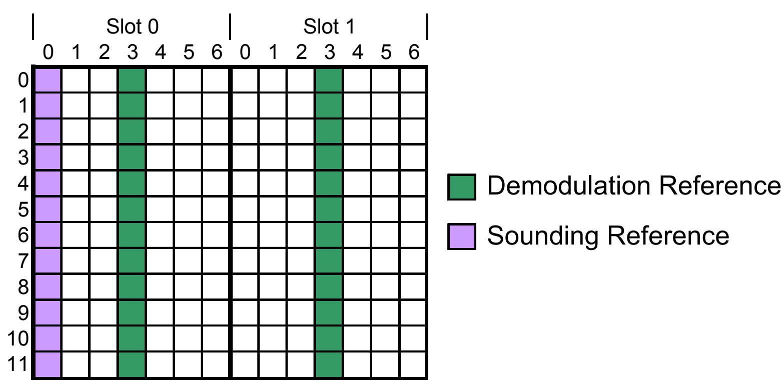
Figure 3 - Downlink Resource Block



A RB contains 168 REs, 16 are reserved for reference signals, 20 reserved for PDCCH, leaving 132 for data.

The uplink RB is similar in structure to the downlink with a difference in the reference symbol allocation. The sounding reference symbol is optional, hence there are 24 RS per RB, and hence 144 REs are available for data per RB.

Figure 4 - Uplink Frame and Resource Block



3.2 Channel Bandwidths

LTE can be implemented in any of the following channel bandwidths {1.4, 3, 5, 10, 15, 20} MHz. Further information is given below.

Table 1 - Channel Bandwidths

Channel Bandwidth MHz	1.4	3	5	10	15	20
Sub-Frame Duration	1.0 ms					
Sub-carrier Spacing	15 kHz					
Sampling Frequency	1.92 MHz (1/2x3.84)	3.84 MHz	7.68 MHz (2 x 3.84)	15.36 MHz (4x3.84)	23.04 MHz (6x3.84)	30.72 MHz (8x3.84)
FFT Size	128	256	512	1024	1536	2048
Number of sub-carriers	72	180	300	600	900	1200
Number of OFDM symbols per sub-frame (Short/Long CP)	14/12					
Useful symbol time (us)	66.67					
CP Length (us/samples) Short	(4.69/9)x6, (5.21/10)x1*	(4.69/18)x6, (5.21/20)x1	(4.69/36)x6, (5.21/40)x1	(4.69/72)x6, (5.21/80)x1	(4.69/108)x6, (5.21/120)x1	(4.69/144)x6, (5.21/160)x1
CP Length (us/samples) Long	(16.67/32)	(16.67/64)	(16.67/128)	(16.67/256)	(16.67/384)	(16.67/512)

*{(x1/y1)xn1, (x2/y2)xn2)} means (x1/y1) for n1 OFDM symbols and (x2/y2) for n2 OFDM symbols

Clearly with a fixed sub-carrier spacing of 15 kHz and variable channel bandwidths the number of sub-carriers per channel bandwidth varies, and therefore so do the maximum number of RBs available, as shown below.

Table 2 - Number of RBs per Channel Bandwidth

Channel Bandwidth (MHz)	1.4	3	5	10	15	20
Max # of RBs	6	15	25	50	75	100

With a 1.4 MHz channel bandwidth only 6 RBs exist, the UL PRACH channel requires 6 RBs, and hence sub-frames where the UL PRACH is in use cannot be used for data transmission. Hence the overhead of the control signals becomes more significant at lower channel bandwidths.

3.3 SFBC

SFBC (Space Frequency Block Code) is Transmit diversity, coding in the frequency domain rather than the conventional time domain. At time t1, *information symbols* x1 and x2 are transmitted from antennas 1 and 2 respectively. At time t2 (the next OFDM symbol) information symbols -x2* and x1* are transmitted from antennas 1 and 2 respectively. Hence the same information is transmitted twice, with a slight change in the modulation applied, this is the Alamouti [2] coding and creates orthogonal channels between the transmit and receive antennas even when the propagation channel itself is correlated.

Because the information is transmitted twice, there is twice as much energy transmitted per information bit, this is a transmit power gain, that is taken into account in the link budget at the transmit end.

The increased order of diversity (now four-fold diversity compared to two-fold diversity) lowers the required SNR, and provides additional link budget improvement. The SNR varies with channel model and BLER and is found from link level simulation as discussed in section x.

SFBC is used when the SNR is low, i.e. typically at cell edge or a heavily shadowed area. SFBC increases the robustness of the radio link between the BS and the UE. It is used for all downlink link budget calculations.

3.4 HARQ

HARQ - Hybrid Automatic Repeat request is a PHY layer technique to improve the robustness of the channel. It can also be thought of as a form of time-diversity and as such lowers the required SNR for a given BLER performance. HARQ requires re-transmission of the information bits, and as such decrease the PHY throughput. The amount of throughput decrease is dependent on the number of re-transmissions and the probability of occurrence of the re-transmissions. In a noise limited environment the probabilities of re-transmission vary with channel model i.e. EPA, ETU, EVA. In an interference environment, HARQ can be used to correct transmissions that have failed due to interference.

The throughput can be adjusted using the normalized throughput equation given below.

$$Tn = \frac{1 - Pn}{1 + \sum_{i=1}^{n-1} Pi}$$

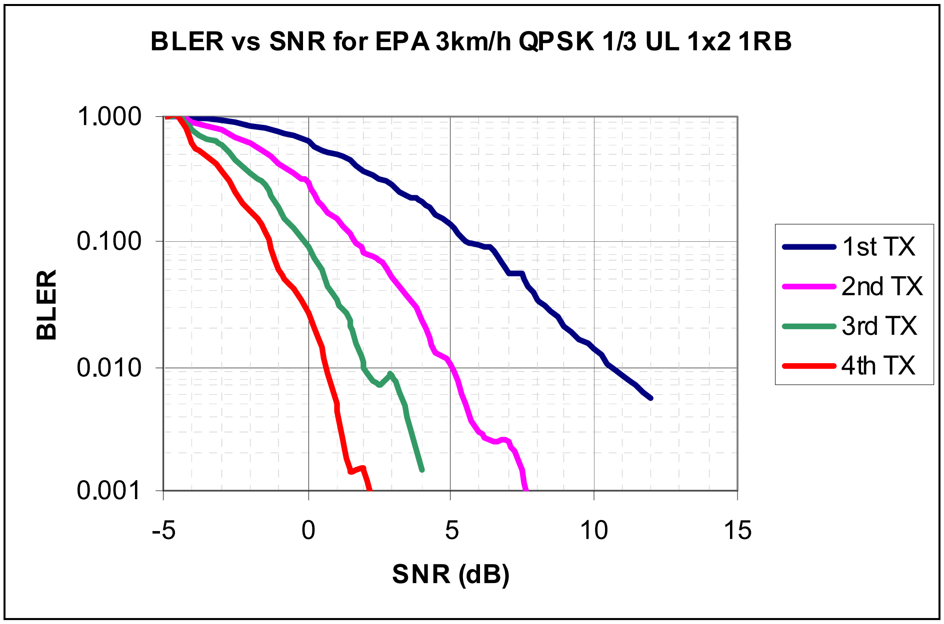


Figure 5 - Example BLER vs. SNR with HARQ

UL HARQ Information EPA 3km/h 1 RB				
	1 Transmission	2 Transmissions	3 Transmissions	4 Transmissions
SNR	**10.625**	**5.045**	**2.000**	**0.737**
BLER 4	N/A	N/A	N/A	0.01000000
BLER 3	N/A	N/A	0.01000000	0.04771053
BLER 2	N/A	0.01000000	0.08050000	0.17176316
BLER 1	0.01000000	0.13381818	0.36600000	0.52515789
Tn	**0.99000000**	**0.87315587**	**0.68441065**	**0.56745505**

Table 3 - Example HARQ SNR and Throughput Calculation

Hence HARQ lowers the SNR dramatically but with some impact to the throughput.

3.4.1 Derivation of HARQ Throughput Formula

(Acknowledgement: Mike Petras)

Throughput = bits delivered / time taken.

Bits delivered = bits sent *(1- Pn), where Pn the residual error rate after the nth transmission. But since we are concerning ourselves with the normalized throughput, Tn, then bits delivered is proportional to (1-Pn).

Time taken is the weighted time, some bits get through in one slot, some in two slots, some in n slots.

1-P1 we use 1 slot, i.e. when we succeed first time

P1 - P2 we use 2 slots when we succeed on first retry, e.g. at 10% HARQ retransmission, P1 = 0.1, P2 = 0.01, so P1 - P2 = 0.09 is probability of using exactly 2 tries

...

Pn-1 - Pn we use n slots and succeed

Pn we use n slots and fail

Number of slots used to send these bits: 1(1 - P1) + 2 (P1 - P2) + 3(P2 - P3) + … + n(Pn-1 - Pn) + nPn = 1 + P1 + P2 + … + Pn-1

And hence,

$$Tn = \frac{1 - Pn}{1 + \sum_{i=1}^{n-1} Pi}$$

3.5 Frequency Selective Scheduling

The SNRs used in the link budget, derived from link level simulations are the so-called long-term SNRs. These are the average SNR assuming the UE is on that channel continuously over time. They do not take into account any possible scheduling gains, such as frequency selective scheduling. In a recent RFP request, a customer asked for EPA SNRs, these are however the worst case SNRs, as shown in the figure below, and without consideration to other factors may lead to pessimistic conclusions about the performance of LTE. For this reason, it was decided to include the FSS gains in the link budget to enable a prediction of actual system performance. The FSS was simulated and gains of approximately 3 dB calculated for the EPA channel. Note that to achieve FSS gains, several assumptions and considerations need to be understood. FSS relies of the sounding channel (SRS) so it is implicitly assumed that the SRS has sufficient signal strength (SNR) to work accurately, and that the frequency of the SRS (periodicity) is sufficient to track changes in the channel - with mobility FSS fails, and if there are many UEs in the cell, each UE may not get short enough interval between SRS for accurate channel tracking.

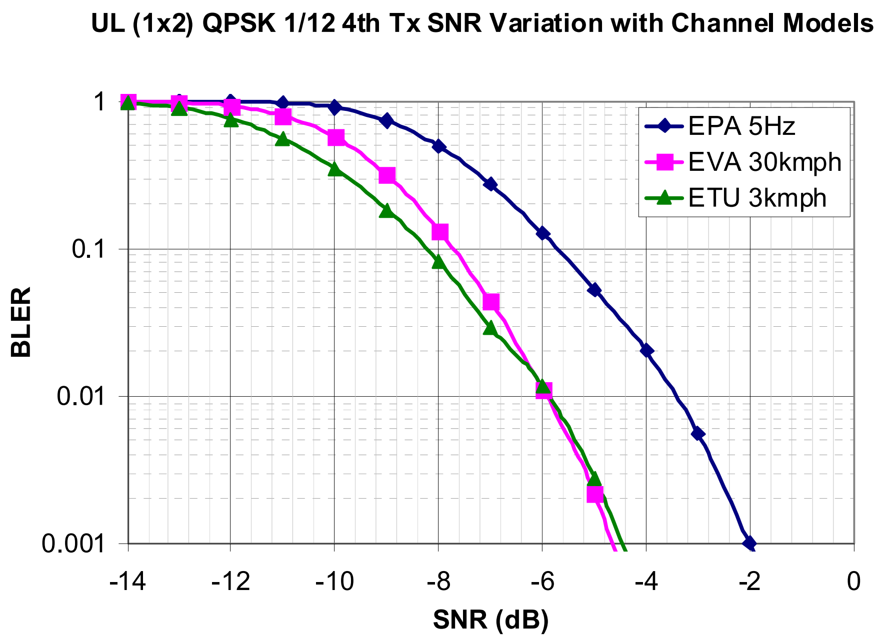


Figure 6 - Variation of SNR with Channel Model

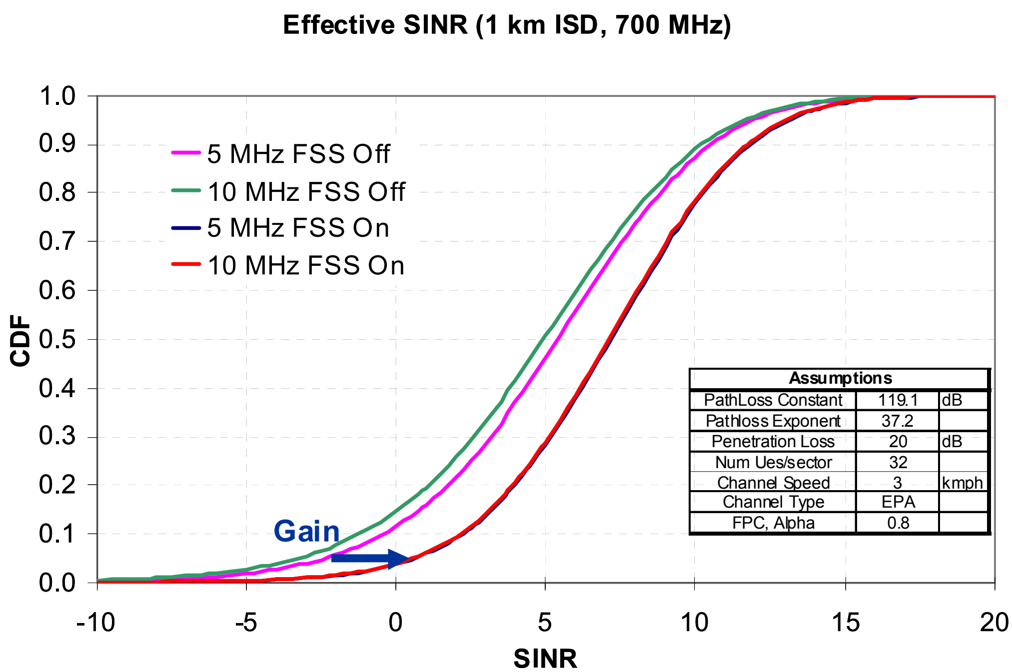


Figure 7 - FSS Scheduling Gain

4.0 Link Budget Calculation

4.1 Generic Description for Downlink

For the purposes of explanation a generic downlink link budget is given below. Note this particular example assumes a radio located at the base of a tower, with associated cabling. For downlink, where the PA transmit power is divided across all sub-carriers, the number of RBs allocated to an individual UE does not change the Tx power per sub-carrier. Hence the data rate for an individual UE can be changed by increasing / decreasing the number of RBs allocated without effecting the system gain. Link budgets are generated using a robust modulation code set - QPSK 1/3. The PHY data rate is calculated using this MCS and the number of RBs allocated and assuming this allocation is maintained in every sub-frame.

The link budget is calculated on a “per tone” basis, that is, the transmit power per tone or sub-carrier is calculated, taking into account antenna gain and cable loss. The receive sensitivity is then also calculated on a per tone basis, so the receive noise bandwidth is 15 kHz, irrespective of the number of RBs allocated. The SNR is obtained for a given error rate or application type for the channel model specified. The SNR is given in a look-up table which was derived from either measured data or simulation. The system gain is then simply the difference between the Tx EIRP (per tone) and the receive sensitivity (per tone) plus the UE antenna gain.

4.1.1 Downlink PHY Data Rate Calculation

One RB contains 168 REs, 16 are reserved for reference signals, 20 reserved for PDCCH, leaving 132 for data. The duration of an RB is one complete sub-frame (1ms). The data rate is then calculated as the number of REs(132) multiplied by the information per RE (based on the modulation and coding) divided by the time duration. For QPSK 1/3 the modulation efficiency is 2/3=0.667, i.e. 3 REs contain two bits of information, hence one RB contains 88 bits of information, and since this takes 1ms, the data rate is 88/ 1e-3= 88 kbps per RB.

Table 4 - Generic LTE FDD Downlink Link Budget

LTE FDD Downlink			
BS Transmit			
PA Power	43	dBm	a=input
	20	W	b=10log10(a)+30
MIMO Mode	SFBC		c=SFBC or SIMO
Number of PAs	2		d=if(c=SIMO,1, 2)
Total PA Power	46	dBm	e=b+10log10(d)
Channel Bandwidth	10	MHz	f=input
Number of carriers	600		g=standard
Number of RBs	12		h=allocation
Modulation	QPSK 1/3		i=modulation
Modulation Efficiency	0.67	bits/tone	j=modulation efficiency
PHY Data rate	1056	kbps	k=PHY data rate
Power per tone	18.2	dBm	l=e-10log10(g)
BS Antenna Gain	17.5	dBi	m=input
BS Jumper Cable Loss	0.5	dB	n=input
Cable Loss	2.0	dB	o=input
Tower Top Jumper Cable Loss	0.5	dB	p=input
Total EIRP	60.5	dBm	q=e+m-n-o-p
EIRP per tone	32.7	dBm	r=l+m-n-o-p
UE Receive			
kT	-174	dBm/Hz	s=thernal noise
subcarrier bandwidth	15	kHz	t=standard
kTB	-132.2	dBm	u=s+10log(t)+30
UE Noise Figure	8.0	dB	v=input
kTBF	-124.2	dBm	w=u+v
Channel Model	Ped B		x=input
Required SNR (BLER=0.2)	-0.7	dB	y=from link level simulation
Rx Sensitivity	-124.9	dBm	z=w+y
UE Antenna Gain	0.0	dBi	aa=input
System Gain	**157.7**	**dB**	**bb=r-z+aa**

4.1.2 Reference Signal Power Allocation

There are four reference signals transmitted per slot, per antenna, with two antennas. As shown in Figure 3 - the reference signals from each antenna are in different locations (REs) with nulls transmitted on the other antenna to avoid interference of the reference signals. The power transmitted in the reference signals can be boosted or attenuated as defined in the LTE standard, also the power per RE in symbols not containing any reference signals can be different from the power of REs carrying data in symbols that contain the reference signals. Parameters Pa and Pb have been defined to allow vendors to configure the relative powers of the REs. The actual values for Pa and Pb that Nortel will use are to be determined, by simulation. And once set, will be communicated to the UEs via control channels, to ensure accurate channel estimation and demodulation.

Pa is the PDSCH-to-RS EPRE (energy per RE) ratio among PDSCH REs in all the OFDM symbols not containing RS. Pb is the PDSCH-to-PDSCH EPRE ratio between PDSCH REs in all the OFDM symbols containing RS and PDSCH REs in all the OFDM symbols not containing RS.

Pa is permitted to be any of the following values {3, 2, 1, 0, -1, -2, -3, -6} dB. Pb is permitted to be {1.25, 1.0, 0.7, 0.5}, though some checks are required because certain combinations violate other rules!

Once the values of Pa and Pb have been determined, an assessment will be made to see whether there is any impact to the link budget, for example, the transmit power per RE in the PDSCH link budget may change slightly. Until that assessment has been made we will assume that the PA power is divided equally between all subcarriers for the channel bandwidth of interest, and that all REs assume the same transmit power, (this is a valid configuration).

4.2 Generic Description for Uplink

The table below shows a generic uplink link budget. The UE transmit power is considerably lower than the BS transmit power for obvious reasons. Also of note is that the UE transmit power is also lower than the GSM mobile transmit power, which will be discussed in more detail later. However the UE does not have to transmit on all available RBs simultaneously like the BS has to. This is sometimes referred to as subchannelisation gain. As the number of RBs allocated increases, to increase the data rate, the transmit power per tone or sub-carrier decreases and hence the system gain and range also decrease. There is a direct relationship between data rate and range, the higher the data rate the shorter the range. The rest of the link budget calculation is exactly the same as the downlink.

Note that there is a selection for 1x2 or 1x4, indicating either two or four BS receivers, this is discussed in more detail later.

4.2.1 Uplink PHY Data Rate Calculation

The uplink calculation follows the same methodology as the downlink except that the numbers of REs available for data is 144 (assuming no sounding reference symbols are transmitted), and hence for QPSK 1/3 one RB has a PHY data rate of 96 kbps.

Table 5 - Generic LTE FDD Uplink Link Budget

LTE FDD Uplink			
UE Transmit			
UE Tx Power	23	dBm	a=input
	200	mW	b=10^(a/10)
Number of RBs	1		c=input
Number of carriers	12		d=c*12
Modulation	QPSK 1/3		e=modulation
Modulation	0.67	bits/tone	f=modulation efficiency
PHY Data rate	96	kbps	g=PHY data rate
Power per tone	12.2	dBm	h=b-10log10(d)
UE Antenna Gain	0.0	dBi	i=input
Total EIRP	23.0	dBm	j=a+i
EIRP per tone	12.2	dBm	k=h+i
BS Receive			
kT	-174	dBm/Hz	l=thermal noise
subcarrier bandwidth	15	kHz	m=standard
kTB	-132.2	dBm	n=l+10log10(m)+30
BS Noise Figure	2.5	dB	o=input
kTBF	-129.7	dBm	p=n+o
Rx Architecture	1x2		q=input
Channel Model	Ped B		r=input
Required SNR (BLER=0.2)	2.8	dB	s=from link level simulation
Rx Sensitivity	-126.9	dBm	t=p+s
Cable Loss	2.0	dB	u=input
Tower Top Jumper Cable Loss	0.5	dB	v=input
BS Antenna Gain	17.5	dBi	w=input
BS Jumper Cable Loss	0.5	dB	x=input
System Gain	**153.6**	**dB**	**y=k-t-u-v+w-x**

5.0 Propagation

5.1 Propagation Models

Macro-cell propagation models are published in papers and books. They are generally frequency dependent and valid over a specified set of frequencies, BS antenna and UE antenna heights. They may or may not have correction factors for each morphology classification or clutter type. The models are statistical in nature and predict the median path loss at a given range. More complicated models exist that have dependencies on street width and building heights, these are generally more applicable to micro-cells, where more detailed local information is available. Macro-cell propagation models are generally valid in ranges exceeding 1km and where the BS antenna is located higher than local buildings (above roof-top). The smaller the cell range the more deterministic the models become, requiring detailed site knowledge to predict the range to a reasonable level of accuracy.

Models can also be tuned, with measurements performed in the location of interest or morphology of interest. This is generally a recommended practice, especially when deploying a wireless network in a location that does not match either previously deployed networks or the descriptions given by propagation model authors. Nortel has the expertise to perform model tuning and this service is recommended.

The Macro-cell propagation models are generally of the form given below.

$$\text{Pathloss(dB)} = \dot{n}10\log(r) + \alpha$$

Where n is the range power law exponent, typically n=3.5, but decreases with increasing BS or UE antenna height and can vary with morphology; urban, sub-urban, rural. Alpha is a offset correction factor; often this varies with morphology.

A popular model, the COST-231 Hata model can be found in Chapter 4, section 4.4, of the COST report at *http://www.lx.it.pt/cost231/final_report.htm*

For convenience this has also been put on livelink here:

http://livelink-ott.ca.nortel.com/livelink/livelink.exe?func=ll&objId=31127722&objAction=browse&sort=name&viewType=1

The main equations of interest are presented below.

Okumura-Hata Urban model (for use below 1 GHz)

$$\text{Pathloss(dB)} = 69.55 + 26.16\log(F) - 13.82\log(H_b) - a(h_{mobile}) + (44.9 - 6.55\log(H_b))\log(d)$$

In the above, F is in MHz, d is in km, log is log base10, and,

$$a(h_{mobile}) = (1.1\log(F) - 0.7)h_{mobile} - (1.56\log(F) - 0.8)$$

The model is restricted to

F: 150 ... 1000 MHz

Hb: 30 ... 200 m

hmobile: 1 ... 10 m

d: 1 ... 20 km

A correction factor (Cm) can be added for dense urban, sub-urban and rural environments.

$$\text{Dense Urban Cm} = 3$$

$$\text{Sub-urban Cm} = -2\left(\log\left(\frac{F}{28}\right)\right)^2 - 5.4$$

$$\text{Rural quasi-open Cm} = -4.78(\log(F))^2 + 18.33\log(F) - 35.94$$

$$\text{Rural open Cm} = -4.78(\log(F))^2 + 18.33\log(F) - 40.94$$

COST 231 extended the model to 1500 <= F <= 2000 MHz. The extended model is called the COST-Hata Model and is:

$$\text{Pathloss(dB)} = 46.3 + 33.9\log(F) - 13.82\log(H_b) - a(h_{mobile}) + (44.9 - 6.55\log(H_b))\log(d) + Cm$$

The COST-Hata model is restricted to the following range of parameters:

F: 1500... 2000 MHz

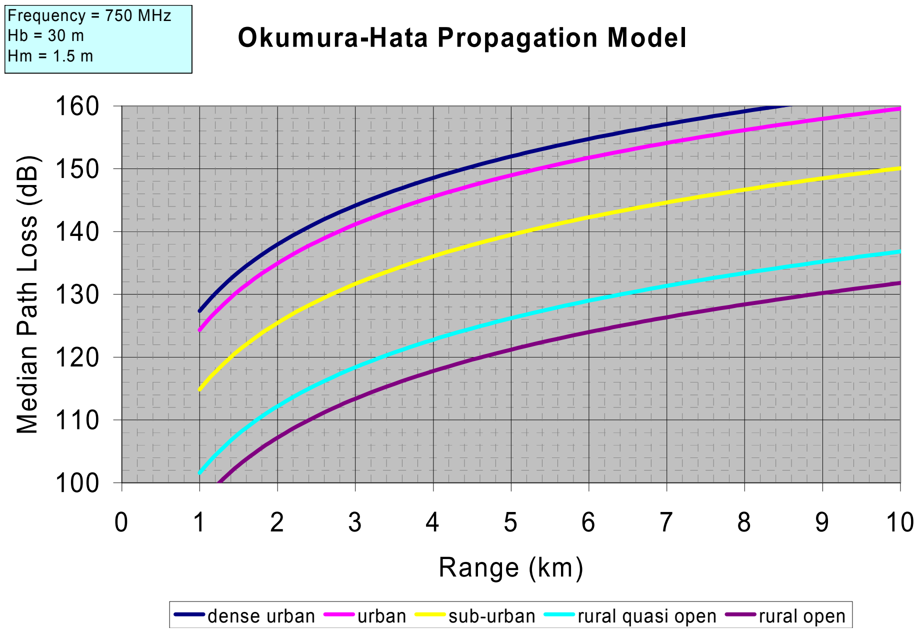
Hb: 30 ... 200 m

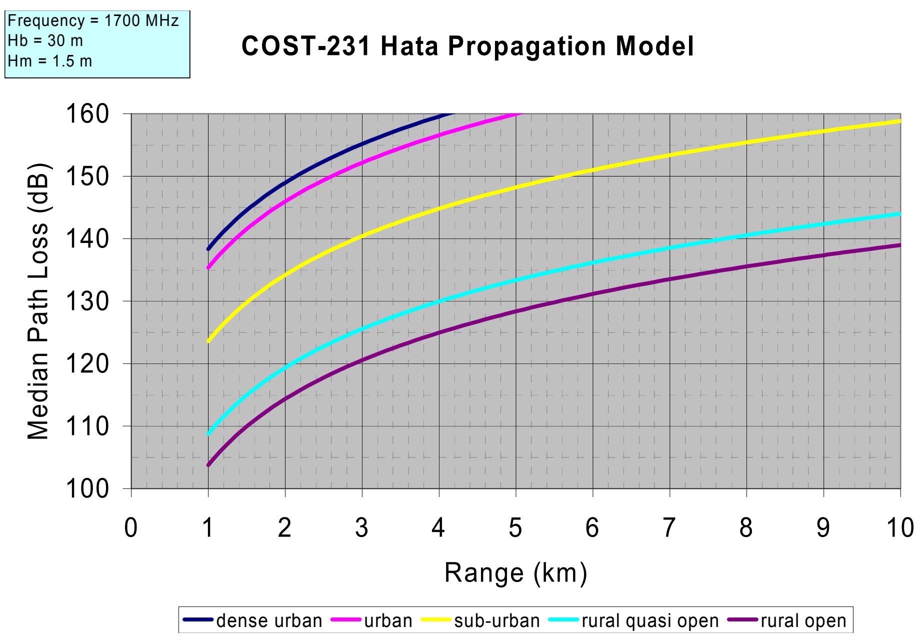
hmobile: 1 ... 10 m

d: 1 ... 20 km

It should be noted that the COST-231-Hata model is actually quite pessimistic compared to other published models and also Nortel's own measured data. It is however well referenced and known, and some customers request that we use this model.

Figure 8 - Propagation Models at 750 MHz and 1700 MHz





5.2 Shadowing

The path loss models described above predict the median path loss. The actual path loss will vary about the median, the distribution of the variability follows a normal distribution on a log scale and is more commonly called log-normal shadowing. Another way to think about shadowing is that if the propagation models were 100% accurate, the signal strength or path loss predictions from cell planning tools would be perfect and the radio planners would not need any margins in there design to account of inaccurate models. However, clearly this is not the case, and a shadow margin is required so that the radio planners can design using median path loss models plus a shadow margin to obtain a desired area coverage metric, typically 90% or 95% area coverage.

Without a shadow margin, i.e. 0 dB shadow margin, the perimeter of the cell would have a 50% chance of sufficient signal strength (50% because the path loss model predicts the median path loss). So closer to the cell site a similar perimeter, would have higher coverage reliability, because there would be less path loss. The integration over distance from the BS to the edge of cell, of the edge availability provides the area availability. The equation to calculate this integration has been derived in Jakes' famous book [4] for a single omni directional cell. The shadow margin required is a function of the shadowing sigma (typically 8 dB) and the path loss exponent (typically 3.5), hence every time the sigma changes or the path loss exponent changes a new shadow margin must be calculated (note that in the propagation models above, the path loss exponent varies with antenna height).

The shadowing sigma varies with frequency, as describes in Saunders' book [1] by the equation below;

$$\sigma = A + 0.65(\log(F))^2 - 1.3\log(F)$$

Where A=5.2 in Urban and 6.6 in sub-urban environments, and F is the frequency in MHz.

Some operators specify what shadow sigma they prefer the link budgets use, in these cases of course we will use their recommendation, in all other case we shall use the Saunders' formula.

More information about shadowing can be found in [ref Muhieddin's work].

A shadow margin calculator spreadsheet is available on livelink at:

http://livelink-ott.ca.nortel.com/livelink/livelink.exe?func=ll&objId=31044339&objAction=browse&sort=name&viewType=1

For example, the following shadow margins were generated using this spreadsheet.

Table 6 - Outdoor Shadow Margins as a Function of Frequency Assuming a Path Loss Exponent of 3.52

Frequency (MHz)	Sigma	Shadow Margin (dB) for 90% Area Availability		Shadow Margin (dB) for 95% Area Availability	
		Isolated	Network	Isolated	Network
700	6.8	4.1	2.6	6.9	5.1
800	6.9	4.3	2.7	7.1	5.3
900	7.0	4.4	2.8	7.3	5.4
1700	7.8	5.2	3.3	8.3	6.2
1800	7.9	5.3	3.4	8.4	6.2
1900	7.9	5.4	3.5	8.5	6.3
2100	8.1	5.5	3.6	8.7	6.4

Table 6 - Outdoor Shadow Margins as a Function of Frequency Assuming a Path Loss Exponent of 3.52

Frequency (MHz)	Sigma	Shadow Margin (dB) for 90% Area Availability		Shadow Margin (dB) for 95% Area Availability	
		Isolated	Network	Isolated	Network
2600	8.3	5.8	3.8	9.1	6.8

5.3 Channel Models

Several channel models exist, common ones quoted and simulated are the ITU channels model, most commonly the Pedestrian B 3 km/h (ped B) channel and the Vehicular A 30km/h channel. The LTE standard has specified minimum performance criteria in slightly different but related channel models; Extended Pedestrian A (EPA), Extended Typical Urban (ETU) and Extended Vehicular A channel (EVA).

These channels together with typical frequency responses are given in;

http://livelink-ott.ca.nortel.com/livelink/livelink.exe?func=ll&objId=31127722&objAction=browse&sort=name&viewType=1

5.4 Cell count

There is a direct relationship between the link budget and the number of cell sites required to cover a specified geographic region. Expressing the link budget in terms of site count is a dramatic way to explain the benefit of a dB in link budget to someone not familiar with link budgets or dBs, but who is very familiar with dollars! Fewer cell sites obviously means less cost, both in terms of purchased equipment and site installation as well as ongoing OPEX.

The cell count can be quickly estimated from the range, assuming a perfectly tessellated equally spaced site arrangement and a noise limited system. Of course as the system becomes capacity limited and operators deploy more sites to meet the extra demand, the benefits of a dB in link budget diminish. However, the link budget and site count are important early considerations for operators when rolling out a new network, since they wish to reduce the CAPEX day-one and maximize the coverage to help their business case.

Assuming a hexagonal sector area (three hexagons comprising the coverage area of a cell site), the sector area can be found from the formula below

$$\mathrm{SectorArea} = \frac{3\sqrt{3}R^2}{8}$$

This equation and the dB to site count calculation can be found as a worksheet within the link budget spreadsheet. Example results of the dB to site count reduction are shown below (assuming perfect cell layout and hexagonal grid arrangement).

Table 7 - dBs to Site Count

Range baseline (km)	2	2	2	2
Link budget improvement (dB)	**0**	**1**	**2**	**3**
Range power law	**3.5**	**3.5**	**3.5**	**3.5**
New range (km)	2.0	2.1	2.3	2.4
sector area (km^2)	2.60	2.96	3.38	3.86
cell area (km^2)	7.79	8.89	10.14	11.57
Number of bases to cover 1000km^2	128	112	98	86
% reduction	ref	12.5%	26.8%	42.9%

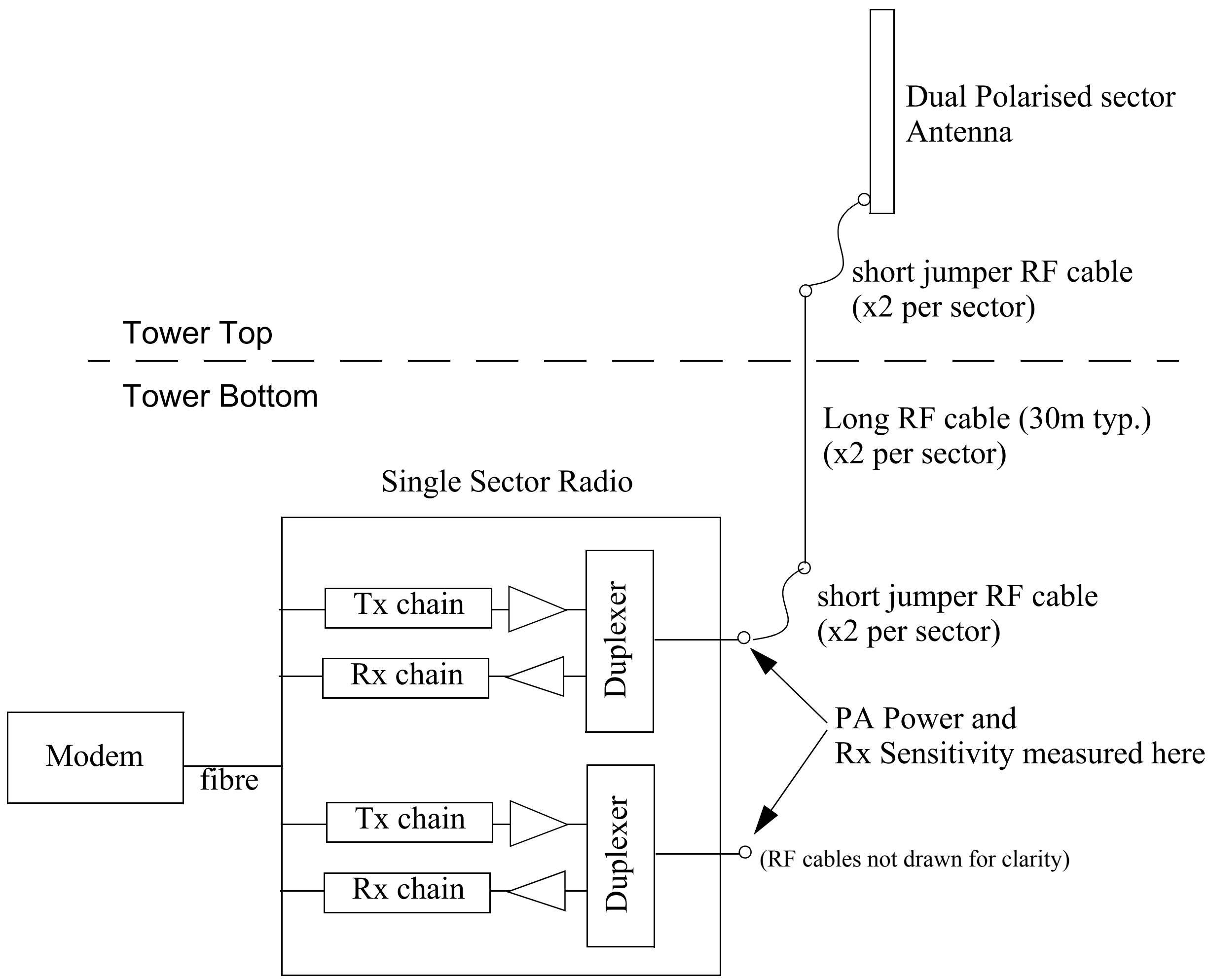
6.0 Architecture

6.1 Conventional BS

This BS has all electronics located at the base of the tower with RF cables connecting the radio Tx/Rx ports to the antennas. This architecture is popular because the electronics are easy to maintain, replace and upgrade. All components up the tower are passive and have high reliability. In many instances techniques are used to combine different signals onto a shared antennas, this saves cabling and antennas.

A zero-footprint version is where the electronics are not located within a cabinet but are compact enough to be mounted to a pole. This architecture tends to represent the lowest cost option for an operator in terms of OPEX per BS. However from a link budget viewpoint both the cabinet and zero-footprint designs are similar, the only differences may be in the available transmit power.

Figure 9 - Conventional BS Drawing



6.1.1 Cable Loss

RF cables attenuate the RF signal, the loss is usually specified in data sheets in dB/100m or dB/100ft. The loss increases with frequency. Different cable types are available with different attenuation factors, large diameter cables offer the lowest loss, but these are more expensive (more material), have increased weight, and the bend radius may be restrictive. The increased weight is a problem for operators when renting space on a tower, more weight more cost. Hence there is a trade-off between cable loss and cost that needs to be considered. Some examples of commercially available popular cables and their characteristics are given below.

Table 8 - Example Common Cable Types and their Characteristics

Cable Type	Diameter	Weight (kg/m)	Loss (dB/100m)		
			@700MHz	@1900MHz	@2600MHz
AVA7-50	1 5/8"	1.07	1.840	3.258	3.927
AL7-50	1 5/8"	0.77	2.037	3.582	4.306
AVA5-50	7/8"	0.45	3.093	5.364	6.412
AL5-50	7/8"	0.39	3.421	5.904	7.044

Data sheets for the above cables can be found at:

http://awapps.commscope.com/catalog/product.aspx?id=269

and on livelink at:

http://livelink-ott.ca.nortel.com/livelink/livelink.exe?func=ll&objid=31044339&objAction=browse&sort=name

The high cable loss associated with the higher frequencies mean of course a degraded link budget. To improve the link budget the RF amplifiers can be located closer to the antenna to minimize the length of RF cable - RRH (Remote Radio Head). This then leads to concerns about reliability and the increased cost of replace failed electronics located high up a tower as well as concerns about the physical size and weight and installation. Since the most unreliable single part is the high power Tx power amplifier, and that usually the system is uplink limited, an alternative architecture is to split the Tx and Rx locations, thereby locating the Tx power amplifier at the base of the tower and the Rx RF amplifier (LNA) at the top of the tower, this is commonly called (at least within Nortel) a TTLNA (Tower Top LNA).

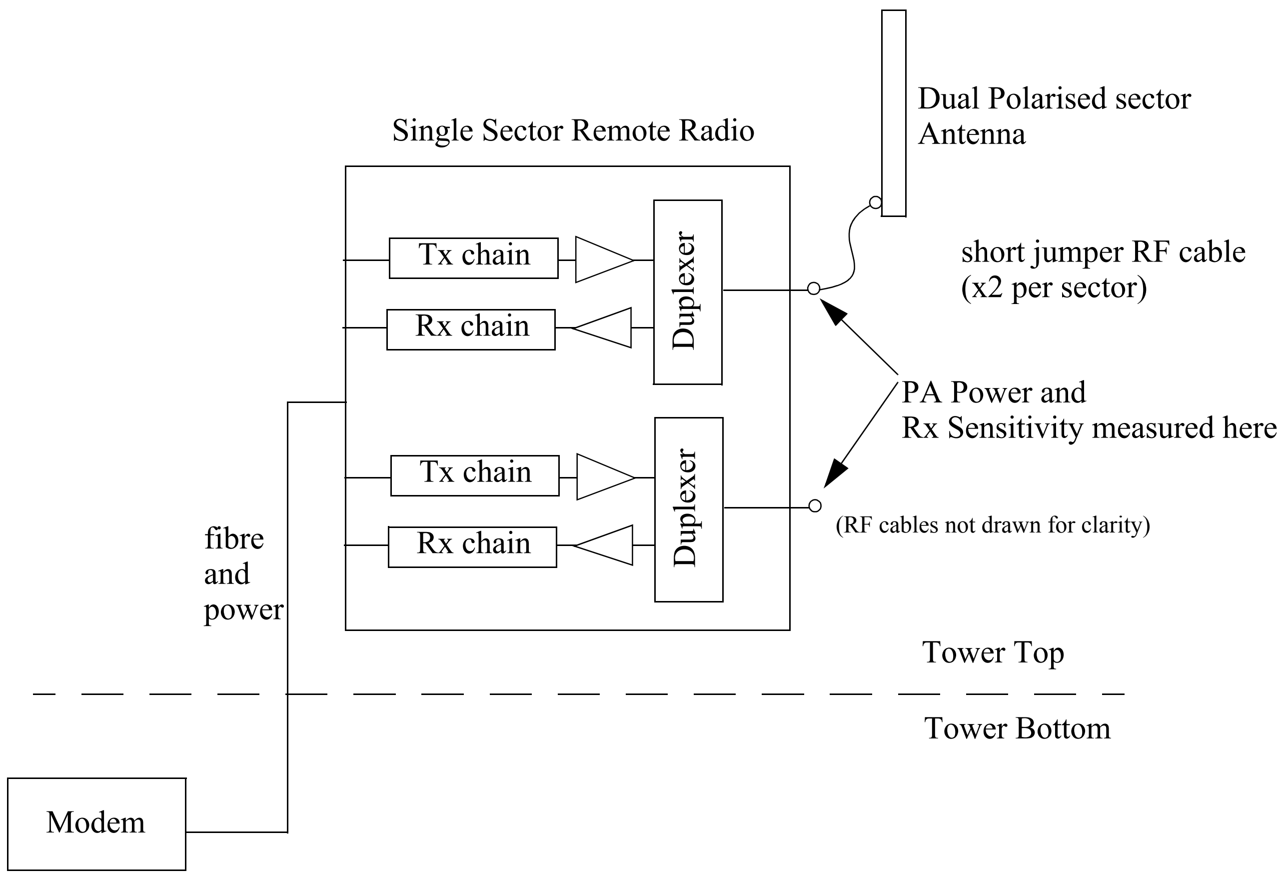
6.2 RRH (Remote Radio Head)

As discussed in 6.1.1 a RRH can be used to reduce the RF cable losses, this is especially important at high frequencies. They can also be used to eliminate numerous RF cable runs up the tower. For example architectures with complex antenna systems may require more than the traditional one or two RF cables which becomes an obstacle. Since most link budgets are uplink limited one way to improve the uplink is to provide four receivers at the BS. However four receivers with a conventional BS requires four RF cables (per sector), with the associated increased cost and weight, to overcome this disadvantage a RRH may be used to reduce the cable runs and hence reduce the cost. Another use for the RRH is when each sector is physically located (antennas) a reasonable distance apart, for example on a building roof-top, each sector antenna may be separated by 20 to 50m or more.

In summary RRH should be considered if any of these situations arise:

- The Frequency of operation and RF cable length degrade the link budget significantly.
- More than two BS receivers are required.
- More than two BS transmitters are required.
- Sector antennas are remote from the backhaul connection point

Figure 10 - RRH Drawing



6.2.1 RRH Link Budget

LTE RRH FDD Downlink		
BS Transmit		
PA Power	40	dBm
	10	W
MIMO Mode	SFBC	
Number of PAs	2	
Total PA Power	43	dBm
Channel Bandwidth	10	MHz
Number of carriers	600	
Number of RBs	12	
Modulation	QPSK 1/3	
Modulation Efficiency	0.67	bits/tone
PHY Data rate	1056	kbps
Power per tone	15.2	dBm
BS Antenna Gain	17.5	dBi
Tower Top Jumper Cable Loss	0.5	dB
Total EIRP	60.0	dBm
EIRP per tone	32.2	dBm
UE Receive		
kT	-174	dBm/Hz
subcarrier bandwidth	15	kHz
kTB	-132.2	dBm
UE Noise Figure	8.0	dB
kTBF	-124.2	dBm
Channel Model	Ped B	
Required SNR (BLER=0.2)	-0.7	dB
Rx Sensitivity	-124.9	dBm
UE Antenna Gain	0.0	dBi
System Gain	**157.2**	**dB**

LTE RRH FDD Uplink		
UE Transmit		
UE Tx Power	23	dBm
	200	mW
Number of RBs	1	
Number of carriers	12	
Modulation	QPSK 1/3	
Modulation	0.67	bits/tone
PHY Data rate	96	kbps
Power per tone	12.2	dBm
UE Antenna Gain	0.0	dBi
Total EIRP	23.0	dBm
EIRP per tone	12.2	dBm
BS Receive		
kT	-174	dBm/Hz
subcarrier bandwidth	15	kHz
kTB	-132.2	dBm
BS Noise Figure	2.5	dB
kTBF	-129.7	dBm
Rx Architecture	1x2	
Channel Model	Ped B	
Required SNR (BLER=0.2)	2.8	dB
Rx Sensitivity	-126.9	dBm
Tower Top Jumper Cable Loss	0.5	dB
BS Antenna Gain	17.5	dBi
System Gain	**156.1**	**dB**

6.3 TTLNA (Tower Top Low Noise Amplifier)

A TTLNA can be used to improve the uplink link budget by locating the LNA very close to the antenna. The BS receiver still resides at the base of the tower, and RF cables are required for both Tx and Rx. The overall system noise figure then becomes a cascaded noise figure, where the LNA gain reduces the impact of the RF cable loss. It should also be noted that adjustments in the Rx gain in the BS are required when using a TTLNA to avoid saturation of ADCs etc. Hence the BS NF (noise figure) used in the cascaded noise figure calculation is actually slightly higher than that of a conventional BS, because of the additional attenuation required to maintain the signal at the desired level.

For example the WiMAX BS Noise figure varied with cable loss as shown below [Note this will be updated with LTE product information when available].

Table 9 - (For example) WiMAX BS NF Variation with Cable Loss (when used with TTLNA)

BTS Noise Figure Variation with Cable Loss		
Cable Loss (dB)	BTS Noise Figure typical	BTS Noise Figure guaranteed
2	4.58	6.94
3	4.55	6.42
4	4.29	5.96
5	4.08	5.56
6	3.90	5.21
7	3.75	4.91
11	3.53	4.50

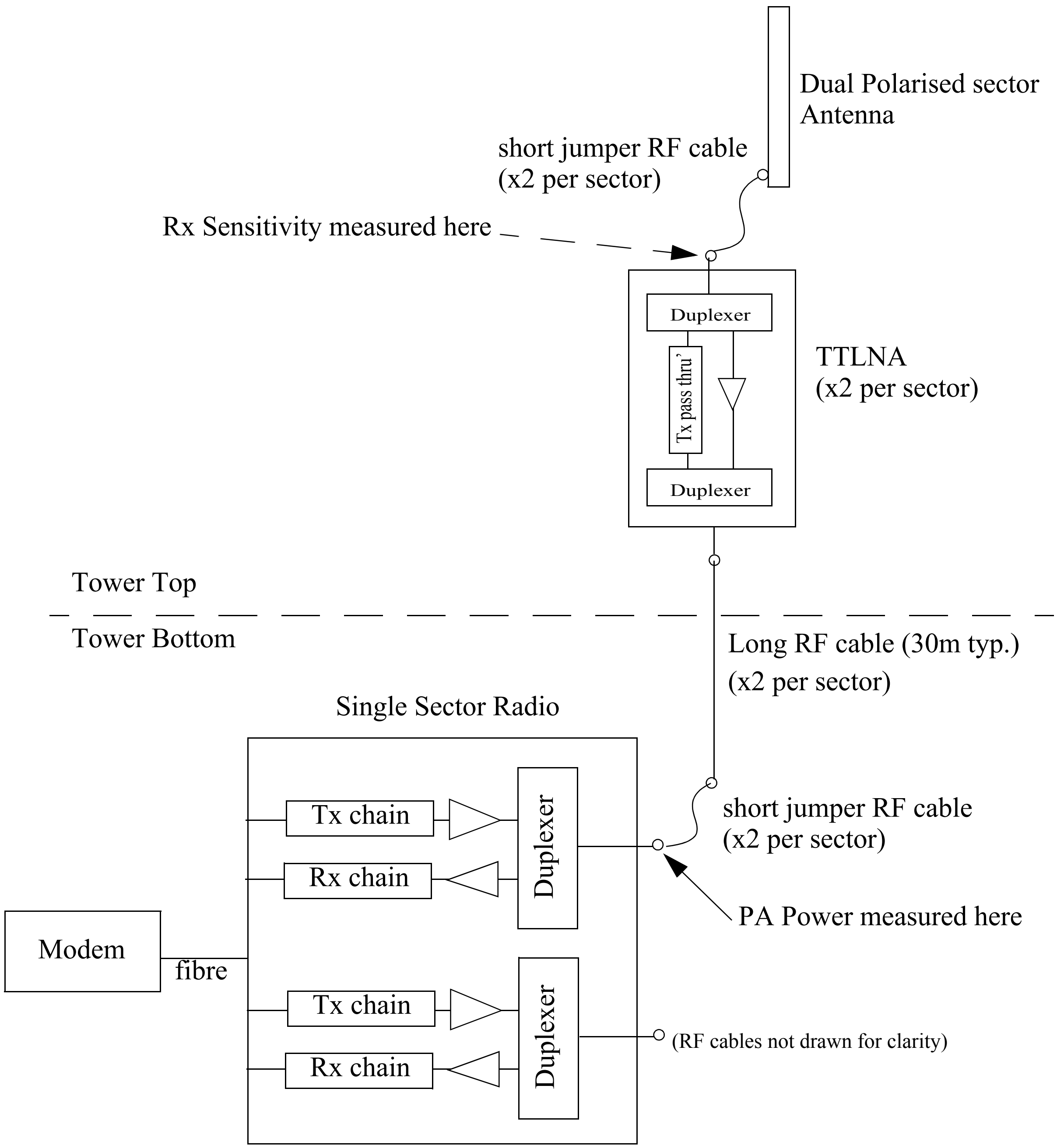


Figure 11 - TTLNA with BS Drawing

6.3.1 Cascaded Noise Figure Calculation

A well known RF technique to improve the system noise figure is to place a low noise amplifier close to the antenna. The overall cascaded noise factor is given by Friis' formula, below.

$$F_{system} = L_1 + F_1 + \frac{(F_2 - 1)}{G_1} + \frac{(F_3 - 1)}{G_1 G_2} + \frac{(F_4 - 1)}{G_1 G_2 G_3} + \ldots$$

.Noise figure is simply 10log10(Noise Factor).

This formula is implemented in an excel spreadsheet located here:

http://livelink-ott.ca.nortel.com/livelink/livelink.exe?func=ll&objId=31044339&objAction=browse&sort=name&viewType=1

6.3.2 TTLNA Link Budget

LTE TTLNA FDD Downlink		
BS Transmit		
PA Power	43	dBm
	20	W
MIMO Mode	SFBC	
Number of PAs	2	
Total PA Power	46	dBm
Channel Bandwidth	10	MHz
Number of carriers	600	
Number of RBs	12	
Modulation	QPSK 1/3	
Modulation Efficiency	0.67	bits/tone
PHY Data rate	1056	kbps
Power per tone	18.2	dBm
BS Antenna Gain	17.5	dBi
BS Jumper Cable Loss	0.5	dB
Cable Loss	2.0	dB
TTLNA Pass thru'	0.5	dB
Tower Top Jumper Cable Loss	0.5	dB
Total EIRP	60.0	dBm
EIRP per tone	32.2	dBm
UE Receive		
kT	-174	dBm/Hz
subcarrier bandwidth	15	kHz
kTB	-132.2	dBm
UE Noise Figure	8.0	dB
kTBF	-124.2	dBm
Channel Model	Ped B	
Required SNR (BLER=0.2)	-0.7	dB
Rx Sensitivity	-124.9	dBm
UE Antenna Gain	0.0	dBi
System Gain	**157.2**	**dB**

LTE TTLNA FDD Uplink		
UE Transmit		
UE Tx Power	23	dBm
	200	mW
Number of RBs	1	
Number of carriers	12	
Modulation	QPSK 1/3	
Modulation	0.67	bits/tone
PHY Data rate	96	kbps
Power per tone	12.2	dBm
UE Antenna Gain	0.0	dBi
Total EIRP	23.0	dBm
EIRP per tone	12.2	dBm
BS Receive		
kT	-174	dBm/Hz
subcarrier bandwidth	15	kHz
kTB	-132.2	dBm
BS Noise Figure	2.5	dB
kTBF	-129.7	dBm
Rx Architecture	1x2	
Channel Model	Ped B	
Required SNR (BLER=0.2)	2.8	dB
Rx Sensitivity	-126.9	dBm
Tower Top Jumper Cable Loss	0.5	dB
BS Antenna Gain	17.5	dBi
System Gain	**156.1**	**dB**

6.4 Performance Gain of Four Receivers

The performance gain of four branch receive diversity compared to two branch receive diversity was researched extensively by the WiMAX team [3]. Since LTE uses similar technology one can expect similar performance gains with LTE, however, to be sure, and to quantify the exact gains this is recommended for further analysis.

This issue of the document contains only WiMAX results for four branch receive gains.

6.4.1 Antenna Configurations

With four receivers, four separate antennas are required, typically this could be done with two cross-pol antennas, horizontally separated by several wavelengths. The gain of four branch varies with the amount of separation between the antenna and the amount multipath angle spread, the two together form different correlations.

6.4.2 Correlations

The correlations between the four antennas are defined by a 4x4 matrix as shown in Figure 12 - . The correlation values are calculated based on the element (antenna) spacing and the multi-path angle spread (which varies with environment) and are shown in Table 10 - (p.33)

Figure 12 - Antenna Correlation Definition and Analysis

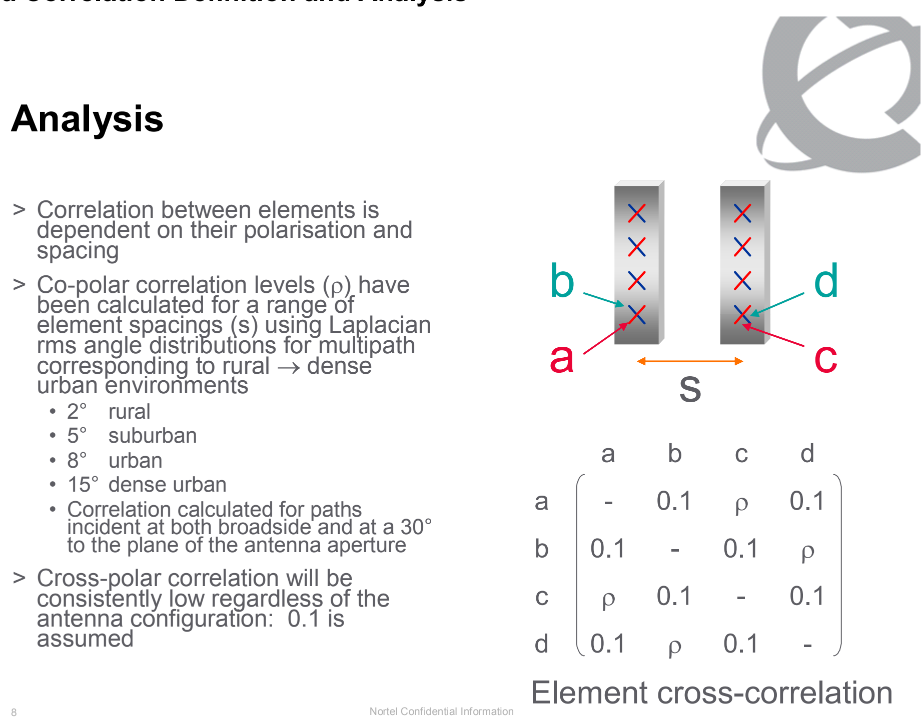


Table 10 - Antenna Correlations vs. Spacing and Environment

		Correlation for co-polar elements vs element spacing (wavelengths)										
Half-power beamwidth of Laplacian	Angle from broadside of Laplacian peak	0.5	0.7	1	1.5	2	2.5	3	3.5	4	6	10
2°	0°	0.994		0.977	0.949	0.912	0.869	0.822	0.773	0.722	0.536	0.295
Rural	30°	0.996		0.982	0.961	0.933	0.899	0.861	0.819	0.776	0.606	0.357
5°	0°	0.964	0.932	0.87	0.748	0.625	0.516	0.425	0.352	0.293	0.156	0.062
Suburban	30°	0.973	0.948	0.9	0.799	0.691	0.588	0.497	0.42	0.356	0.197	0.081
8°	0°	0.915	0.844	0.725	0.536	0.393	0.293	0.223	0.174	0.139	0.067	0.025
Urban	30°	0.935	0.879	0.78	0.61	0.465	0.356	0.277	0.219	0.177	0.087	0.033
15°	0°	0.759	0.606	0.421	0.245	0.154	0.105	0.075	0.056	0.044	0.02	0.008
Dense-Urban	30°	0.812	0.685	0.507	0.295	0.191	0.139	0.098	0.069	0.058	0.028	0.012

6.4.3 Performance

The performance gains of four branch receive diversity compared to two branch receive diversity are quantified in Table 11 - (p.33) for both QPSK 1/2 and QPSK 1/2 with repetition coding of two, for BLER of 0.1%, 1% and 10% for a variety of antenna correlations (as defined above). From this we can see that even with 100% correlation there is over 2 dB of gain, this attributed to a 3 dB power gain minus increased channel estimation loss at low SNR. As the correlation decreases (antennas either spaced further apart or increased multi-path angle spread or both), the diversity gain increases to an upper limit of about 4 dB. For reasonable antenna separations and multipath angle spread one can reasonably expect 3 dB of gain due to four branch receive diversity.

Table 11 - Uplink 4br Diversity Gains (WiMAX)

Gain (dB) of 1x4 cf. 1x2 (QPSK ½ rate)						
	Correlation					
BLER	0.1	0.3	0.5	0.7	0.9	1
10%	3.4	3.3	3.3	3.2	2.7	2.3
1%	3.8	3.7	3.6	3.3	2.7	2.1
0.10%	4.2	4	4.1	3.6	2.9	2.1

Gain (dB) of 1x4 cf. 1x2 (QPSK ½ rate repetition 2)						
	Correlation					
BLER	0.1	0.3	0.5	0.7	0.9	1
10%	3	3	2.8	2.5	2.3	2.1
1%	3.5	3.5	3.3	2.9	2.5	2.2
0.10%	4.1	4	3.7	3.2	2.8	2.4

6.5 Antennas

There are many suppliers of traditional cellular antennas covering many frequency bands. This section highlights some of the key specifications of interest for the radio planners and link budgets.

Antennas are passive and reciprocal (transmit and receive operational performance is identical - assuming the same frequency of operation). Antennas have gain, gain is referred to an isotropic radiator and in dB is represented as dBi. The larger the antenna the more directive it is, or the more gain it has. Gain is referred to the peak gain of the antenna. An antenna with 0 dBi gain compared to an antenna with 10 dBi gain with the same input power, radiate the same amount of total energy or power, however the 10 dBi antenna focusses the energy more in a specific direction, the peak gain in this direction is 10 dB higher than the 0 dBi antenna. And hence the received signal strength of a mobile in the direction of the peak gain is 10 dB more than that received by a 0 dBi antenna. To take into account the antenna gain the link budget uses a concept called EIRP (Effective Isotropic Radiated Power) usually measured in dBm. This is simply the power input into the antenna plus the antenna gain. The EIRP is then used to calculate the system gain, and hence the maximum allowable path loss.

Generally, the antenna gain is related to the size and frequency (wavelength) by the following equation.

$$\text{AntennaGain} = \frac{4\pi A_e}{\lambda^2}$$

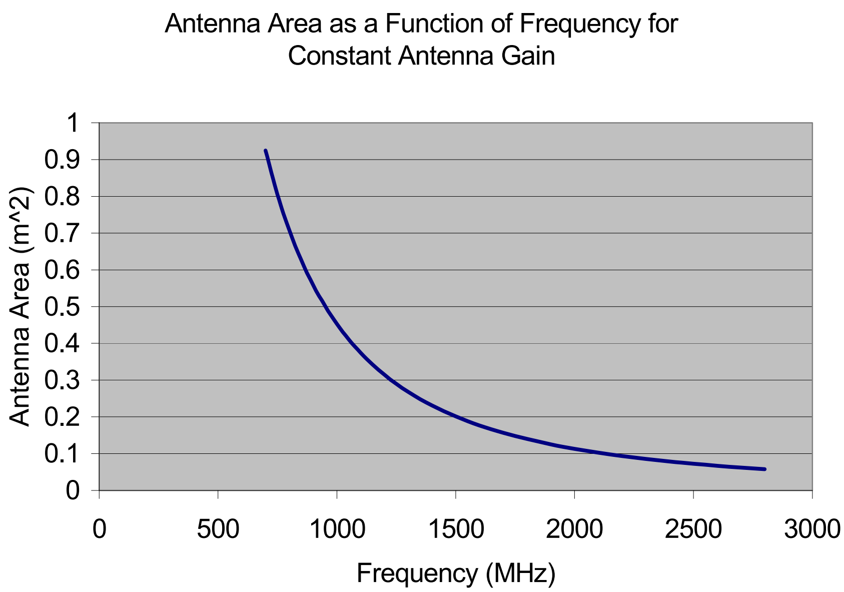
Where Ae represents the effective area, typically

$$A_e = \eta A$$

Where A is the physical area of the antenna and efficiency is between 20 and 70% depending on the internal losses and radiation efficiency.

From this it is easy to see that as frequency decreases, to maintain the same antenna gain, the area of the antenna increases. This is shown graphically below.

Figure 13 - Antenna Area vs. Frequency



6.5.1 Recommended Antenna Gain for LTE Link Budgets

Nortel has several approved antenna suppliers including; Kathrein, Andrew, Powerwave, RFS, CSS, Argus and XAHT. Several antenna types exist, in numerous frequency bands covering different azimuth beamwidths and different peak gains. Typically Nortel recommends deployment with 65 degree beamwidth[1] antennas, and depending on size constraints the gain will vary with frequency band of operation.

Below are some recommended antenna gains to be used in link budgets. These can be used to represent typical sector antenna gains at the respective frequencies. It may be the case however and certain RFI/ RFP responses dictate a specified antenna gain.

Table 12 - Recommended Antenna Gains for Link Budgets

Frequency (MHz)	Typical Antenna Gain (dBi)	Example Part No.
700-800	14 TBC	TBD
1700-2100	17.5	
2500-2700	18	

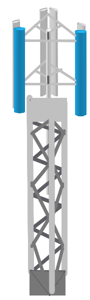
1.beamwidth is defined as the -3 dB power beamwidth.

6.6 SDMA

Figure 14 - The SDMA Antenna

- The following are some recommended antenna configurations for LTE deployments
  - Other configurations are possible, but are not covered in detail

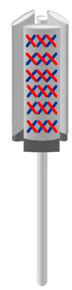
- Standard X-Pol or Dual X-Pol Antenna Deployment
  - LTE deployed using standard X-Pol (2x2 MIMO) and/or dual X-Pole (4x2 MIMO) antennas
  - Depending on frequency band for LTE deployment, existing antennas and feeders may be re-used
  - Supports 2x2 MIMO and 4x2 MIMO deployments
  - Shared 2G/3G/LTE requires broadband/multi-band antennas and combiners
  - Capacity growth and scalability for high capacity sectors
    - Upgrade to dual X-pole



Standard X-Pol

- **Conventional single and/or dual X-Pol antennas**

- Dual Beam Panel Antenna Deployment
  - LTE deployed using dual-beam antenna
  - Provides higher capacity solution relative to dual X-Pol with same eNB equipment and feeder cables
  - Lower sail area compared to dual X-Pol
  - Single radome per sector, no space diverse requirement
  - Supports 2x2 MIMO and 4x2 (dual 2x2) MIMO dual beam deployments



Dual-Beam Antenna Panel

- **Single radome per sector**
- **Dual beam, dual polarization**
- **Option for combined dual beam pattern – this configuration provides improved performance vs a standard X-Pol**

The SDMA concept is shown in the lower part of Figure 14 - above - and labelled “Dual-Beam Antenna Panel”. Each beam of the SDMA panel is narrower than a typical tri-sectored antenna, with a beamwidth of approximately 38 degrees. The narrower beam increases the gain of the antenna by approximately 2 dB compared to a conventional antenna with the same height. Hence for link budget purposes, the SDMA concept can be modelled as an antenna with gain 2 dB greater than a typical antenna for the frequency band of interest.

The increased size of the SDMA antenna may make widescale deployment in lower frequency bands (e.g. 700 MHz) unlikely, however at the higher frequencies (e.g. >2GHz) where operators may be interested in capacity overlays and not simply broad coverage, the SDMA antenna is relatively compact.

Generally the feedback from operators is that the SDMA solution will be deployed in “hot spot” cells or sectors.

7.0 Required SNR

The link budgets are heavily dependent of the required SNR for the modulation and coding chosen. The required SNR varies with channel model, BLER and the number of HARQ transmissions, or alternatively application QoS. The SNRs are calculated via link level simulations. To date only a partial database of results exist, these have also been supplemented, in some cases, by measured results.

Downlink link level simulation results have been documented by LGE and placed in livelink here:

http://livelink-ott.ca.nortel.com/livelink/livelink.exe?func=ll&objId=31845238&objAction=browse&sort=name&viewType=1

Uplink link level simulation results have been documented by LG-NT and placed also in the livelink folder above.

HARQ results to-date are not known. But we can assume that when HARQ is present the residual BLER will improve considerably, thus the first transmission may have a high BLER, say around 20%. Hence until HARQ results are available we will use BLER of 20% for SNRs in the link budget.

The SNRs used in the link budget, at present, are;

Table 13 - DL and UL SNRs used in the Link Budget

DL SNRs at 20% BLER

	PedB 3km/hr		VehA 30km/hr		VehA 120km/hr	
	SIMO	SFBC	SIMO	SFBC	SIMO	SFBC
QPSK 1/3	1.4	-0.7	1.3	-0.2	1.3	-0.2

UL (1x2) SNRs at 20% BLER

	PedB 3km/hr	VehA 30km/hr	VehA 120km/hr
QPSK 1/3	2.8	3.0	2.7

8.0 MAC Overhead

8.1 MAC Overhead Per TTI

Every TTI has an associated MAC overhead. This is comprised of a 2 byte MAC header, a 2 byte RLC and a 2 byte PHY CRC. Every packet has a 2 byte PDCP. Note that the sizes quoted above are nominal and may vary slightly.

Since allocation of the frame resource is in RBs, depending on the MCS selection, the number of bytes transmitted per TTI varies according to the number of RBs and the MCS selected. For a given size packet it is possible to calculate how many TTI intervals are required to transmit the packet, from this we can then calculate the MAC overhead.

This calculation has been put into a spreadsheet format as shown in Table 14 - (p.38) below.

Table 14 - MAC Overhead Analysis Spreadsheet Example

MAC Overhead Analysis		
	Downlink	Uplink
Packet size (B)	**40**	**40**
Modulation and Coding	**QPSK 1/3**	**QPSK 1/3**
Modulation Efficiency	0.67	0.67
Channel Bandwidth (MHz)	**10**	
Number of SRBs Allocated	**2**	**2**
Overhead per TTI		
MAC (B)	2	2
RLC (B)	2	2
PHY (CRC) (B)	3	3
Overhead per Packet		
PDCP (B)	2	2
Analysis		
Bytes per TTI	**22**	**24**
Number of TTIs required	**3**	**3**
Overhead	**65%**	**80%**
MAC throughput (kbps)	**106.7**	**106.7**
PHY throughput (kbps)	**176.0**	**192.0**

The MAC overhead spreadsheet calculator can be found within the link budget spreadsheet at:

http://livelink-ott.ca.nortel.com/livelink/livelink.exe?func=ll&objId=31044339&objAction=browse&sort=name&viewType=1

The impact of the MAC overhead is most significant on the uplink link budget, because to maximize uplink, few RBs are required, with one RB (desirable for link budget maximum power per tone), little information can be sent because the data carrying REs are mostly carrying MAC overhead information, dimensioning with one RB is hence very inefficient. Hence it is recommended that the minimum number of RBs allocated for link budget calculations is two (with QPSK 1/3).

The inefficient MAC with small RB allocations is particularly problematic for VoIP, the standards groups have been working to solve this with “TTI bundling”, essentially combining multiple consecutive sub-frames so that the MAC overhead is shared over multiple sub frames and is therefore more efficient.

8.2 TTI Bundling for VoIP

To maximize the coverage of low bit rate services such as VoIP, the MAC overhead per TTI needs to be lowered such that sufficient data can be transmitted using only one RB on the uplink. A method of reducing the MAC overhead per TTI is to bundle several consecutive TTI intervals together, and assign the MAC overhead per TTI bundle, hence the MAC overhead per TTI interval is reduced, allowing more data per RB to be transmitted. This method has been proposed and accepted in the LTE standards group as a method of extending the coverage of VoIP.

HARQ with TTI is slightly different than without TTI bundling, in that the repeat transmit time is extened from 8ms to 16ms, this effectively limits the number of re-transmissions for VoIP applications, because of the sensitivity of this application to latency. Below is a graph showing conservative 1 re-transmission SNR requirements.

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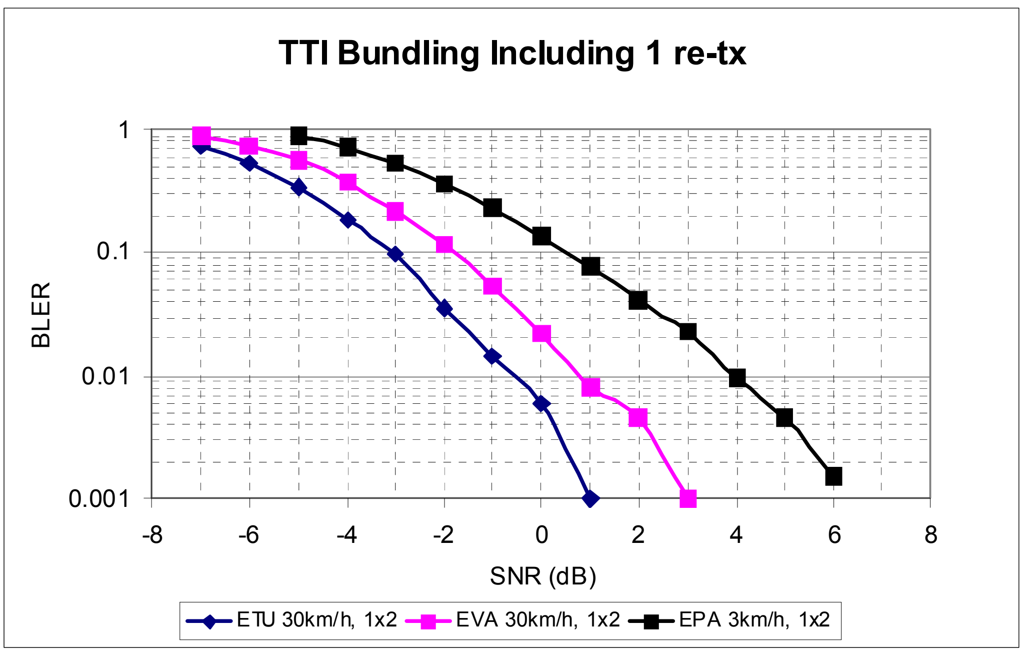


Figure 15 - TTI Bundling SNR Requirements

Other analysis has also been done to improve the SNR requirements for VoIP - to enable better competitive analysis against existing standards. For example the inclusion of frequency hopping as well as increased latency (more HARQ transmissions) was investigated, as shown in the figure below.

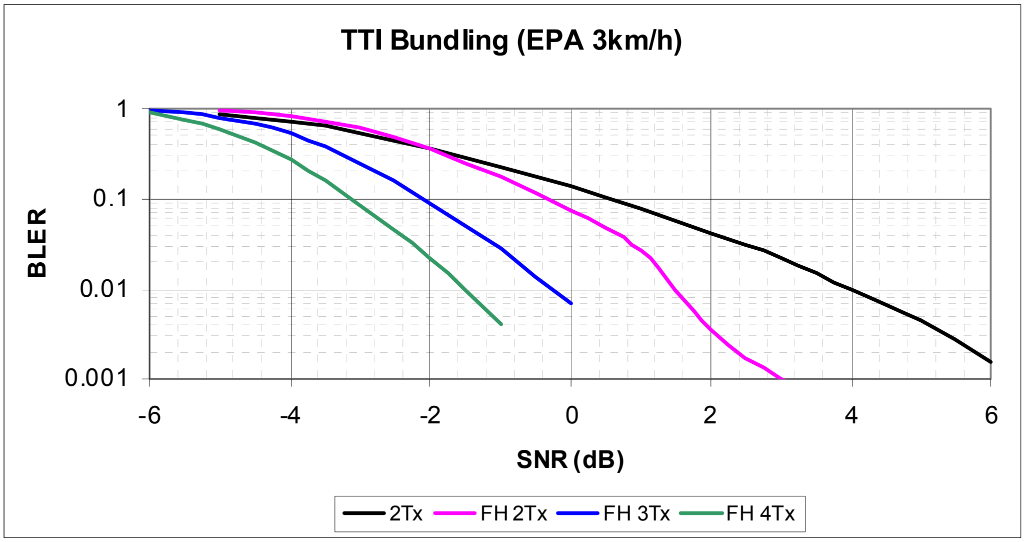


Figure 16 - TTI Bundling and Frequency Hopping (FH) with HARQ Re-transmissions

Hence either frequency hopping or increased over-the-air delay budget or a combination thereof can reduce the required SNR for TTI enabling VoIP applications to have greater coverage. A combination of techniques may be required to ensure LTE can be overlaid over existing technologies without comprising the coverage. A simple explanation for this is that the smallest allocation for LTE uplink - one RB - is effectively a 88 kbps PHY data rate, which is significantly higher (~10dB) than the vocoder requirements of existing 2G networks.

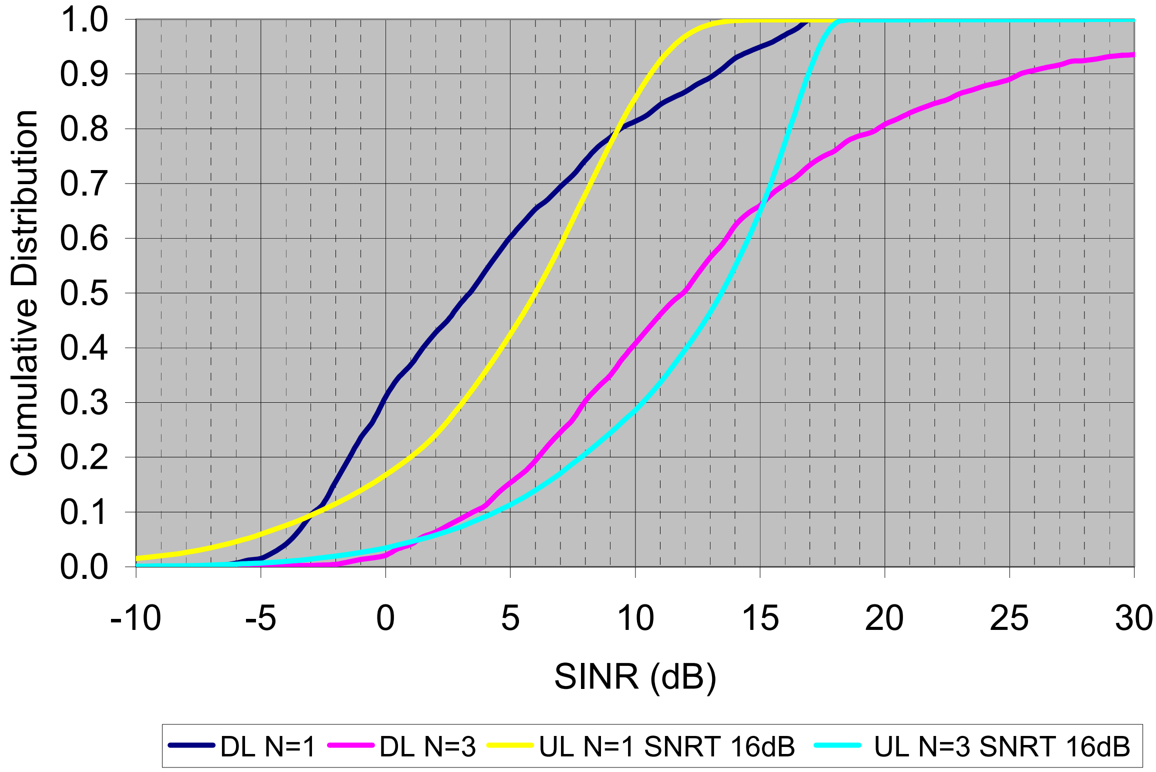
9.0 Interference

9.1 Introduction

In a fully deployed and loaded network the system becomes interference limited, hence SNR alone is not sufficient to define the coverage. The addition of co-channel interference effectively increases the thermal noise floor of the system, reducing the coverage for a given MCS. The effect of co-channel interference can be found by performing network level simulations. One such case can be done using fully loaded equally spaced cells in several surrounding tiers. The SNIR is calculated for each UE in both the DL and UL, for many thousands of random locations and shadowing, from this a cumulative distribution function of the SNIR is obtained. This can be done for different frequency re-use patterns, for example N=1 and FFR 3. The results of such a simulation are shown below.

In Figure 17 - SNRT refers to the target SNR on the UL. The UEs are power controlled and the BS asks the UEs to transmit with a power to try a hit the BS receivers with an SNR of 16 dB. The UEs however have limited power capability and in most cases cannot be received at the BS with a SNIR of 16 dB.

Figure 17 - DL and UL SNIR CDF (Fully Loaded)



9.2 Interference Margin Analysis

The required interference margin, and the derivation thereof have been studied, these have been documented in a powerpoint presentation and excel spreadsheet and are available on livelink at:

http://livelink-ott.ca.nortel.com/livelink/livelink.exe?func=ll&objId=36451316&objAction=browse&sort=name&viewType=1

For the completeness of this document the interference margin derivation and some examples will follow.

In a system without interference, i.e. a single cell, the SNR equals the SNIR, and the required SNR is given by the link level simulation for the channel model, antenna configuration, MCS and MIMO mode of choice at a specified BLER for the application of interest. This is shown diagrammatically in the figure below on the left.

In a system with interference (here we deal with in-band, co-channel interference from LTE UEs or eNBs), the required SNIR must still be met (the requirement derived from link level simulations), but we note that the interference, assumed white, adds to the noise, on a power basis raising the noise floor i.e. N+I. The SNR is the ratio of the required signal power to the thermal noise power (or noise floor), and the required signal power, in the presence of interference is higher to ensure SNIR is met. This is shown diagrammatically below on the right.

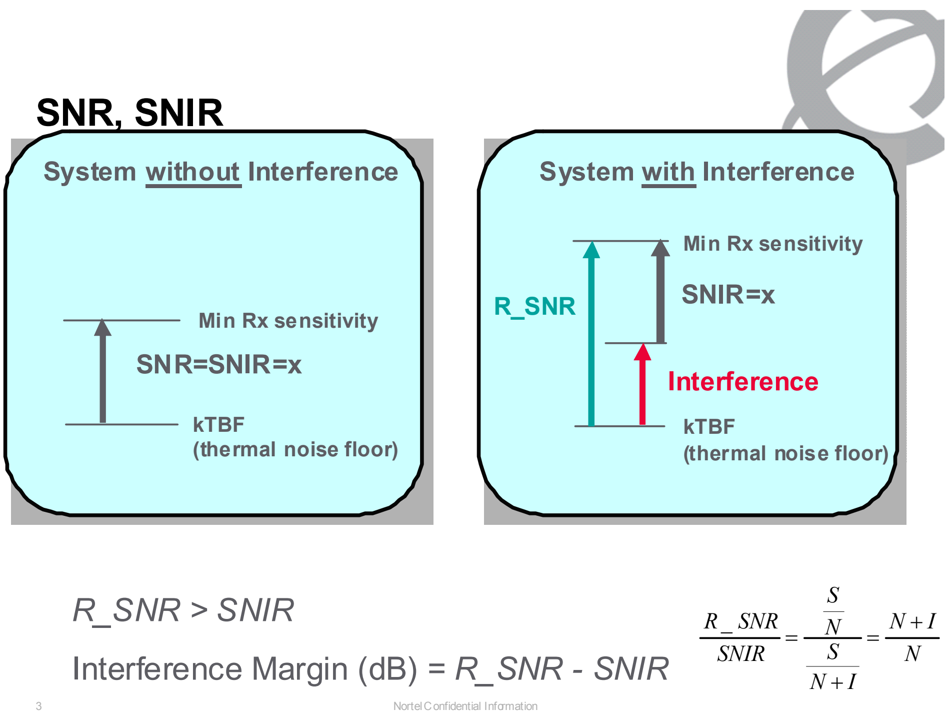


Figure 18 - SNR and SNIR

We note that ideally we would like to perform a simple spreadsheet style link budget calculation, i.e. SNR based and somehow account for the interference. The problem is that the interference is more statistical in nature, coming from many sources and varying with loading. On the downlink the interfering sources are known - they are the neighbouring co-channel cells (or sectors) and we assume that all eNBs tansmit at the same (full) power level. For the uplink, the interfering sources are UEs which by their very nature are scattered randomly throughout the cell, furthermore the UEs are power controlled, with open and closed loop power control schemes (which are still under study). We note the relationships between SNR, SNIR and SIR as follows,

$$\mathrm{SNIR} = \frac{\mathrm{S}}{\mathrm{N}+\mathrm{I}} \qquad \mathrm{SNIR}^{-1} = \frac{\mathrm{N}}{\mathrm{S}} + \frac{\mathrm{I}}{\mathrm{S}} = \mathrm{SNR}^{-1} + \mathrm{SIR}^{-1}$$

$$\mathrm{SNR} = (\mathrm{SNIR}^{-1} - \mathrm{SIR}^{-1})^{-1}$$

And hence if the SNIR is known (a requirement from link level simulations) and the SIR is also known (from a simulation) then the SNR can be calculated. The interference margin is then the difference (in dBs) between the SNR and the SNIR (the difference in required signal power between a system without interference and a system with interference). We can also note that this is also equivalent to the noise rise due to interference. The reason for analysiing in terms of a ratio rather than absolute powers, is that the ratio scales with transmit power, cell spacing etc. whereas absolute powers have to be tracked very carefully.

Downlink and uplink simulations were performed as a function of loading. Loading was swept from 10% to 100% in 10% increments. The definition of loading used in the simulation was as follows; loading is chance than an RB in an adjacent cell was also being used. Briefly the assumptions behind the simulations are given below.

Generic simulation assumptions

- Antenna pattern defined by 3GPP, 70 deg beamwidth and 20dB front-to-back ratio
- No elevation pattern used, i.e. no downtilt
- 700 MHz and outdoor shadowing sigma of 6.8 dB
- Correlated shadowing (0.5) between bases, and 1.0 between sectors
- UE attaches to strongest server eNB
- 19 eNBs, each with 3 sectors, total 57 sectors, regularly spaced
- SIR calculated per UE, collect stats to produce cdf of SIR
- Loading performed as activity factor per RB, per eNB
- N=1 and N=1/3 re-use

Simulation assumptions specific to Downlink

- UEs randomly located within central sector

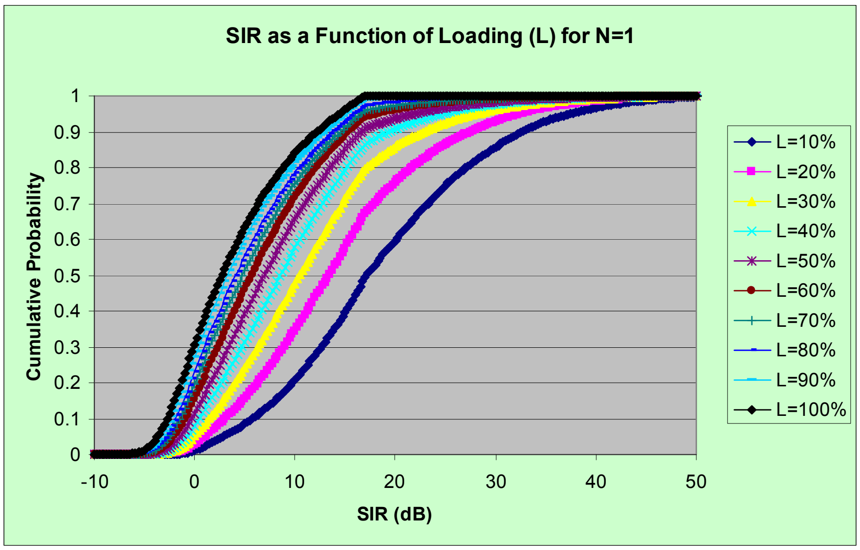
Simulation assumptions specific to Uplink

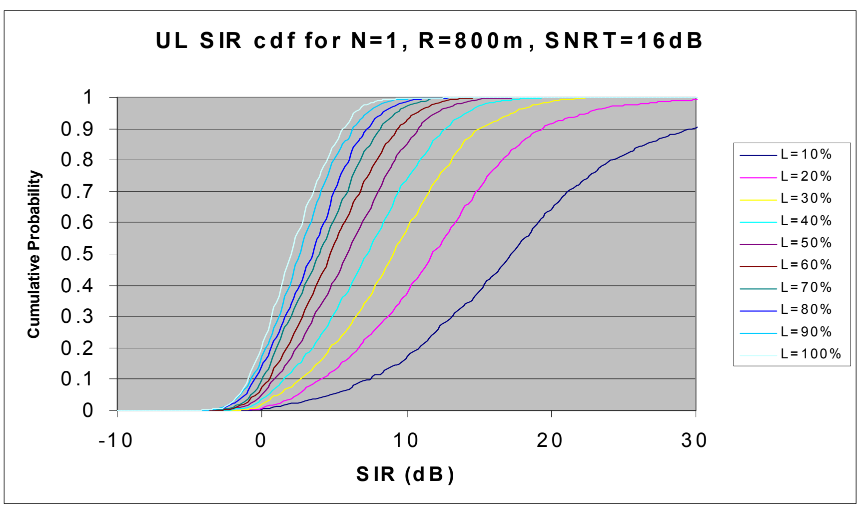
- UEs randomly located within each sector, all sectors used to generate UL interference
- UE is power controlled using SNR target

The Matlab code for the simulations can be found here:

http://livelink-ott.ca.nortel.com/livelink/livelink.exe?func=ll&objId=36454060&objAction=browse&sort=name&viewType=1

The simulations produced curves for SIR cdf (cumulative distribution function). Shown below are DL and UL SIR distributions for N=1.





These were then used with a lookup facility in excel and coupled into a link budget style calculation, so that the interference margin can be calculated as a function of frequency re-use, loading and required SNIR at a given coverage reliability. Two examples are shown below of how the interference margin fits into the link budget.

LTE FDD Downlink		
BS Transmit		
PA Power	46	dBm
	40.0	W
MIMO Mode	SFBC	
EIRP per tone	38.0	dBm
UE Receive		
kTBF	-124.2	dBm
Channel Model	EPA 3km/h	
SIR @ 70% loading	6.5	dB
SNR to meet coverage reliability of 90%	-2.48	dB
Required SNIR	**-3.0**	dB
Rx Sensitivity	-127.2	dBm
UE Antenna Gain	0.0	dBi
System Gain	165.3	dB

Loading	70%	
Frequency	700MHz	
Coverage Reliability	90%	
Frequency Re-use	FFR N=1/3	
Shadow Margin (90%, outdoor, 700 MHz))	**2.6**	dB
Building Loss	**0**	dB
Interference Margin	0.5	dB
MAPL	162.1	dB

LTE FDD Uplink		
UE Transmit		
UE Tx Power	23.0	dBm
Total EIRP	23.0	dBm
EIRP per tone	12.2	dBm
BS Receive		
kTBF	-129.7	dBm
Channel Model	EPA 3km/h	
SIR @ 70% loading	7.3	dB
SNR to meet coverage reliability of 90%	0.3	dB
SNIR	**-0.5**	dB
Rx Sensitivity	-130.2	dBm
System Gain	154.4	dB

Loading	70%	
Frequency	700MHz	
Coverage Reliability	90%	
Frequency Re-use	N=1/3	
Shadow Margin (90%, outdoor, 700 MHz)	**2.6**	dB
Building Loss	**0**	dB
Interference Margin	**0.80**	dB
MAPL	151.0	dB

There are few cautionary notes and concluding remarks from the presentation that are worth repeating here;

- The SIR curve represents the upper bound, SNIR will always be less than SIR, no amount of Tx power can make the SNIR greater than SIR
- If the SIR at the desired coverage reliability is less than that required for a given MCS, then the criteria are not met, something must be changed, either,
    - reduce the coverage reliability
    - decrease the loading
    - reduce the MCS
    - relax frequency re-use (N=1/3 or FFR)
    - or a combination of the above
- Results presented are dependent on numerous assumptions, but allow us to understand the mechanisms and trade-offs involved
- The analysis presented is from a link budget and coverage perspective, capacity of the system also needs to be considered, generally systems that are interference limited rather than noise limited have higher capacity

- The simulations are somewhat simplified, in that they only consider ‘geometry’, i.e. frequency selective fading is not considered, traffic is not modeled, scheduler is not modeled and interference is assumed to be white

Nortel is also actively investigating advanced algorithms to improve the coverage of an N=1 system, for example Tiered FRR or Adaptive FFR. Tiered FFR was also simulated and is contained in the spreadsheet, however the results for Tiered FFR need more review before a decision is made to include this in our POR.

What we can do in the interim however is describe an area where we think the operation of Tiered or Adaptive FFR will lie, as depicted below.

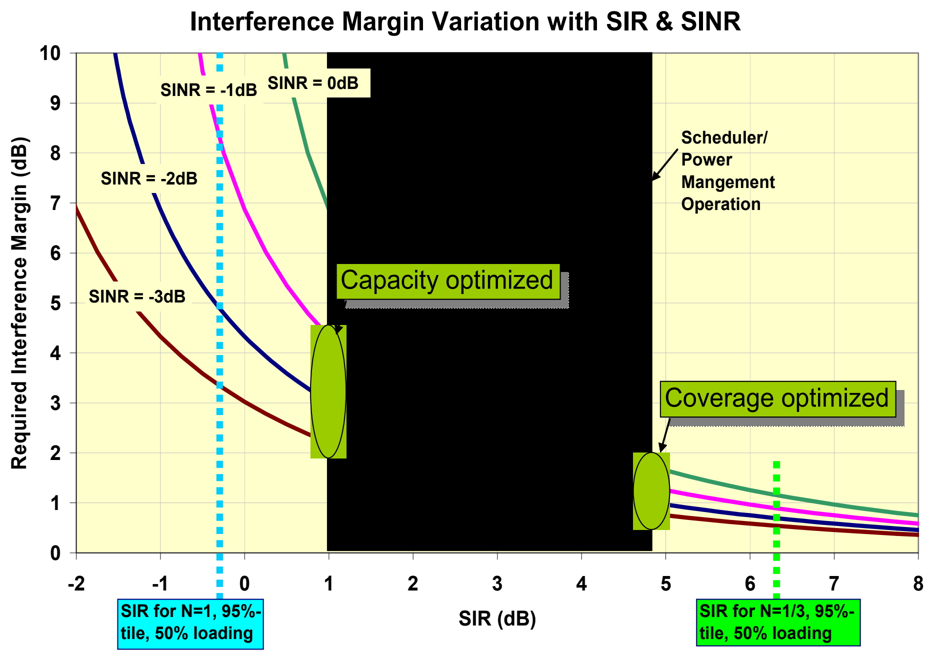


Figure 19 - Where Tiered or Adaptive FFR would lie

9.3 Interference From Neighbouring Services - 700MHz Band

The analysis presented in this section is based (or directly copied) from Reid Chang’s work for an AT&T presentation on the 9th October 2008. Reid’s interference analysis has been uploaded to livelink and can be found here:

http://livelink-ott.ca.nortel.com/livelink/livelink.exe?func=ll&objId=36455314&objAction=browse&sort=name&viewType=1

For completeness of this document - aim is to have all relevant R&D link budget related work contained herein - the analysis that Reid conducted will be presented herein.

The first problem is the lower part of the 700MHz band as shown in the diagram below. There is a strong transmitter (digital TV) adjacent to channel A and also the MediaFlo transmitter located in channel D. Both these transmitters are problematic to channels A, B and C - eNB Rx band.

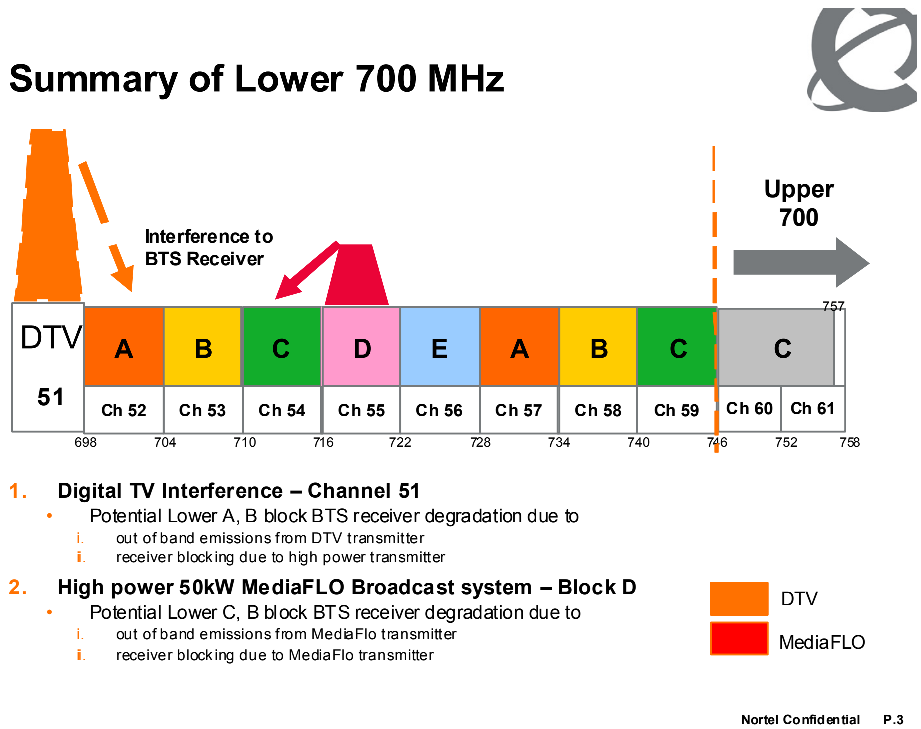


Figure 20 - Lower 700 MHz Spectrum

Digital TV broadcasts in channel 51 with very high EIRP. This can cause eNB receive blocking due to high power in adjacent channel, and also the out-of-band emissions of the DTV transmitter will fall in band of LTE Channel A, B and C. The receiver blocking can be mitigated by strong filtering at the eNB and careful deployment, i.e. proximity of eNB w.r.t. to DTV transmitters and pointing angle of antennas - these can be used to increase the path loss between the DTV and the eNB. Out-of-band emissions can only be tackled by a DTV Tx filter and/or careful site placement. What follows is a technical analysis of the requirements for filtering and isolation (path loss).

Consideration #1 - LTE Channel bandwidths

Channels A, B and C are each 6 MHz wide. The channel bandwidths of LTE (of interest) are 5 MHz and 10 MHz, each having 300 and 600 OFDMA tones of 180 kHz width. Hence the occupied bandwidths are a little less than the nominal channel bandwidths. Thus it may be possible to off-center the channels within the spectrum to increase the guard band (transition bandwidth) to ease the filter design.

not complete

10.0 Other Channels

[Editor note: this section needs to reference other work on the control channels and be consistent with it, work is not complete yet]

The control channels have been analyzed by Kevin Luo and are documented in the L2 SA :

http://livelink-ott.ca.nortel.com/livelink/livelink.exe?func=ll&objId=32914027&objAction=browse&sort=name&viewType=1

The link budget requirements have summarized and put into a spreadsheet on livelink at:

http://livelink-ott.ca.nortel.com/livelink/livelink.exe?func=ll&objId=33229050&objAction=browse&sort=name&viewType=1

Further the Airlink SA has documented the link budget requirements in the above location for different radio configurations and all channels, a sample is shown below.

LTE FDD Downlink							
BS Transmit							
	PDSCH EoC	PDSCH Core	PDCCH (F0, F1)	PBCH	PCFICH	PHICH	
PA Power	46	46	46	46	46	46	dBm
	40	**40**	**40**	**40**	**40**	**40**	W
MIMO Mode	SFBC	SFBC	SFBC	SFBC	SFBC	SFBC	
Number of PAs	2	2	2	2	2	2	
Tiered FFR Boosting	4	4					
Total PA Power (effective)	46.5	45.5	49	49	49	49	dBm
Channel Bandwidth	10	10	10	10	10	10	MHz
Number of carriers (simultaneous)	200	400	600	600	600	600	
Number of RBs	8	5	5	5	5	5	
Modulation	QPSK 1/3	QPSK 1/2	QPSK 1/3	QPSK	QPSK 1/16	BPSK	
Aggregation level			8				
Modulation Efficiency	0.67	1.00					bits/tone
PHY Data rate (kbps) 0 BLER	704	660					kbps
Power per tone	23.5	19.5	21.2	21.2	21.2	21.2	dBm
eNB Antenna Gain	**14.0**	**14.0**	**14.0**	**14.0**	**14.0**	**14.0**	dBi
eNB Jumper Cable Loss	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	dB
Cable Loss	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	dB
Tower Top Jumper Cable Loss	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	dB
Total EIRP	58.7	57.7	61.2	61.2	61.2	61.2	dBm
Combined Tiered FFR EIRP	61.2						
EIRP per tone	35.7	31.7	33.4	33.4	33.4	33.4	dBm
UE Receive							
kT	-174	-174	-174	-174	-174	-174	dBm/Hz
subcarrier bandwidth	15	15	15	15	15	15	kHz
kTB	-132.2	-132.2	-132.2	-132.2	-132.2	-132.2	dBm
UE Noise Figure	**8.0**	**8.0**	**8.0**	**8.0**	**8.0**	**8.0**	dB
kTBF	-124.2	-124.2	-124.2	-124.2	-124.2	-124.2	dBm
Channel Model	EPA 3km/h	EPA 3km/h	EPA 3km/h	EPA 3km/h	EPA 3km/h	EPA 3km/h	
BLER after 1st Tx	10%	10%	3%	1%	1%		
Residual BLER after 2 Tx	0.18%	0.18%					
Required SNR*	**5.3**	7.0	-5.4	-10.0	-6.2	-10.0	dB
Rx Sensitivity	-118.9	-117.2	-129.6	-134.2	-130.4	-134.2	dBm
UE Antenna Gain	**-3.0**	**-3.0**	**-3.0**	**-3.0**	**-3.0**	**-3.0**	dBi
System Gain	**151.6**	**145.9**	**160.1**	**164.7**	**160.9**	**164.7**	**dB**

Table 15 - Link Budget for PDSCH and Downlink Control Channels

LTE FDD Uplink										
UE Transmit										
	PUSCH	PUSCH	PUSCH	PUCCH (20, A)	PUCCH (1a, S)	SRS (WB)	SRS (MB)	SRS (NB)	PRACH	
UE Tx Power	**23**	**23**	**23**	**23**	**23**	**23**	**23**	**23**	**23**	dBm
	200	200	200	200	200	200	200	200	200	mW
Number of RBs	4	2	**3**	1	1	40	20	4	6	
Number of carriers	48	24	36	12	12	240	120	24	72	
Modulation	QPSK 1/12	QPSK 1/3	QPSK 1/3	QPSK	BPSK				OOK	
Modulation Efficiency	0.17	0.67	0.67							bits/tone
PHY Data rate (kbps) (no SRS, 0 BLER)	96	192	288							kbps
Power per tone	6.2	9.2	7.4	12.2	12.2	-0.8	2.2	9.2	4.4	dBm
UE Antenna Gain	**-3.0**	**-3.0**	**-3.0**	**-3.0**	**-3.0**	**-3.0**	**-3.0**	**-3.0**	**-3.0**	dBi
Total EIRP	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	dBm
EIRP per tone	3.2	6.2	4.4	9.2	9.2	-3.8	-0.8	6.2	1.4	dBm
BS Receive										
kT	-174	-174	-174	-174	-174	-174	-174	-174	-174	dBm/Hz
subcarrier bandwidth	15	15	15	15	15	15	15	15	15	kHz
kTB	-132.2	-132.2	-132.2	-132.2	-132.2	-132.2	-132.2	-132.2	-132.2	dBm
eNB Noise Figure	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	dB
kTBF	-129.7	-129.7	-129.7	-129.7	-129.7	-129.7	-129.7	-129.7	-129.7	dBm
Rx Architecture	1x2	1x2	1x2	1x2	1x2	1x2	1x2	1x2	1x2	
Channel Model	EPA 3km/h	EPA 3km/h	EPA 3km/h	EPA 3km/h	EPA 3km/h	EPA 3km/h	EPA 3km/h	EPA 3km/h	EPA 3km/h	
BLER after 1st Tx			10%	1%	0.1%	1%	1%	1%	1%	
Residual BLER after 2 Tx			0.5%							
Residual BLER after 4 Tx	1.0%	1.0%								
Required SNR*	-2.8	1.4	**6.6**	-6.4	-8.0	-6.0	-2.5	5.0	-8.5	dB
Rx Sensitivity	-132.5	-128.3	-123.1	-136.1	-137.7	-135.7	-132.2	-124.7	-138.2	dBm
Cable Loss	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	dB
Tower Top Jumper Cable Loss	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	dB
eNB Antenna Gain	**14.0**	**14.0**	**14.0**	**14.0**	**14.0**	**14.0**	**14.0**	**14.0**	**14.0**	dBi
eNB Jumper Cable Loss	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	dB
System Gain	**147.9**	**146.7**	**139.8**	**157.5**	**159.1**	**144.1**	**143.6**	**143.1**	**151.9**	**dB**

Table 16 - Link Budgets for PUSCH and Uplink Control Channels

11.0 MCS Selection

Discuss MCS switch points, measurements CQI, tracking of shadowing etc.

To be completed in a later version.

12.0 Applications

Analyse different common applications, every message from start to finish, including management overhead control messages include timing diagrams etc. Analyse from link budget viewpoint.

To be completed in a later version.

13.0 Hand-off

Include a section on hand-off to ensure messages are consistent with link budget.

To be completed in a later version.

14.0 GSM Overlay

LTE is an evolution from GSM and UMTS and as such many operators will be either upgrading to LTE or operating both GSM and LTE side-by-side. In such a case operators want to re-use as much of the existing infrastructure as possible, to enable this, the LTE link budget needs to be at least as good as GSM. GSM is a mature network, with many more sites deployed than are actually required for coverage. The additional sites are mainly required for increased capacity (cell splitting) and indoor penetration. Hence the site spacings for GSM cell sites are generally considerably smaller than is required from a link budget perspective. Clearly, putting LTE on each GSM site, day one, would be cost prohibitive, so GSM operators are probably going to want to understand how many of their sites need LTE, and how many they can leave alone until capacity of LTE picks up.

GSM has many classes of mobiles, some of which have relatively high transmit powers, certainly a lot more than is currently envisioned for LTE. This is mostly due to GSM's GMSK modulation which is a constant envelope modulation and does not require PAPR back-off like SC-OFDMA of LTE.

An LTE/GSM overlay analysis and comparison of link budgets has been done and may be found here:

http://livelink-ott.ca.nortel.com/livelink/livelink.exe?func=ll&objId=31044344&objAction=browse&sort=name&viewType=1

The analysis includes what DL PA power is required for LTE for it to have a comparable DL link budget to GSM. It also compares two and four branch uplink diversity for LTE and concludes that for LTE to match the coverage of GSM, with reasonable data rates (two RBs) four branch receive is required at least, and preferably with mast head electronics too. This is primariliy due to the GSM mobile high transmit power used in the analysis.

For EDGE (data over GSM), an edge of cell data rate is approximately 60 kbps, this requires several timeslots, but does not impact the link budget. Hence LTE, with higher data rates, requires advanced receiver architectures to enable a cost effective deployment.

15.0 CDMA/1xEV-DO Overlay

A 1xRTT and EV-DO Release A overlay analysis was completed for a Verizon presentation. The contents of which can be found here:

http://livelink-ott.ca.nortel.com/livelink/livelink.exe?func=ll&objId=31893700&objAction=browse&sort=name&viewType=1

The overlay analysis was done in the respective frequency bands of the technologies, and since LTE is planned for deployment at 700 MHz, LTE benefits from the propagation at the lower frequency band. If LTE is required to provide a reasonable uplink data rate, using two RBs or more, then an improved uplink link budget is required. Options for improving the uplink budget include RRH or four branch rx, or TTLNA or a combination thereof. The RRH at 700 MHz is probably too large and heavy (comments from Verizon) for serious consideration. A TTLNA with cable reduction to allow four branch receive with only two RF cables may be a viable option for improving the uplink link budget enabling reasonable data rates with ranges approaching those of existing deployments.

16.0 Other

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17.0 References

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