White Paper

Coverage Analysis of LTE-M Category-M1

Contributing and Supporting Companies:

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Executive Summary

LTE-M provides low-cost LTE devices suitable for massive Machine-Type Communications (MTC) and the Internet of Things (IoT) with substantially enhanced coverage compared to normal LTE devices. 3GPP has only published LTE-M coverage targets and since coverage is a key pillar to all LPWA technologies, it is very important to understand how much coverage LTE-M can actually provide. To this end, the group of supporting companies listed on the title page conducted a thorough link layer simulation analysis to evaluate the actual coverage performance of 3GPP's LPWA LTE-M technology.

The key finding is that LTE-M can realistically support a coverage gain of 21 dB relative to legacy LTE devices, which exceeds the 18 dB 3GPP target. This 21 dB gain corresponds to a data rate of 1400 bps in downlink and 250 bps in uplink. For IoT applications that can tolerate lower data speeds and longer acquisition times, a gain of beyond 21 dB can be supported. Also important to note is that these results are achieved without using eNB power spectral density (PSD) boosting.

The analysis shows that the 155.7 dB maximum coupling loss (MCL) targeted by 3GPP was assuming a 20 dBm UE power class with conservative noise figures from 3GPP TR 36.888. This 155.7 dB MCL target translates to a 160.7 dB MCL by assuming a 23 dBm UE power class and the less conservative noise figures used in the Celluar IoT study on EC-GSM-IoT and NB-IoT documented in 3GPP TR 45.820. The key finding is that using these assumptions with 21 dB gain, LTE-M can support 164 dB MCL.

This analysis shows that LTE-M supports a very similar coverage gain compared to other LPWA technologies and thus confirms LTE-M to be a very versatile LPWA technology. For IoT applications requiring higher data rates, low latency, full mobility, and voice in typical coverage situations, LTE-M is the best LPWA technology choice. And for IoT applications requiring deep coverage where latency, mobility and data speed requirements are less stringent, LTE-M is a strong LPWA contender as well. Overall, this versatility allows LTE-M to support an extremely wide array of IoT applications which helps to increase volume and drive economies of scale.

KEY FINDING

LTE-M provides +21 dB of coverage gain at a data speed of 1400 bps DL and 250 bps UL exceeding 3GPP target of 18 dB.

KEY OBSERVATION

Assuming a 23 dBm UE and less conservative noise figures, LTE-M supports 164 dB MCL.

CONCLUSION

LTE-M is a versatile LPWA technology, supporting high data rates, full mobility, and voice in typical coverage and also supports deep coverage scenarios.

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FACT
3GPP has not assessed to what extent the maximum achievable coverage exceeds the 3GPP target.

FACT
Given that extended coverage is defined as a feature within the standards, this means any category UE can support the extended coverage feature.

1 Introduction and Scope

Release 13 LTE-M was specified during the 3GPP eMTC work item [1] which was completed in March 2016 and defined one new user equipment (UE) category – "Category-M1". Although coverage analyses were conducted during this work, 3GPP has not assessed to what extent the maximum achievable coverage exceeds the target that the normative specification provides. This white paper includes the results from such a coverage analysis. The analysis was supported through link level simulations (LLS) conducted by several of the supporting companies. The coverage performance is reported both in terms of Signal-to-Noise Ratio (SNR) and Maximum Coupling Loss (MCL).

Even though this analysis only considers the CAT-M1 UE, given that Coverage Enhancement Mode A and B are defined as features within the standards, any category UE can support the extended coverage feature. The uplink coverage performance is similar to CAT-M1 but given that most other LTE category UEs have two receive antennas (where CAT-M1 only has one), the downlink performance is 3-4 dB better than shown in this paper.

Before going into the LLS simulation results, the paper presents the foundation and assumptions used to calculate the MCL. Also to provide some technical background, several coverage techniques used in the LTE-M specification are described.

2 Abbreviations

3GPP	Third Generation Partnership Project	MAC	Media Access Control	RRC	Radio Resource Control
BLER	Block Error Rate	MCL	Maximum Coupling Loss	RV	Redundancy Version
CRC	Cyclic Redundancy Check	MIB	Master Information Block	RX	Receive
CRS	Cell-specific Reference Signals	MPDCCH	MTC Physical Downlink Control Channel	SCH	Synchronization Channel
dB	Decibel	MTC	Machine Type Communications	SF	Subframe (1 ms)
dBm	Power Ratio in decibels referenced to one milliwatt	NF	Noise Figure	SFN	System Frame Number
DL	Downlink (from eNB to UE)	PA	Power Amplifier	SNR	Signal to Noise Ratio
eMTC	Enhanced Machine-Type Communications	PBCH	Physical Broadcast Channel	SSS	Secondary Synchronization Signal
eNB	Enhanced Node B (LTE base station)	PDSCH	Physical Downlink Shared Channel	TBS	Transport Block Size
FDD	Frequency Division Duplex	PRACH	Physical Random Access Channel	TM	Transmission Mode
HARQ	Hybrid Automatic Repeat Request	PSS	Primary Synchronization Signal	TR	Technical Report
I/Q	In-phase and Quadrature	PUCCH	Physical Uplink Control Channel	TS	Technical Specification
LNA	Low Noise Amplifier	PUSCH	Physical Uplink Shared Channel	TX	Transmit
LLS	Link Layer Simulation	PRB	Physical Resource Block	UE	User Equipment
LPWA	Low Power Wide Area	PSD	Power Spectral Density	UL	Uplink (from UE to eNB)
LTE	Long Term Evolution	RLC	Radio Link Control	WID	Work Item Description

FACT

MCL is a very common measure to describe the amount of coverage a system can support.

FACT

Without coverage enhancement, LTE can normally operate to a maximum of approximately 142 dB MCL.

FACT

If a device is underground or deep inside a building, the in-building penetration loss can in total exceed 50 dB.

3 Maximum Coupling Loss (MCL)

MCL is a very common measure to describe the amount of coverage a system or design can support. It is the limiting value of the coupling loss at which a service can be delivered, and therefore defines the coverage of the service. Of course intuitively, it would be better to provide "km of coverage" but "km of coverage" is not an appropriate measure as it highly depends on the carrier frequency and the environment (e.g. indoor, outdoor, urban, sub-urban, and rural). Therefore, MCL is a better measure of the design as it is independent of frequency and environmental factors and thus MCL is used in this paper.

Without coverage enhancement, Legacy LTE systems (before Release 13) can operate up to approximately 142 dB MCL and in most cases for outdoor urban or sub-urban environments, the cellular network provides adequate signal strength to satisfy this MCL. However, indoor coverage is more difficult because in-building penetration loss can be very high. For example, if a device is underground or deep inside a building, the external wall penetration loss and in-building penetration loss can in total exceed 50 dB.

Table 1 below shows the inputs and calculations for MCL (from TR 36.888 [6]):

MCL INPUT	VALUE
Transmitter	
(0) Max Tx power (dBm)	PA power of UE or eNB
(1) Power in Channel Bandwidth (dBm)	Calculated
Receiver	
(2) Thermal noise density (dBm/Hz)	Constant -174 dBm/Hz
(3) Receiver noise figure (dB)	Depends on LNA
(5) Occupied channel bandwidth (Hz)	Bandwidth of signal
(6) Effective noise power = (2) + (3) + 10 log((5)) (dBm)	Calculated
(7) Required SNR (dB)	Value comes from link simulation
(8) Receiver sensitivity = (6) + (7) (dBm)	Calculated
(9) MCL = (1) - (8) (dB)	Calculated

Table 1: MCL Calculation

As seen from the above table, the MCL calculation is a straightforward calculation and is based on four inputs; UE PA Power, receiver noise figure (NF), occupied channel bandwidth and required SNR.

Max TX Power: For the downlink (DL) MCL calculation, this is the Power Amplifier (PA) power of the eNB and for this analysis the eNB supports PA power of +46 dBm (same was used in [6, 7]). For the uplink (UL) MCL calculation, the PA power of the UE is used. LTE-M supports two UE power classes; a 23 dBm Power Class 3 UE, and a new 20 dBm Power Class 5 UE. In this paper, since the maximum coverage is of interest, a 23 dBm class 3 UE is assumed thus 23 dBm is used in the MCL calculation.

FACT

The noise figure depends mainly on the front-end insertion loss, LNA quality, and current draw of the LNA but does not depend on the bandwidth of the signal.

Receive Noise Figure (NF): Similarly to how Max Transmit (TX) Power is based on the PA, the NF is based on the receiver's front end Low Noise Amplifier (LNA). The front-end insertion loss, quality, and current draw of the LNA can affect the NF and so typically the NF for the UEs are higher than for the eNB (which generally has less concerns with respect to power consumption and cost). One common misconception is that the NF depends on the bandwidth of the signal (e.g. 200 kHz for GSM versus >1.4 MHz for LTE) but given that UEs and eNBs need to be able to support many different channels within a band, the front end LNA needs to be wide enough to cover the entire band (e.g. band 20 is 30 MHz wide). 3GPP has used different NFs depending on situation; a conservative set (including extreme conditions) and a less conservative set. The following NFs shown in Table 2 have been used by 3GPP:

NOISE FIGURE SOURCE	eNB	UE
Conservative (TR 36.888 [5])	5	9
Less Conservative (TR 45.820 [6])	3	5

Table 2: 3GPP Noise Figures

In this paper, the less conservative NFs from TR 45.820 "Cellular system support for ultra-low complexity and low throughput Internet of Things (CIoT)" are used, since they are equally applicable to both NB-IoT and LTE-M.

Bandwidth of Signal: This is the bandwidth of the actual signal transmitted (not the bandwidth of the system). For example, if 2 physical resource blocks (PRBs) are used, then 2*180,000 Hz is used, not the full system bandwidth.

FACT

The "Required SNR" is a measure of how much noise the system can tolerate while maintaining a certain system performance (e.g. 10% error rate).

Required SNR: This value is a measure of how much noise the design (e.g. modulation, coding rate, coding type, transmission mode, and diversity scheme) can tolerate and still work within a certain performance. The performance metric is often Block Error Rate (BLER) but can also be acquisition time or speed. In this white paper, the SNR was obtained through LLS. Since SNR is also a common performance metric, all LLS results include both the MCL and SNR.

4 Coverage Targets

This section provides background information on the 3GPP targets that were used in the development of the LTE-M specification.

4.1 MCL TARGETS USING CONSERVATIVE NOISE FIGURES AND 20 dBm UE

3GPP initially started considering LTE-M in Release 11, producing the TR 36.888 study item technical report [6]. This technical report documents performance targets and an analysis of some technical approaches for adapting LTE in order to make it suitable for MTC applications. From the Release 13 work item description (WID) [1], the 3GPP target was to provide 15 dB of coverage gain for LTE-M with UE power class of 23 dBm, relative to a baseline CAT-1 Release 10 UE. However, the same coverage enhancement should be available for the new 20 dBm Power Class 5 UE as well, meaning that the actual target for LTE-M was to provide at least 18 dB of additional coverage for the limiting physical channel. Table 3 (below) shows the MCL calculation and the required gain for LTE-M channels where the conservative NFs are from [6] and a 20 dBm Power Class UE is assumed. The baseline SNR values are from [6] which were based on CAT-1 but are adjusted by 4 dB loss due to the single receiver that was assumed for CAT-M1:

PHYSICAL CHANNEL NAME	PUCCH	PRACH	PUSCH	PDSCH	PBCH	SCH	MPDCCH
TRANSMITTER							
(0) Max Tx Power (dBm)	20	20	20	46	46	46	46
(1) Power in Channel Bandwidth (dBm)	20	20	20	32	36.8	36.8	36.8
RECEIVER							
(2) Thermal Noise Density (dBm/Hz)	-174	-174	-174	-174	-174	-174	-174
(3) Receiver Noise Figure (dB)	5	5	5	9	9	9	9
(5) Occupied Channel Bandwidth (Hz)	180,000	1,080,000	360,000	360,000	1,080,000	1,080,000	1,080,000
(6) Effective Noise Power = (2) + (3) + 10log((5))	-116.4	-108.7	-113.4	-109.4	-104.7	-104.7	-104.7
(7) Required SNR (dB)	-7.8	-10	-4.3	0	-3.5	-3.8	-0.7
(8) Receiver Sensitivity = (6) + (7) (dBm)	-124.2	-118.7	-117.7	-109.4	-108.2	-108.5	-105.4
(9) Baseline MCL = (1) - (8) (dB)	144.2	138.7	137.7	141.4	145.0	145.3	142.2
Required Gain	11.5	17.0	18.0	14.3	10.7	10.4	13.5
Target MCL	155.7	155.7	155.7	155.7	155.7	155.7	155.7

Table 3: MCL calculation using conservative NF assumptions with 20 dbm Power Class UE

KEY FINDING

The LTE-M 3GPP coverage gain target was 18 dB.

Note: the baseline reference data rate used in TR 36.888 for the PUSCH and PDSCH MCL calculation was 20 kbps using a transport block size (TBS) of 72 bits with 2 physical resource blocks (PRB).

The gain required to reach the target MCL is different for each channel, where the largest gain is required for the PUSCH at 18 dB, and thus the 3GPP gain target was 18 dB.

4.2 MCL TARGETS USING LESS CONSERVATIVE NOISE FIGURES AND 23 dBm UE

Most of the recent Low power wide area (LPWA) 3GPP coverage analyses have been using less conservative noise figures from TR 45.820 [7] for calculating MCL (e.g. for NB-IoT and EC-GSM-IoT). TR 45.820 is a 3GPP study item technical report documenting assumptions and findings on the cellular support of low complexity IoT devices. It reported the MCL supported by NB-IoT and EC-GSM-IoT, but the assumptions are equally applicable to LTE-M, thus for the remainder of this white paper, the noise figures in [7] are used. The following (Table 4) shows the updated targeted MCL when less conservative NFs from [6] and a 23 dBm Power Class 3 UE are assumed:

PHYSICAL CHANNEL NAME	PUCCH	PRACH	PUSCH	PDSCH	PBCH	SCH	MPDCCH
TRANSMITTER							
(0) Max Tx Power (dBm)	23	23	23	46	46	46	46
(1) Power in Channel Bandwidth (dBm)	23	23	23	32	36.8	36.8	36.8
RECEIVER							
(2) Thermal Noise Density (dBm/Hz)	-174	-174	-174	-174	-174	-174	-174
(3) Receiver Noise Figure (dB)	3	3	3	5	5	5	5
(5) Occupied Channel Bandwidth (Hz)	180,000	1,080,000	360,000	360,000	1,080,000	1,080,000	1,080,000
(6) Effective Noise Power = (2) + (3) + 10log((5))	-118.4	-110.7	-115.4	-113.4	-108.7	-108.7	-108.7
(7) Required SNR (dB)	-7.8	-10	-4.3	0	-3.5	-3.8	-0.7
(8) Receiver Sensitivity = (6) + (7) (dBm)	-126.2	-120.7	-119.7	-113.4	-112.2	-112.5	-109.4
(9) Baseline MCL = (1) - (8) (dB)	149.2	143.7	142.7	145.4	149.0	149.3	146.2
Required Gain	11.5	17.0	18.0	14.3	10.7	10.4	13.5
Target MCL	160.7	160.7	160.7	159.7	159.7	159.7	159.7

Table 4: MCL calculation using less conservative NF assumptions with 23 dBm Power Class 3 UE

KEY FINDING

Using less conserverative NFs with a 23 dBm UE, the target MCL changed from 155.7 dB to 160.7 dB.

The input values that changed compared to the table in Section 4.1 have been highlighted. As can be seen, changing the UE PA power from 20 to 23 and changing the noise figures, the MCL targets and MCL baselines have now changed when the required gains are kept the same. Using less conservative NFs from TR 45.820, the baseline MCL changed from 137.7 dB to 142.7 dB. Using both less conservative NFs from TR 45.820 and assuming a 23 dBm Power Class 3 UE, the LTE-M targeted MCL is 160.7 dB for the uplink and 159.7 dB for the downlink.

FACT
To support the different levels of coverage, Mode A and B support different maximum numbers of repetitions.

5 LTE-M Coverage Enhancement Mode A and B

The LTE-M specification has defined two Coverage Enhancement Modes: Mode A and Mode B. The main difference is that Coverage Enhancement Mode A supports only moderate coverage enhancements whereas Mode B supports very deep coverage. Coverage Enhancement Mode A is a mandatory feature for CAT-M1 whereas Coverage Enhancement Mode B is an optional feature. This paper analyses the coverage performance for Mode B.

To support the different levels of coverage, Mode A and B support different maximum number of repetitions. Table 5 (below) shows those maximums [4, 5]:

LTE-M CHANNEL	MODE A REPETITIONS	MODE B REPETITIONS
PSS/SSS	1	1
PBCH	1*	5
MPDCCH	16*	256
PDSCH	32	2048
PUSCH	32	2048
PUCCH	8	32
PRACH	32*	128

* Practical values

Table 5: Maximum number of repetitions for Mode A and Mode B

Another difference is that there are some functions/features which are only supported in Mode A such as connected mode mobility, 8 hybrid automatic repeat request (HARQ) processes, and several transmission modes (TMs). The Coverage Enhancement Mode only applies when the UE is in the Radio Resource Control (RRC) connected state. Mainly based on UEs' periodically reported signal quality, the eNB decides which coverage enhancement mode the UE should be in. In general, the eNB keeps the UE in Coverage Enhancement Mode A unless the UE is in very poor coverage.

6 Coverage Techniques

The following section provides background information and technical insights into many of the techniques used to provide the coverage enhancement for the LTE-M specification.

FACT
CAT-M1 supports two UE Power classes: 23 dBm Class 3 and 20 dBm Class 5.

6.1 TX POWER

For every dB the TX power is increased, there is a 1 dB increase in MCL. As mentioned in the MCL section, LTE-M supports two UE Power Classes of PA; Class 3 PA 23 dBm, and Class 5 PA 20 dBm, so a Class 3 UE would have a 3 dB better UL MCL. Although increasing UE TX power above 23 dBm sounds like an easy method to gain coverage, there are several issues in doing so – increased cost, regulatory issues (e.g. specific absorption limits), increased inter-cell interference, and peak current issues. In fact, for IoT devices the trend is to lower the TX power to make the PA more practical to be integrated and thus reduce the cost. This is why the 20 dBm Class 5 UE was added as part of the LTE-M work.

FACT

Repetition is the most common technique used by all LPWAs to improve coverage where doubling the repetitions results in ~3 dB coverage gain but half the speed.

FACT

Accurate channel estimation starts to become a dominant issue at the lower SNRs.

6.2 REPETITION

Repetition is the most common technique used by all LPWAs to improve coverage. Generally, there is a linear relationship between repetition and gain (e.g. double the repetitions results in 3 dB coverage gain). This however only holds true if the UE or eNB can obtain accurate channel estimations and frequency tracking and other low level functions (more on this later in sections 6.3 and 6.6) which is often not the case. The major downside to repetition is that it slows down the transmission linearly (e.g. double the repetitions, halves the speed/doubles the latency).

6.3 CROSS SUBFRAME & CROSS PRB CHANNEL ESTIMATION

As mentioned above, repetition only provides linear gain if the UE or eNB can obtain good estimates of the channel. Accurate channel estimation starts to become a dominant issue at the lower SNRs (i.e. when more than ~12 dB of coverage gain is required). Using cross subframe (SF) and cross PRB (physical resource block) channel estimation was found to be a very effective method to improve channel estimation (see [8, 16, 17, 22]) and thus coverage. During the LTE-M standardization, it was assumed that the deep coverage enhancement mode (i.e. Coverage Enhancement Mode B) would mainly be used to overcome the large losses due to in-building penetration (e.g. reaching meters in basements). As such, slow moving mobile channels (e.g. ETU 1 Hz, and EPA 1 Hz) were used where the channel does not vary quickly in time or frequency, which allows the use of cross SF and cross PRB channel estimation. When the UE is moving quickly, the channel changes rapidly limiting the number of SFs and PRBs which can be used.

6.4 MULTI-SUBFRAME FREQUENCY HOPPING

Given that an LTE-M UE's maximum channel bandwidth (1.08 MHz) is typically smaller than the LTE system bandwidth (e.g. 10 MHz), frequency hopping was specified to provide some frequency diversity (see [18, 19, 20]). Unlike other frequency hopping techniques in LTE, the LTE-M frequency hopping allows cross subframe channel estimation to still be used by the UE and eNB because the hopping occurs across multiple subframes.

6.5 REDUNDANCY VERSION (RV) CYCLING

It was found that it was more spectrally efficient to send larger transport blocks (e.g. 1000bits) versus fragmenting and sending small transport blocks (see [9, 15] for details) due to the CRC and media access control (MAC) and radio link control (RLC) header overhead. The issue was that the coding rate is not sufficient to support larger transport blocks, especially in the UL in Mode B, when only 1 or 2 PRBs are allocated. Cycling redundancy versions across different subframes improves the coding rate which allows the support for larger transport blocks when only 1 or 2 PRBs are allocated.

6.6 USING SAME RV AND SCRAMBLING FOR SEVERAL SF

The degree of cross subframe channel estimation that can be used mainly depends on the ability to minimise any residual frequency error, so the LTE-M standard made some changes to allow the eNB and UE to better minimize residual frequency error. It was determined that if the contents of the SF are exactly the same for several SF, this allows the UE and eNB to apply a differential phase detection algorithm on the data, allowing the data to be used for frequency offset correction, in addition to the cell-specific reference signals (CRS) (see section 4 of [10] for more details). In addition, this allows the option for the UE and eNB to do I/Q combining which can also improve decoding performance.

6.7 POWER SPECTRAL DENSITY (PSD) BOOSTING

PSD boosting is an eNB implementation technique that can be used to improve DL coverage. The eNB will reduce the power applied to certain PRBs which it can then use to boost the power in the other targeted PRBs. If a user is allocated the reduced power PRBs, that user will experience a reduced data rate (see [21]). For LTE-M, the generally accepted maximum amount of PSD boosting possible is 4 dB. PSD boosting can be applied specifically to a channel (e.g. PSS/SSS/PBCH) or to a specific user's data in the PDSCH. However, it should be noted that the coverage analysis done in this paper does not assume any PSD boosting.

KEY ACTIVITY

To determine LTE-M coverage, simulation analysis of every channel was conducted.

KEY TENET

For consistency, the simulation assumptions across the different channels are common.

7 Coverage Analysis

To determine the practical coverage that the Release 13 LTE-M specification can support, an LLS analysis of every LTE-M channel was conducted. Every channel was analysed to find the maximum possible coverage for each channel so that the channel with the lowest maximum coverage could be identified which would set the overall realistic coverage expectation for the LTE-M specification. For consistency, the simulation assumptions across the different channels are common and based on the simulation assumptions used in TR 45.820, as shown in table 6 below:

PARAMETER	PSS/SSS	PBCH	MPDCCH	PDSCH	PUSCH	PUCCH	PRACH
System bandwidth	10 MHz						
Configuration	FDD						
Carrier frequency	2 GHz						
Antenna configuration	2x1, low correlation				1x2, low correlation		
Channel model	ETU 1 Hz						
Number of RBs	N/A	N/A	6	6	1	1	6
Transmission mode	N/A	N/A	Random Beam - Forming	TM2	TM1	N/A	N/A
Frequency tracking error	1 kHz	30 Hz	30 Hz	30 Hz	30 Hz	30 Hz	30 Hz
Channel estimation	N/A	Cross SF and Cross PRB	Cross SF	Cross SF and Cross PRB	Cross SF	Cross SF	N/A
Frequency Hopping	No	No	Yes - 16 SF				
Performance Target	Acq. Time versus SNR 0.1% false Detection Probability	Acq. Time versus SNR	1% BLER DCI Format 6-1B (18 bits)	Data Speed @ 10%BLER versus SNR using TBS from 936 to 152	Data Speed @ 10%BLER versus SNR using TBS from 504 to 175	10% and 1% missed probability, 1% false alarm prob. Format 1A	10% and 1% missed probability 0.1% false alarm prob. Format 0

Table 6: LLS Assumptions

The approved versions of the Release-13 LTE-M specifications [2,3,4,5] were used in developing the simulations.

KEY TENET

For the PSS/SSS, the MCL limit is not defined by an error rate target but by an acceptable acquisition time which is a more subjective measure.

7.1 PRIMARY SYNC SIGNAL (PSS) AND SECONDARY SYNC SIGNAL (SSS)

This section includes the LLS results for the PSS and SSS. For system acquisition, the PSS and SSS are the first signals the UE needs to acquire. The PSS/SSS are used mainly to help the UE acquire system timing, frequency offset, and the cell ID. Given that these are the initial signals that the UE has to decode, the assumed residential frequency offset for this channel was set to 1 kHz versus a frequency tracking error of 30 Hz that was used for all the other channels. The raw frequency error due to crystal inaccuracies can be larger than 1 kHz so the UE may need to perform some initial coarse frequency offset algorithm or parallel PSS/SSS correlations with different frequency errors (e.g. in steps of 2 kHz). Figure 1 (below) provides the acquisition time versus SNR/MCL for the combined detection time for PSS and SSS:

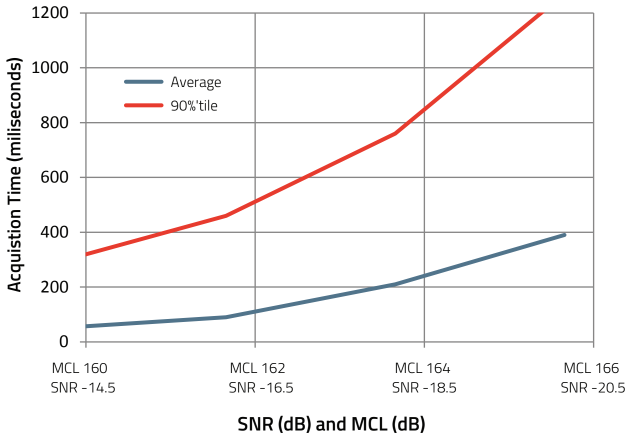

Figure 1: PSS/SSS Acquisition Time versus SNR/MCL

KEY FINDING

At 164 dB MCL, the average PSS/SSS acquisition time is 240 ms and 90th percentile acquisition time is 850 ms which can be expected to meet most IoT application requirements.

As seen from Figure 1, the PSS/SSS can still be detected beyond 165.5 dB MCL but the acquisition time gets longer which may not be suitable for some applications. The PSS/SSS can be acquired by non-coherently combining many PSS/SSS copies thus in deep coverage the amount of time required to acquire the PSS/SSS goes up. Due to this accumulation, the MCL limit is not defined by BLER but by an acceptable acquisition time. Given that IoT applications have different acquisition time requirements, this limit is subjective and somewhat arbitrary so a maximum MCL is not specifically defined for this channel and instead the PSS/SSS acquisition time is provided for many MCLs. As seen from the above Figure 1, at a 164 dB MCL, the average (or 50th percentile) PSS/SSS acquisition time is only 240 ms and the 90th percentile acquisition time is 850 ms which can be expected to meet most IoT application requirements.

The PSS/SSS detection method analysed used the combined PSS and SSS sequences for correlation which is generally only computationally practical when the cell-ID is known. This holds at resynchronization, which is by far the most common situation given that Coverage Enhancement Mode B is intended for stationary/in-building scenarios. The longer acquisition time that may occur at the rare exceptions of unknown Cell-ID due to movement or at initial UE power on is not deemed to have a significant impact on power consumption or latency.

7.2 PHYSICAL BROADCAST CHANNEL (PBCH)

This section includes the LLS results for the Physical Broadcast Channel (PBCH). In general, after the PSS/SSS is acquired, the next step in the system acquisition process is to decode the PBCH (which transports the master information block (MIB)). The PBCH has 24 bits of information and a 16 bit cyclic redundancy check (CRC) and contains essential information about the system time, the system bandwidth, and the new essential scheduling information for LTE-M system information. The following (Figure 2) shows the acquisition time versus MCL/SNR for a correlation decoder where the false detection rate is <0.01% (see [11] for details on the correlation decoder):

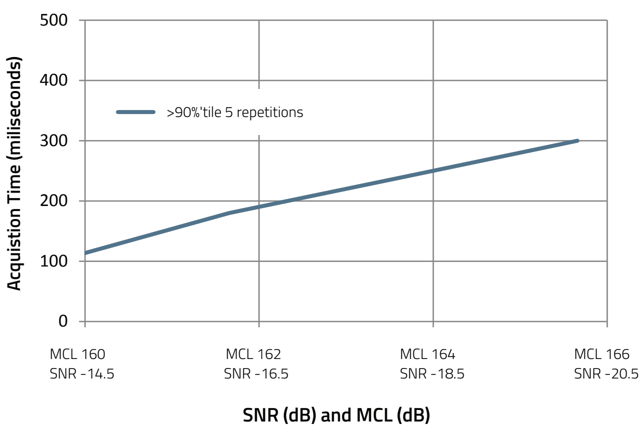

Figure 2: PBCH Acquisition Time versus SNR/MCL for Correlation Decoder

The above results were obtained using 5 PBCH repetitions fully occupying SF#0 and SF#9, which is the maximum supported in the LTE-M specification.

Like PSS/SSS, the PBCH coverage limit is not defined by a BLER target but is defined by a more subjective acquisition time limit. As seen from Figure 2, the PBCH can still be detected beyond 165.5 dB MCL but the acquisition time gets longer which may not be suitable for some applications. At 164 dB MCL, the 90%'tile PBCH acquisition time is 240 ms using a PBCH correlation decoder.

KEY FINDING

At 164 dB MCL, the 90%'tile PBCH acquisition time is 240 ms using a PBCH correlation decoder.

The above results are for a PBCH correlation decoder which works by correlating the received rate matched symbols against possible transmitted PBCH symbols and then tests the multiple hypotheses. The results shown above are for a re-acquisition scenario similar to what was shown for the PSS/SSS which is by far the most common case. For the PBCH re-acquisition scenario in general, only the system frame number (SFN), an 8 bit field, is unknown. For a cold acquisition scenario, this PBCH correlation decoder may not be practical so a different PBCH decoder may be used. The following (Figure 3) shows the results for the “Keep Trying” PBCH decoder (see [12, 13]) which was also studied by 3GPP:

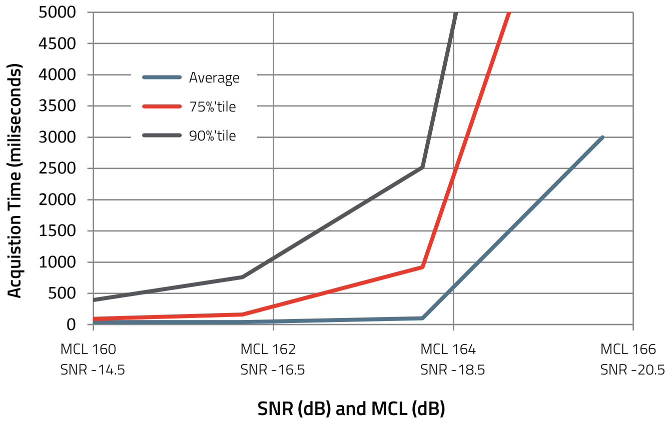

Figure 3: PBCH Acquisition Time versus SNR/MCL for "Keep Trying" Decoder

KEY FINDING

Although the acquisition times are longer, the "Keep Trying" PBCH decoder can successfully decode the PBCH at >164 dB MCL.

Although the acquisition times for the "Keep Trying" decoder are longer, it can also successfully decode the PBCH at 164 dB MCL and unlike the PBCH Correlation decoder works in all acquisition scenarios. A key finding is that the "Keep Trying" PBCH decoder can successfully decode the PBCH at >164 dB MCL.

If shorter acquisition times are desired also for scenarios with unknown PBCH content, such as power-on initial acquisition, it is possible to use a third type of decoder that is able to accumulate soft values over several PBCH transmissions even when the SFN counter changes its value. Such a decoder based on modified handling of branch and/or path metrics in the Viterbi decoder was presented in [14].

7.3 MTC PHYSICAL DOWNLINK CONTROL CHANNEL (MPDCCH)

This section includes the LLS results for the MTC Physical Downlink Control Channel (MPDCCH). The MPDCCH is a control channel which is used mainly to assign dedicated PDSCH/PUSCH resources to the UE. The following (Figure 4) provides the 1% BLER versus SNR/MCL for the various MPDCCH repetition levels:

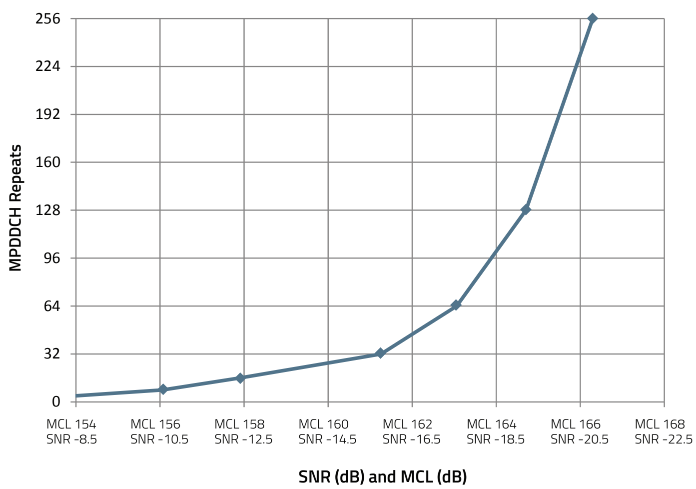

Figure 4: MPDCCH Repeats at 1% BLER versus SNR/MCL

KEY FINDING

164 dB MCL can be supported using between 64 and 128 MPDCCH repetitions which is below the possible 256 repetitions that the LTE-M standard allows.

As seen from Figure 4, a maximum MCL of 166.3 dB is possible with 1% BLER when using 256 repeats. At 164 dB MCL, between 64 and 128 MPDCCH repeats are required. A key finding is that 164 dB MCL can be supported using between 64 and 128 MPDCCH repetitions which is below the possible 256 repetitions that the LTE-M standard allows.

7.4 PHYSICAL DOWNLINK SHARED CHANNEL (PDSCH)

This section includes the LLS results for the Physical Downlink Shared Channel (PDSCH). The PDSCH carries the DL user data. Instead of providing several BLER curves for various transport block size (TBS) and repetition combinations, this section provides the data rate versus SNR/MCL, as this measure has more intrinsic benefit for the reader. Also, supporting higher data rates at high MCL values is the more challenging metric. For this reason, TR 45.820 had the requirement to not only support an MCL of 164 dB but to provide a data rate of at least 160 bps at 164 dB MCL. The following (Figure 5) shows the data rate versus the SNR/MCL for the PDSCH:

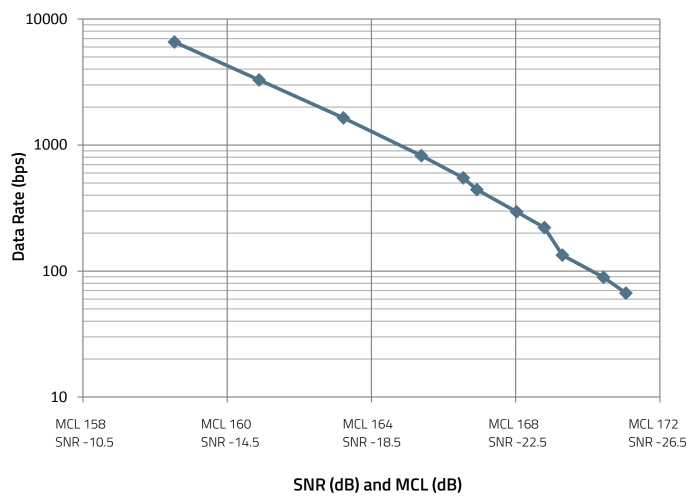

Figure 5: PDSCH data rate at 10% BLER versus the SNR/MCL

KEY FINDING

At 164 dB MCL, LTE-M can support a down-link data rate of 1400 bps which is well beyond the TR 45.820 requirement of 160 bps.

Note: The above physical layer data rate doesn't include MAC/RLC/PDCP/IP header overhead or scheduling delays.

Like PSS/SSS and PBCH, the maximum supported MCL is rather subjective because the standard supports such high repetitions. The maximum supported MCL is obtained when the highest number of repeats (2048) is used with a small TBS (152 bits), but this results in a very slow 67 bps data rate which may not meet the application needs and may not meet the spectral efficiency needs of the operator. As mentioned above, TR 45.820 had a requirement to support 160 bps at MCL of 164 dB and as seen from the above graph the LTE-M PDSCH can support a data rate of 1400 bps at an MCL of 164 dB which is 8.5X faster than the TR 45.820 requirement.

7.5 PHYSICAL RANDOM ACCESS CHANNEL (PRACH)

This section includes the LLS results for the Physical Random Access Channel (PRACH). The PRACH is an UL control channel mainly used by the UE to start a random access request. The following (Figure 6) provides the 1% and 10% detection rates versus SNR/MCL with less than 0.1% false alarm probability for various PRACH repetition levels:

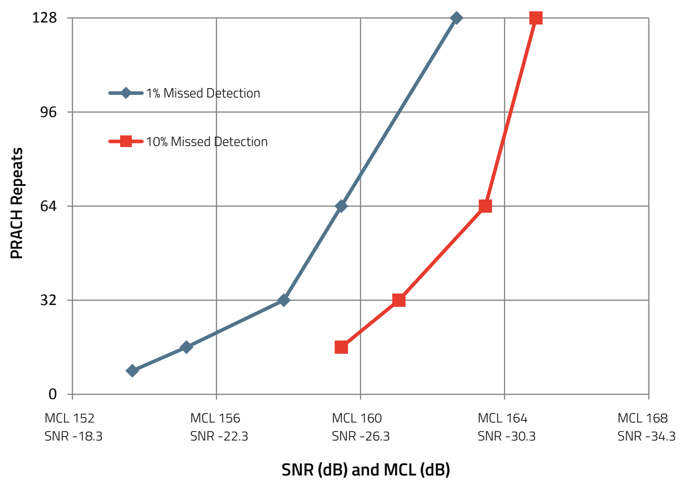

Figure 6: PRACH Repetition versus SNR/MCL

KEY FINDING

164 dB MCL can be supported using between 64-128 PRACH repeats.

Given that LTE-M is designed for latency tolerant applications, the 10% missed PRACH detection target is the applicable target and also used in TR 45.820 [7]. However, the missed detection target is not specified and thus is up to network implementation. As seen from the above Figure 6, the maximum MCL of 165 dB is possible using 128 repeats. A key finding is that 164 dB MCL can be supported using between 64-128 PRACH repeats.

7.6 PHYSICAL UPLINK SHARED CHANNEL (PUSCH)

This section includes the LLS results for the Physical Uplink Shared Channel (PUSCH). This channel carries the UL user data. As with the PDSCH, instead of providing several BLER curves for various TBS and repeat combinations, this section provides the data rate versus SNR/MCL. The following (Figure 7) shows the PUSCH data rate versus the SNR/MCL:

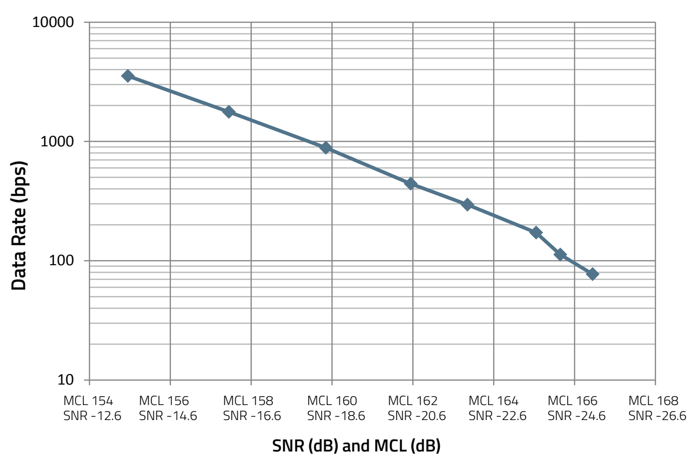

Figure 7: PUCSH data rate at 10% BLER versus the SNR/MCL

Note: The above physical layer data rate doesn't include MAC/RLC/PDCP/IP header overhead or scheduling delays.

KEY FINDING

At 164 dB MCL, LTE-M can support an uplink data rate of 250 bps which is beyond the TR 45.820 requirement of 160 bps.

TR 45.820 has a requirement to support 160 bps at MCL of 164 dB and as seen from the above graph the LTE-M PUSCH can support a data rate of 250 bps at an MCL of 164 dB which is beyond the TR 45.820 requirement. Even greater coverage can be supported, with a corresponding reduction in data rate.

7.7 PHYSICAL UPLINK CONTROL CHANNEL (PUCCH)

This section includes the LLS results for the Physical Uplink Control Channel (PUCCH). The PUCCH is an UL control channel mainly used by the UE to send acknowledgements. The following figure provides the 1% and 10% BLER rates versus SNR/MCL for various PUCCH repetition levels:

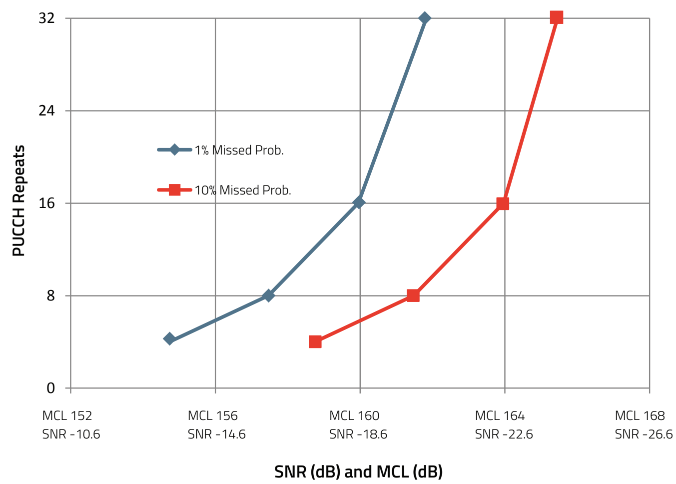

Figure 8: PUCCH Repetition versus SNR

KEY FINDING

164 dB MCL can be supported using between 16-32 PUCCH repeats.

As seen in Figure 8, a maximum MCL of 165.5 dB can be achieved at the target 10% PUCCH missed detection rate (10% is the target used in TR 45.820 [7]). A key finding is that 164 dB MCL can be supported using between 16-32 PUCCH repeats.

8 Summary

As mentioned above, the determination of the coverage is not simply a matter of looking at block error rates. For some channels, it is more appropriate to measure against an application level performance criterion so in this paper we also measured data speed and acquisition times. Table 7 summarizes the performance results from the LLS evaluation at an MCL of 164 dB:

LTE-M CHANNEL	MCL	PERFORMANCE	MAX MODE B REPEATS
PSS/SSS	164 dB	Acquisition Time=850 ms (90th %'tile)	-
PBCH	164 dB	Acquisition Time=240 ms (90th %'tile)	5
MPDCCH	164 dB	99% detection using 128 repeats	256
PDSCH	164 dB	1400 bps using 512 repeats	2048
PUSCH	164 dB	250 bps using 1536 repeats	2048
PRACH	164 dB	90% detection using 64-128 Repeats	128
PUCCH	164 dB	90% detection using 16-32 Repeats	32

Table 7: Summary of Performance at 164 dB MCL

KEY FINDING

Through LLS, all the LTE-M channels are well balanced and can realistically support 164 dB MCL.

KEY FINDING

LTE-M can realistically provide 21.3 dB of gain which exceeds the 18 dB 3GPP target by 3.3 dB.

As can be seen from Table 7, not only is LTE-M capable of operating at an MCL of 164 dB but the performance in terms of data speed and acquisition time are very good. If the application can tolerate lower speeds and longer acquisition times, an MCL of beyond 164 dB can also be supported. The coverage balance of the LTE-M channels is also very good where there is at least one more repetition level available in the standard for all the LTE-M control channels. A key finding is that through LLS, all the LTE-M channels are well balanced and can realistically support a 164 dB MCL.

As mentioned, coverage performance can be expressed in MCL or gain. As shown in section 4.2, the baseline is at 142.7 dB MCL thus in terms of gain, considering that LTE-M supports 164 dB MCL, LTE-M can realistically provide 21.3 dB of gain relative to Release 12 LTE which exceeds the 18 dB target by 3.3 dB.

The key purpose of this paper was to determine the coverage provided by the LTE-M specification through LLS but there are other key performances indicators that can be evaluated. For example, battery life and the message delivery time at different MCL levels are additional performance indicators which are important. This work can serve as a basis for further study of those topics.

9 References

The references are provided to offer the reader more detailed information on the coverage techniques and decoder types mentioned in this paper. These papers may also include simulation results but since the simulation assumption are not the same as this paper, the simulation result from these references are not comparable to those in this paper.

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