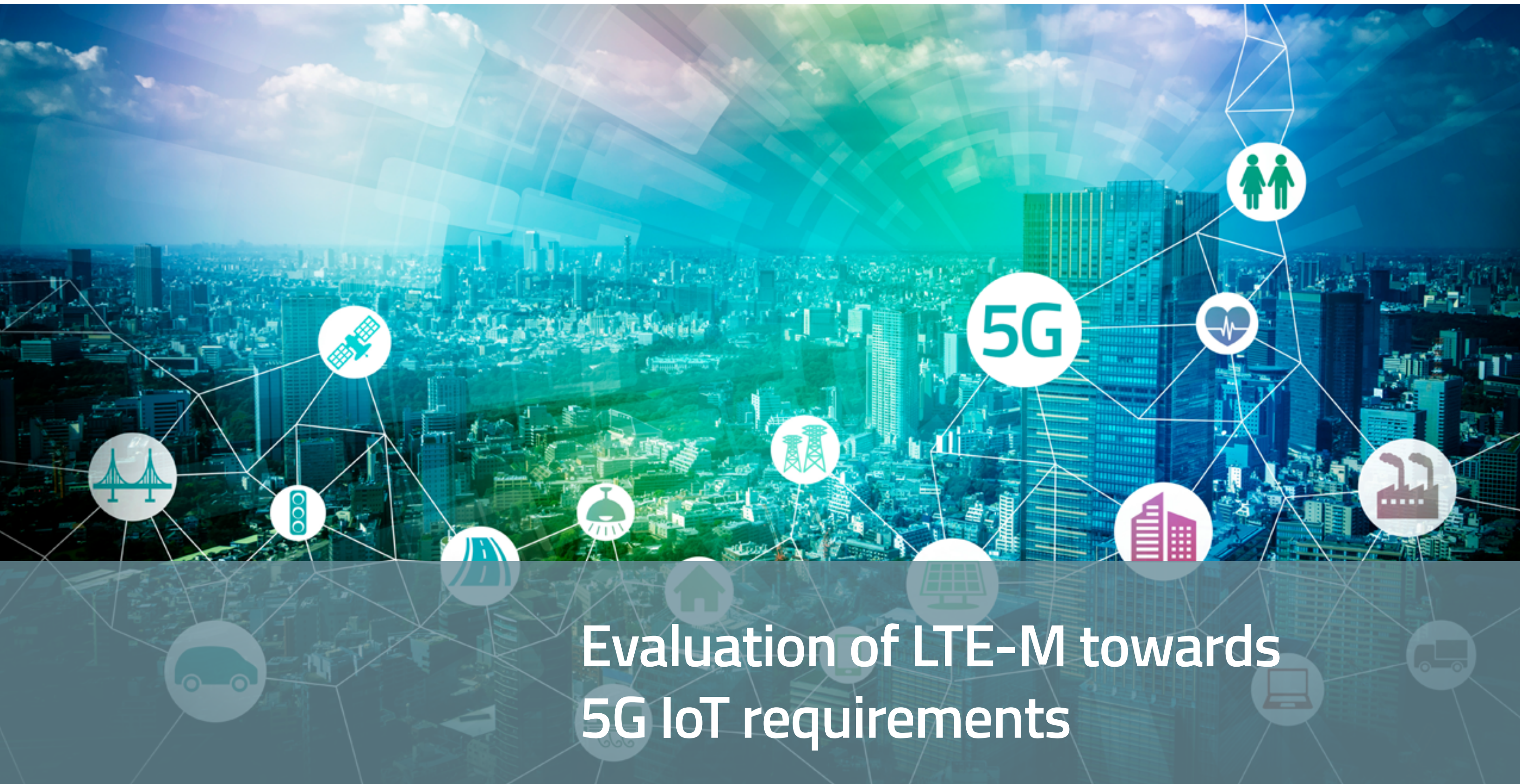
White Paper



Evaluation of LTE-M towards 5G IoT requirements

Contributing and Supporting Companies:

V1.0 December 2017

Executive Summary

LTE-M, a machine-focused variant of the 3GPP LTE standard, is designed to meet the high-coverage, low-cost, and low-power consumption requirements of the Internet of Things (IoT). In January 2017, a group of more than a dozen industry players evaluated LTE-M's coverage performance, and published a white paper which concludes that LTE-M supports the very deep coverage required for IoT applications [1]. This follow-up paper takes the next step to evaluate the message latency, battery life, and capacity performance for LTE-M category-M1 devices.

More specifically, this paper evaluates LTE-M performance against the initial Cellular IoT (CIoT) requirements in 3GPP TR 45.820 [2], but – perhaps more importantly – also compares LTE-M performance to the more recently published 3GPP 5G IoT or massive Machine-Type Communications (mMTC) requirements. The 5G IoT requirements for coverage, message latency, and battery life are specified in 3GPP TR 38.913 [3] and the capacity requirements are defined by the two ITU reports IMT-2020 evaluation guidelines [4] and IMT-2020 requirements [6].

Starting with the CIoT requirements, the message latency for LTE-M in extremely deep coverage conditions was found to be 6.2 seconds, which is well under the stated goal of 10 seconds. Battery life in extremely deep coverage conditions was determined to be 10.4 years, which is over the 10-year requirement assuming one 200 byte uplink message per day. At the edge of normal coverage (i.e. where your smart phone stops working today), the performance improves significantly, where message latency was found to be 0.1 seconds and battery life to be 35.7 years.

As for 5G IoT requirements, even though the 5G coverage requirements are up to 4 dB more difficult than the CIoT requirements, the analysis in this paper shows that LTE-M also gets a passing grade for 5G. The results are summarized in Table 1.

5G REQUIREMENT	5G TARGET	LTE-M PERFORMANCE
Bandwidth required to serve a capacity of 1 million devices per km^2	50 MHz	70% of a 5 MHz system
Data rate at the maximum coupling loss of 164 dB	160 bps	UL 363 bps & DL 1200 bps*
Message latency at the maximum coupling loss of 164 dB	10 seconds	6.7 seconds*
Battery life at the maximum coupling loss of 164 dB	10 years	10.9 years*

Table 1: MCL Calculation

** Assumes four receive and two transmit antennas at the base station and +4 dB downlink PSD boosting*

Keep in mind the above performance is for extremely deep coverage. In normal coverage, the performance will be improved significantly.

The evaluation is based on the Release 13 LTE-M specifications (along with uplink control channel repetitions from Release 14). However, 3GPP's work on Release 15 LTE-M enhancements promises to improve the coverage, message latency, battery life, and capacity results shown in this paper. If the early indications hold true, Release 15 enhancements can be expected to support the 5G IoT requirements in all system configurations, including base station antenna configurations with just two receive antennas and two transmit antennas, without the need for downlink Power Spectral Density (PSD) boosting.

When these results for coverage, message latency, battery power, and capacity are taken into account, it becomes clear that LTE-M is on track to support the future 5G IoT and mMTC application requirements. What's more, LTE-M is a very versatile Low Power Wide Area (LPWA) technology, since it also supports higher data rates, real-time traffic, full mobility, and voice.

Table of Contents

1 Introduction and Scope

KEY MESSAGE

This paper evaluates all the ITU and 3GPP 5G requirements and the Cellular IoT requirements.

In addition to serving a versatile set of LPWA use cases, LTE-M has been designed to support requirements on data rate, latency, battery life, and system capacity, even under the most stringent coverage requirements. This guarantees that LTE-M can serve large-scale IoT deployments, covering the last mile and beyond with guaranteed quality of service and minimum maintenance requirements.

This white paper is a follow-up to the LTE-M coverage white paper [1] published in January 2017. The LTE-M coverage white paper focused on the CIoT coverage requirement defined in 3GPP TR 45.820 [2] but there are several other performance aspects in TR 45.820 which were not covered in the first white paper. Also, since January 2017, the ITU and 3GPP have published new 5G IoT/mMTC requirements which need evaluation. This paper evaluates all these remaining requirements:

- CIoT TR 45.820 [2] requirements:
  - Message latency
  - Battery life
- 5G IoT requirements from IMT-2020 [4][6]:
  - Connection density (i.e. capacity)
- 5G IoT requirements from TR 38.913 [3]:
  - Coverage
  - Message latency
  - Battery life

The evaluation was done assuming LTE-M category-M1 Release 13 [7], unless otherwise stated.

2 Abbreviations

ABBR.	TERM
3GPP	Third Generation Partnership Project
5G	Fifth Generation Cellular
ACK	Acknowledge
AM	Acknowledged Mode
bps	Bits Per Second
BLER	Block Error Rate
BW	Bandwidth
CIoT	Cellular IoT
dB	Decibel
dBm	Power ratio in decibels referenced to one milliwatt
DL	Downlink (from eNB to UE)
eNB	Enhanced Node B (LTE base station)
ETU	Extended Typical Urban
EVAL	Evaluation
FDD	Frequency Division Duplex
GERAN	GSM Edge Radio Access Network
HARQ	Hybrid Automatic Repeat Request
IMT	International Mobile Telecommunications
IP	Internet Protocol
ITU	International Telecommunication Union
km	Kilometer
LNA	Low Noise Amplifier
LLS	Link Layer Simulation

ABBR.	TERM
LPWA	Low Power Wide Area
LTE	Long Term Evolution
LTE-M	Long Term Evolution for Machine-Type Communications
MAC	Media Access Control
MCL	Maximum Coupling Loss
MHz	Megahertz
MIB	Master Information Block
MO	Mobile Originated
MPDCCH	MTC Physical Downlink Control Channel
MTC	Machine Type Communications
mMTC	Massive Machine Type Communications
NF	Noise Figure
PA	Power Amplifier
PAPR	Peak-to-Average-Power Ratio
PBCH	Physical Broadcast Channel
PDCP	Packet Data Convergence Protocol
PDSCH	Physical Downlink Shared Channel
PDU	Packet Data Unit
PRACH	Physical Random Access Channel
PRB	Physical Resource Block
PSD	Power Spectral Density
PSM	Power Saving Mode
PSS	Primary Synchronization Signal

ABBR.	TERM
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
RAI	Release Assistance Information
RAN	Radio Access Network
RLC	Radio Link Control
RRC	Radio Resource Control
RX	Receive
sec	Second
SF	Sub-frame
SIB	System Information Block
SIB1-BR	System Information Block 1 Bandwidth Reduced
SSS	Secondary Synchronization Signal
SNR	Signal to Noise Ratio
TBS	Transport Block Size
TM	Transmission Mode
TR	Technical Report
TX	Transmit
UE	User Equipment
UL	Uplink (from UE to eNB)
Wh	Watt Hour

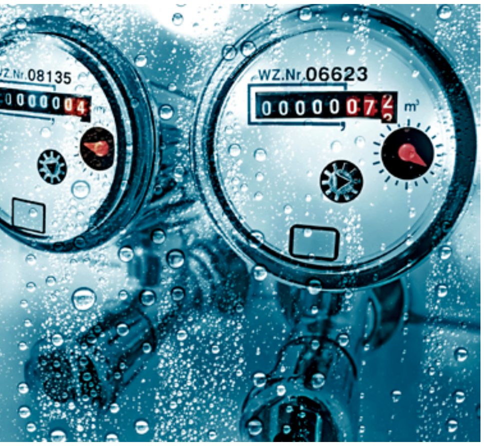
FACT

MCL is a very common measure to describe the amount of coverage a system can support but depends on the assumed noise figures.

3 Maximum Coupling Loss (MCL)

Support for a high coverage range is one of the most fundamental requirements for IoT technologies aiming to provide ubiquitous coverage. In this paper, coverage is referred to in terms of Maximum Coupling Loss (MCL). MCL is a convenient metric since it is defined as the difference in output power at the antenna connector of a transmitting node and the input power at the antenna connector of a receiving node required to provide a targeted quality of service.

This paper analyzes three sets of requirements: one set from the initial 3GPP study on CIoT described in TR 45.820 [2], one set from the 3GPP 5G requirement study in TR 38.913 [3], and one set from the ITU requirements on IMT-2020 systems as captured in ITU reports IMT-2020 evaluation guidelines [4] and IMT-2020 requirements [6]. The achievable MCL is highly dependent on the assumed device (i.e. user equipment or UE) and LTE base station (i.e. Enhanced Node B or eNB) noise figure which defines the level of intrinsic thermal noise in these nodes. Unfortunately, the base station and the device noise figure (NF) assumptions are different for all three mentioned sets of requirements, and this affects the MCL requirements. Table 2 summarizes how MCL is calculated (for more on calculating MCL see [1]):



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
(4) Occupied channel bandwidth (Hz)	Bandwidth of signal
(5) Effective noise power = (2) + (3) + 10 log((4)) (dBm)	Calculated
(6) Required SNR (dB)	Value comes from link simulation
(7) Receiver sensitivity = (5) + (6) (dBm)	Calculated
(8) MCL = (1) - (7) (dB)	Calculated

Table 2: MCL Calculation

FACT

The assumed noise figures for 5G and CIoT requirements are different so the MCL is different.

As seen from the above calculation, the receiver's NF is a direct input into the MCL calculation, so any difference in the NF directly affects the resulting MCL calculated. NF is based on the quality of the receiver's front end, including its Low Noise Amplifier (LNA), so the assumed NF can be a subjective choice. Table 3 gives the NFs used in each set of requirements.

FACT

The 3GPP 5G 164 dB MCL requirement from TR 38.913 is 4 dB more difficult in the DL and 2 dB more difficult in the UL than the 3GPP CIoT 164 dB MCL requirement from TR 45.820.

RECEIVER NOISE FIGURES	APPLICABILITY	BASE STATION	DEVICE
3GPP GERAN Study TR 45.820 (“CIoT”)	Sections 5 & 6	3 dB	5 dB
3GPP 5G RAN Study TR 38.913 (“5G”)	Sections 4, 5 & 6	5 dB	9 dB
5G IMT-2020 Evaluation Guides (“5G IMT”)	Section 7	5 dB	7 dB

Table 3: Receiver Noise Figures

The difference in NFs means that the 164 dB MCL requirement from the 3GPP 5G RAN Study TR 38.913 is 4 dB more difficult in the downlink (DL) and 2 dB more difficult in the uplink (UL) than the 164 dB MCL requirement from the 3GPP GERAN Study TR 45.820.

For clarity, MCL requirements from the CIoT study TR 45.820 have a “CIoT” prefix (e.g. “CIoT 164 dB MCL”) and MCL requirements from the 3GPP 5G study in TR 38.913 have a “5G” prefix (e.g. “5G 164 dB MCL”).

4 Coverage

The main goal of the LTE-M coverage white paper [1] was to show that LTE-M could support extremely deep coverage conditions at CIoT 164 dB MCL with at least a data rate of 160 bps. This section’s aim is to show that LTE-M can provide even further coverage, and meet the even more difficult 5G IoT coverage requirement, while providing a minimum data rate of 160 bps at the 5G 164 dB MCL. As with [1], to determine the coverage that the LTE-M specification can support, Link-Level Simulation (LLS) analysis of every LTE-M channel was conducted. For consistency, the simulation assumptions across the different channels are as common as possible as shown in Table 4.

PARAMETER	PSS/SSS	PBCH	SIB1-BR	MPDCCH	PDSCH	PUSCH	PUCCH	PRACH
Max TX power	46 dBm					23 dBm		
System bandwidth	5 or 10 MHz							
Configuration	Half Duplex FDD							
Carrier frequency	2 GHz							
Antenna configuration	2 TX and 1 RX, low correlation					1 TX and 2 RX, and 1 TX and 4 RX, low correlation		
Channel model	ETU 1 Hz							
Number of PRBs	N/A	N/A	6	6	6	1	1	6
Physical channel format	N/A	PBCH with repetition	208-bit TBS every 5 ms	DCI format 6-1A (18 bits)	Various TBSs	Various TBSs	PUCCH format 1A	PRACH format 2
Transmission mode	N/A	TM2	TM2	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	30 Hz
Channel estimation	N/A	Cross SF	Cross SF	Cross SF	Cross SF	Cross SF	Cross SF	N/A
Frequency hopping	No	No	Yes	Yes - 16 SF				
Performance target	Acquisition time versus SNR at 0.1% false detection probability	Acquisition time versus SNR at 0.1% false detection probability	Acquisition time versus SNR	SNR at 1% BLER	Data speed at 10% BLER versus SNR	Data speed at 10% BLER versus SNR	Misdetection probability at 1% false detection probability	Misdetection probability at 0.1% false detection probability

Table 4: LLS Assumptions

4.1 UPLINK DATA CHANNEL (PUSCH)

This section includes the LLS results for the Physical Uplink Shared Channel (PUSCH) which carries the UL user data. Table 5 shows the UL data rate at the 5G 164 dB MCL for various system configurations.

SYSTEM				DATA RATE
Base Station RX Antennas	System BW	HARQ	MPDCCH PSD Boost	
2	10 MHz	Yes	No	201 bps
4	10 MHz	Yes	No	313 bps
4	5 MHz	Yes	No	363 bps
4	10 MHz	Yes	+4 dB	363 bps

Table 5: PUSCH Data Rates at the 5G 164 dB MCL

Note: The calculation of the above physical layer data rate doesn't include the impacts of header overhead for Media Access Control (MAC), Radio Link Control (RLC), Packet Data Convergence Protocol (PDCP), or Internet Protocol (IP), or MPDCCH scheduling delays.

Note also that Hybrid Automatic Repeat Request (HARQ) was used in all configurations as it was found to improve the average data rate. In all cases, the initial transmission had 512 repeats and then a maximum of two HARQ re-transmissions of 512 repeats were sent. The resulting or residual Block Error Rate (BLER) in every case was less than 10%. The calculated data rate includes the average time to schedule the additional HARQ re-transmissions. The average data rate is calculated based on the BLER achieved after each HARQ cycle.

KEY MESSAGE

At 363 bps, LTE-M meets the 5G IoT UL data rate coverage requirement of 160 bps at the 5G 164 dB MCL.

Since the 5G IoT requirements do not specify a system configuration, different system bandwidths (BWs), base station antenna configurations, and downlink PSD boost configurations were simulated. As can be seen from Table 5, usage of four receive antennas at the base station significantly improves the UL data rate. Also, using +4 dB of downlink PSD boost or having a 5 MHz system bandwidth reduces the number of required MPDCCH repeats from 256 to 128 repeats, which decreases HARQ scheduling time and marginally improves the UL data rate.

4.2 DOWNLINK DATA CHANNEL (PDSCH)

This section includes the LLS results for the Physical Downlink Shared Channel (PDSCH) which carries the DL user data. Table 6 shows the DL data rate at the 5G 164 dB MCL for various system configurations.

SYSTEM				DATA RATE
Base Station RX Antennas	System BW	HARQ	DL PSD Boost	
2	10 MHz	Yes	No	300 bps
4	10 MHz	Yes	No	372 bps
4	5 MHz	Yes	No	1000 bps
4	10 MHz	Yes	+4 dB	1200 bps

Table 6: PDSCH Data Rates at the 5G 164 dB MCL

KEY MESSAGE

At 1200 bps, LTE-M easily meets the 5G IoT DL data rate coverage requirement of 160 bps at the 5G 164 dB MCL.

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

Note that for the HARQ configuration, the initial PDSCH transmission used 1024 repeats, and then one HARQ re-transmission of 512 repeats occurred. As with PUSCH, the calculated data rate includes the average time to schedule the additional HARQ re-transmission and the average data rate is calculated based on the BLER achieved after each HARQ cycle.

4.3 CONTROL CHANNELS

This section includes the LLS results for all the control channels. Table 7 shows the performance at the 5G 164 dB MCL for various system configurations.

CHANNEL	SYSTEM BW	DL PSD BOOST	PERFORMANCE
PSS/SSS	10 MHz	No	Average acquisition time 880 ms
	5 MHz	No	Average acquisition time 350 ms
	10 MHz	+4 dB	Average acquisition time 220 ms
PBCH	10 MHz	No	Average acquisition time 250 ms
	5 MHz	No	Average acquisition time 150 ms
	10 MHz	+4 dB	Average acquisition time 125 ms
SIB1-BR	10 MHz	No	Average acquisition time 650 ms
	5 MHz	No	Average acquisition time 200 ms
	10 MHz	+4 dB	Average acquisition time 150 ms
MPDCCH	10 MHz	No	256 repeats achieve 10% BLER
	5 MHz	No	128 repeats achieve 1% BLER
	10 MHz	+4 dB	128 repeats achieve <1% BLER
PRACH	10 MHz	No	128 repeats achieve 3% misdetection
PUCCH	10 MHz	No	128 repeats achieve <1% misdetection (Release 14)

Table 7: Control Channel Performance at the 5G 164 dB MCL

Note that the 128-repeat level of the Physical Uplink Control Channel (PUCCH) is a Release 14 feature. All other repeat levels are supported in Release 13.

Given the 5G IoT requirements do not specify a system configuration, the performance of the DL control channels was analyzed for different system bandwidths and optionally with PSD boost.

For the Primary and Secondary Synchronization Signals (PSS/SSS), Physical Broadcast Channel (PBCH), and System Information Block 1-Bandwidth Reduced (SIB1-BR), 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. Therefore, the average acquisition time is provided in Table 7. The PSS/SSS detection method analyzed is the same as in [1], which

KEY MESSAGE

LTE-M control channels can effectively operate at the 5G 164 dB MCL coverage level.

combines PSS and SSS sequences for correlation used for re-synchronization. The PBCH detection method analyzed is also the same as used in [1], which correlates the received rate matched symbols against possible transmitted PBCH symbols and then tests the multiple hypotheses to look for a match.

For the remaining channels, a BLER or probability of missed detection is specified.

As seen in Table 7, less than 10% BLER is achieved for all control channels; thus, all control channels can effectively operate at the 5G 164 dB MCL. As can also be seen from Table 7, downlink PSD boosting or a 5-MHz system bandwidth significantly reduces both acquisition time and BLER for the DL channels.

Although not analyzed, a system configuration with four base station receive antennas would significantly improve both the PRACH and PUCCH performance.

KEY MESSAGE

LTE-M meets the 5G 164 dB MCL coverage requirement.

4.4 COVERAGE SUMMARY

Given that the 160 bps data rate target is met by both the UL and DL data channels, and that the LTE-M control channels can effectively operate at the 5G 164 dB MCL coverage level, it can be concluded that LTE-M meets the 5G 164 dB MCL coverage requirement.

5 Message Latency

For the many IoT applications where small data transmission is common, the message latency is an important metric for estimating the performance of the provided service. This section considers the message delivery time or message latency that can be achieved by LTE-M at the 144 and 164 dBs coupling losses, which can be said to correspond to the edge of normal and enhanced coverage, respectively. The analysis is based on LLS results with assumptions from Table 4 (unless otherwise stated) and the message sequence described in Section 5.1. The message latency is calculated up to and including the delivery of an 85-byte uplink message. That is, message latency calculation doesn't include any of the messages after the delivery of the 85-byte uplink message. The message latency is calculated using the 90th percentile for each step, which is a conservative approach. The message latency was analyzed for both the CIoT 164 dB MCL and the 5G 164 dB MCL.

It should be noted that neither the CIoT nor the 5G IoT requirements consider the boot time of the modem which can, depending on implementation, be hundreds of milliseconds. Furthermore, neither set of requirements considers any delays for the network to respond to protocol control messages from the device. This delay depends on many factors, including any congestion in the network. This delay is often on the order of 50 ms for commercially deployed networks. Hence the practical latency may deviate from the estimates in this section depending on factors specific to the implementation and load.

5.1 MESSAGE SEQUENCE

For the latency evaluations, the message sequence in Figure 1 was used. This corresponds to the device waking up from Power Saving Mode (PSM) using the Radio Resource Control (RRC) Resume procedure to resume a suspended RRC connection. The same message sequence was used for the battery life evaluations in Section 6.

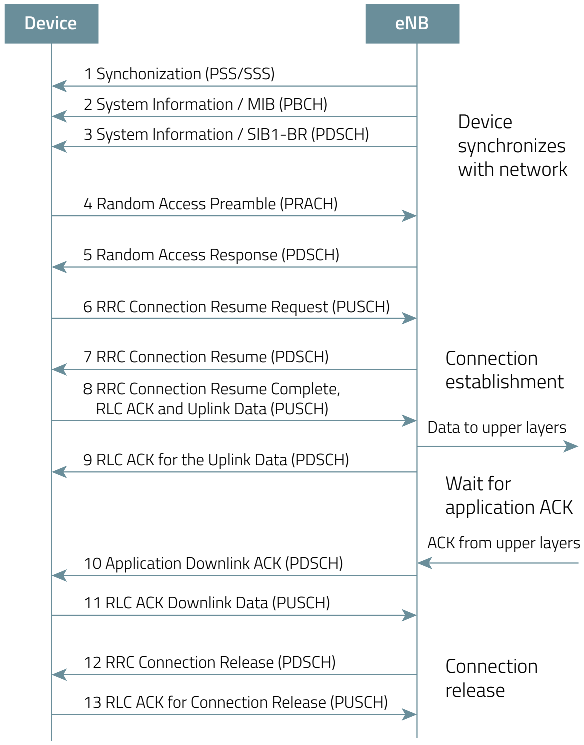


Figure 1: Message sequence for battery life and latency evaluations

Figure 1 depicts the RRC Resume procedure for transmitting a mobile originated (MO) report including the following steps:

1. Synchronizing to the PSS/SSS after waking up from PSM to achieve time and frequency synchronization, and to acquire subframe timing, physical cell identity, and cyclic prefix length information.
2. Reading Master Information Block (MIB), or PBCH, to acquire the System Frame Number and SIB1-BR scheduling information.
3. Reading SIB1-BR to acquire the Hyper System Frame Number and system information value tag, and access barring status (more exactly the SIB14-BR scheduling information status).
4. Sending the random access preamble on PRACH.
5. Receiving Random Access Response (7 bytes), including grant for the next uplink transmission.
6. Sending RRC Connection Resume Request message (MSG3: 7 bytes), including the device identity.
7. Receiving RRC Connection Resume message (MSG4: 20 bytes), together with the device contention resolution identity.
8. Transmitting RRC Connection Resume Complete message, together with Radio Link Control Acknowledge (RLC ACK) for the previous transmission (total 22 bytes) and the uplink data including headers from the LTE radio protocol stack (85 or 200 bytes of data, 5 bytes of headers).
9. Receiving RLC ACK for RRC Connection Resume Complete (3 bytes)
10. Receiving downlink application ACK (20 or 65 bytes).
11. Transmitting RLC ACK for downlink application ACK (3 bytes)
12. Receiving RRC Connection Release (8 bytes).
13. Transmitting the RLC ACK for the RRC Connection Release

The RRC messages are assumed to be sent without optional fields in them; if additional configuration information is added to a specific message, the message size will be correspondingly larger. MAC, RLC, and PDCP headers are added to the RRC messages when appropriate. Uplink data is sent in Step 8, together with the RRC Connection Resume Complete message.

Additionally, the evaluation takes into account the overheads from the HARQ and RLC acknowledgements. The first message using HARQ for repeating the uplink transmission, if needed, is Msg3 in step 6. RLC Acknowledged Mode (AM) is used for all messages starting at Msg4 in step 7. In our analysis, we assume the RLC protocol does not need to ask for retransmissions and that RRC connection and release procedures are always successful.

KEY MESSAGE

LTE-M easily meets CIoT message latency requirements.

5.2 MESSAGE LATENCY AT CIOT 164 DB MCL

The CIoT message latency requirement from TR 45.820 [2] is to be able to send an 85-byte message within 10 seconds at the CIoT 164 dB MCL coverage level. As per CIoT requirements, the evaluation was conducted assuming a 10-MHz system bandwidth and eNBs implementing two transmit and two receive antennas at the base station. The LLS results are shown in Table 8.

CIoT 164 dB MCL	CIoT 144 dB MCL
6.2 sec	0.1 sec

Table 8: 90th Percentile Message Latency

Table 8 shows that the CIoT message latency requirement of 10 seconds is easily met by LTE-M. As table 8 also shows, the message latency is highly dependent on coverage level, so in normal coverage the message latency is much lower.

KEY MESSAGE

LTE-M meets 5G message latency requirements for most system configurations.

5.3 MESSAGE LATENCY AT 5G 164 DB MCL

The 5G IoT message latency requirement from TR 38.913 [3] is to be able to send an 85-byte message within 10 seconds at the 5G 164 dB MCL coverage level. The results are shown in Table 9.

BASE STATION ANTENNA CONFIGURATION	5G 164 dB MCL		
	10 MHz No DL PSD Boost	10 MHz +4 DL PSD Boost	5 MHz No DL PSD Boost
2 RX, 2 TX	14.3 sec	9.6 sec	9.8 sec
4 RX, 2 TX	11.4 sec	6.7 sec	6.9 sec

Table 9: 90th Percentile Message Latency at the 5G 164 dB MCL

Given the 5G IoT requirements do not specify a system configuration, the message latency was analyzed for different system bandwidths, different base station antenna configurations, and with and without downlink PSD boosting.

From the results in Table 9, it can be concluded that a 5-MHz system, or a 10-MHz system using downlink PSD boosting, will meet the 5G message latency requirement. In addition, the results indicate that with four instead of two receive antennas at the base station, the message latency improves by approximately 20%, allowing a 10-MHz system without downlink PSD boosting to almost meet the 5G message latency requirement.

6 Battery Life

In large-scale IoT deployments, it is important to be able to provide services to all types of use cases, including those without access to a mains power supply. This section considers the battery life that can be achieved for an LTE-M device powered by a 5-Wh AA battery when used for daily reporting of 200-byte uplink messages coupled with 20 or 65-byte downlink acknowledgements. The evaluation is based on the message sequence chart of Section 5.1, LLS assumptions from Table 4 (unless otherwise stated), and the power consumption in various modes shown in Table 10. The power consumption values in Table 10 are consistent with the assumptions used in the CIoT Study except for the UL transmit Power. The CIoT Study assumed 500 mW but this study assumed 575 mW, translating to a power amplifier (PA) efficiency difference of approximately 20% due to the higher Peak-to-Average-Power Ratio (PAPR) for LTE-M single Physical Resource Block (PRB) transmissions.

OPERATING MODE	POWER CONSUMPTION
UL TX power	575 mW
DL RX power	80 mW
C-DRX / I-DRX sleep power	3 mW
Deep sleep power	0.015 mW

Table 10: Power Consumption of LTE-M Device in Different Operating Modes

It should be noted that a 5-Wh battery without self-discharge was used for this evaluation. Neither the CIoT nor 5G IoT requirements consider the battery self-discharge, even though self-discharge occurs to some level with all battery technologies and is typically in the range of one to four percent per year. Also, as mentioned in the section on message latency, neither CIoT nor 5G IoT requirements consider the boot time of the modem, which can be hundreds of milliseconds. A significant proportion of device power consumption is associated with the power required to transmit data packets, so the PA efficiency assumption greatly affects the resulting battery life. PA efficiencies of 50% were considered in the CIoT study and 40% in this analysis, but the reality is that commercial modems are likely to use PAs with lower efficiencies to support wider bands, and are likely to have losses associated with front-end filters, switches, and printed circuit boards, which are not taken into consideration. Hence the practical battery life may deviate from the estimates in this section depending on implementation-specific factors.

KEY MESSAGE
LTE-M meets CIoT battery life requirements.

6.1 BATTERY LIFE AT CIOT 164 DB MCL

This section evaluates the CIoT battery life requirement from TR 45.820 [2]. The years of use for LTE-M, for daily transmission of 200-byte UL messages and 65-byte DL messages are given in Table 11. These battery life values were calculated assuming a 10-MHz system bandwidth and eNBs implementing two transmit and two receive antennas.

CIoT 164 dB MCL	CIoT 144 dB MCL
10.4 years	35.7 years

Table 11: Battery Life Based on CIoT MCL

Table 11 shows that the CIoT battery life requirement of 10 years is met by LTE-M for the daily reporting of 200-byte reports in the uplink, even at the extremes of coverage. The battery life was also evaluated at CIoT 144 dB MCL, which is the extreme edge of normal coverage, to show that battery life improves significantly where normal (non-coverage enhanced) devices operate. As seen from Table 11, 10.4 versus 35.7 years of battery life is a large difference for the two coverage cases, showing that battery life is highly dependent on coverage. As LTE networks continue to be deployed and densified, network coverage is expected to improve, and this will in turn significantly improve battery life.

KEY MESSAGE

LTE-M meets 5G battery life requirements.

6.2 BATTERY LIFE AT 5G 164 DB MCL

This section evaluates the 5G IoT battery life requirement from TR 38.913 [3]. The years of use for daily transmission of 200-byte UL messages and 20-byte DL messages at the 5G 164dB MCL are given in Table 12.

BASE STATION ANTENNA CONFIGURATION	5G 164 dB MCL		
	10 MHz No DL PSD Boost	10 MHz +4 DL PSD Boost	5 MHz No DL PSD Boost
2 RX, 2 TX	6.9 years	7.5 years	7.5 years
4 RX, 2 TX	9.6 years	10.9 years	10.8 years

Table 12: Battery Life at 5G 164 dB MCL

KEY MESSAGE

LTE-M battery life improves when eNBs implement four receive antennas.

From Table 12, it can be concluded that a 10-year battery life is possible for LTE-M when the base station implements four receive antennas and either a 5-MHz system bandwidth (without the need for downlink PSD boosting) or a 10-MHz system bandwidth with downlink PSD boosting applied. An uplink message size of 100 instead of 200 bytes supports a 10-year battery life for all the two-receive antenna base station configurations in Table 12.

7 Capacity

7.1 EVALUATION ASSUMPTIONS

System capacity is an important performance indicator for LTE-M, since LTE-M strives to provide connectivity for the mMTC usage scenario. mMTC spans a large variety of services and applications, as described in [5]. ITU-R also specifies a concrete requirement on IMT-2020 systems in terms of a required connection density of 1,000,000 devices per square kilometer. The full set of IMT-2020 requirements, including the connection density requirement, is described in [6] while the methodology for evaluation of the IMT-2020 requirements appears in [4].

In short, an IMT-2020 system should be capable of handling 1,000,000 devices per km^2 that perform a mobile originated access once every two hours, following a Poisson arrival process, where each device is to deliver a 32-byte layer-2 Packet Data Unit (PDU) within 10 seconds. The most important IMT-2020 requirements and configurations defining the connection density key performance indicators are summarized in Tables 13 and 14. Since configuration B is the more challenging configuration, as it needs to support a higher number of devices per cell, it is the focus of this paper.

REQUIREMENT	VALUE
Connection density	≥1,000,000 devices/km^2
Grade of service	≥99%
Quality of service	≤10 seconds service latency

Table 13: IMT-2020 Connection Density Requirement

PARAMETER	VALUE	
	CONFIGURATION A	CONFIGURATION B
Traffic model	32-byte mobile originated message every 2 hours	
Carrier frequency	700 MHz	
Inter-site distance	500 meters	1732 meters
Channel model	Urban Macro A, Urban Macro B	
Device deployment	80% indoor, 20% outdoor	
Building type ratio for indoor users	20% high loss, 80% low loss	
Mobility	3 km/h	
Base station output power	46 dBm	
Base station antenna configuration	Up to 64 TX/RX	
Base station antenna gain per antenna element	8 dBi	
Base station noise figure	5 dB	
Device output power	23 dBm	
Device antenna configuration	Up to 2 TX/RX	
Device antenna gain	0 dBi	
Device noise figure	7 dB	
Bandwidth	≤10 MHz	≤50 MHz

Table 14: IMT-2020 Connection Density Requirement

7.2 EVALUATION RESULTS

To show fulfilment of the IMT-2020 connection density requirement, an LTE-M dynamic system-level simulator was configured according to the parameters summarized in Table 14. In the simulation, a single LTE-M narrowband consisting of six PRBs was configured in 21 cells defining the studied system. This narrowband did not carry any overhead from PSS/SSS or MIB/SIB transmission. The total simulation bandwidth equals 1.08 MHz. Base stations were configured with two cross-polarized transmit/receive antennas, each with 8 elements resulting in an antenna gain of 17 dBi, whereas devices were configured with one transmit/receive antenna.

KEY MESSAGE

Key Finding: For the worst case IMT-2020 configuration, LTE-M can support 357,000 devices per 1.08-MHz narrowband per km².

Figure 2 presents the supported service latency defined from the time the higher layers in a device trigger a mobile originated access attempt to the time the base station receiver confirms successful reception of the packet. Specifically, Figure 2 depicts the latency achieved at the 99th percentile of the latency cumulative distribution function recorded across all simulated packet deliveries during the life time of the simulation. The 99th percentile is of special interest since it corresponds to the Grade of Service requirement.

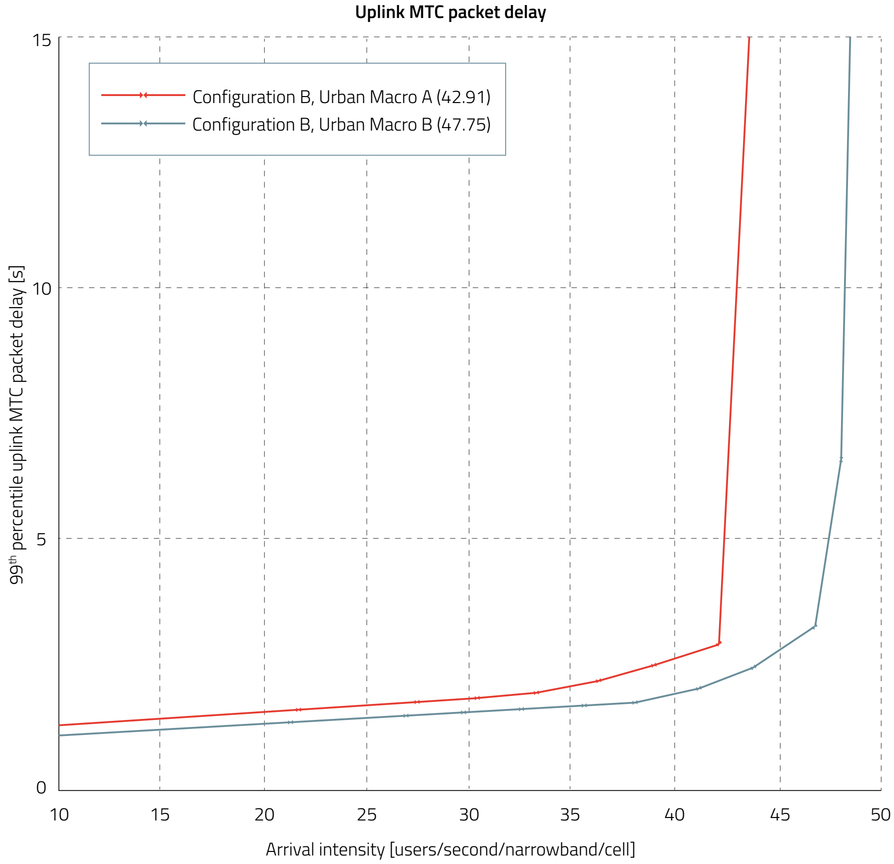


Figure 2: Service latency measured at the 99th percentile

The system-level simulation (SLS) results in Figure 2 show that the most challenging channel model is the Urban Macro A channel. Assuming an Urban Macro A channel, LTE-M can support 43 accesses per second per narrowband per cell, which equates to approximately 357,000 supported devices per 1.08-MHz narrowband per km².

With 357,000 supported devices per narrowband, LTE-M can thus support more than 1,000,000 devices using four narrowbands. For a 5-MHz system bandwidth (see Figure 3) only 70% of the capacity is utilized to meet the requirement. The downlink PRB utilization is only around 25% when the system operates at its capacity limit (43 accesses/second/narrowband/cell), so it can be assumed that this spare downlink capacity can accommodate the overhead from PSS, SSS, and PBCH, which is less than 5%. Compared to the 50-MHz bandwidth limitation stipulated by IMT-2020 evaluation guidelines [4], 5 MHz fulfils the capacity requirement by a large margin.

KEY MESSAGE
70% of a 5-MHz LTE-M system meets the IMT-2020 requirement of 1 million devices per km^2 in 50 MHz.

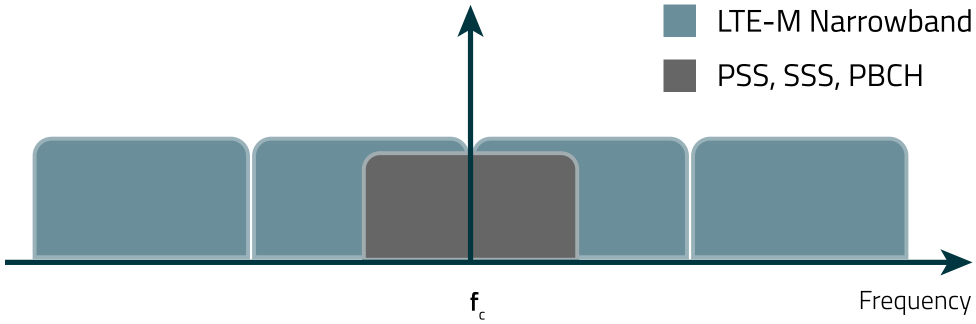


Figure 3: Arrangement of LTE-M narrowbands for a 5-MHz carrier

To ensure that systems are evaluated at a reasonable uplink load, IMT-2020 also requires that the uplink Interference-over-Thermal is kept below 10 dB. In this case, this means that the average noise and interference that the base station experiences in the uplink should be below -106.4 dBm/PRB. For the Urban Macro A channel, the 99th percentile packet delay reaches 10 seconds at approximately 43 users/second/narrowband/cell, and at this point the uplink interference is approximately -111 dBm/PRB and is thus well below -106.4 dBm/PRB.

KEY MESSAGE
Several LTE-M enhancements are coming in Releases 14 and 15 that will improve the battery life, message latency, and capacity results presented in this paper.

8 LTE-M Enhancements in Releases 14 and 15

As seen from the above results, the 5G battery life and message latency requirements are met by LTE-M. In 3GPP releases 14 and 15 further enhancements are currently being developed to improve battery life, message latency, and other aspects of performance, which will make it possible to meet the requirements with more system configurations.

Release 14 [8] introduces Release Assistance Information (RAI) which allows the device to request it be released from the connected state after it has completed all its communications. This reduces the time the device spends in the connected state and thereby reduces power consumption. In addition to this battery-life improvement, Release 14 features also include increased data throughput, a new 5-MHz category-M2 device, multicast support, positioning enhancements, voice optimizations, and improved mobility support. For a full description of the LTE-M features introduced in Release 14, see the work item summary in [9].

Release 15 enhancements for LTE-M are ongoing and expected to be completed by June 2018 [10]. Key objectives for this release include improving latency, spectral efficiency, and power consumption. To improve latency, potential enhancements include reducing system acquisition time (e.g. by improving cell search or system information acquisition performance) and supporting early data transmission (i.e. data transmission already during the random access procedure). The spectral efficiency, and hence the system capacity, is improved in the downlink by the introduction of higher-order modulation (64QAM) and in the uplink by the introduction of finer-granularity (sub-PRB) resource allocation. To reduce power consumption, potential enhancements include introducing the already mentioned early data transmission and sub-PRB resource allocation as well as wake-up signals, new synchronization signals, improved HARQ feedback, and relaxed measurements for cell reselection.

Supporting the features introduced in Releases 14 and 15 is optional for both the device and the network. All UEs and networks are fully backward compatible with Release 13, meaning that the new features can be introduced gradually.

KEY MESSAGE

LTE-M category-M1 meets all CIoT and 5G IoT requirements from 3GPP and ITU.

9 Summary

The LTE-M category-M1 performance is evaluated against the CIoT and 5G requirements for message latency, battery life, and capacity. Table 15 summarizes the results.

As seen from Table 15, LTE-M meets all the CIoT and 5G IoT requirements. The 5G battery life and message latency requirements are met for certain system configurations, and LTE-M enhancements are currently being developed in 3GPP Release 15 to further improve the battery life, message latency, and capacity. Preliminary indications suggest 5G requirements will be supported for all system configurations with these new Release 15 enhancements.

	REQUIREMENT	LTE-M PERFORMANCE
CIoT Requirements		
Message latency	≤10 seconds	6.2 seconds
Battery life	≥10 years	10.4 years
5G Requirements		
Capacity 1 million devices per km2	≤50 MHz	70% of a 5 MHz system
Coverage	≥160 bps	UL 363 bps & DL 1200 bps*
Message latency	≤10 seconds	6.7 seconds*
Battery life	≥10 years	10.9 years*

Table 15: LTE-M Performance Summary

** Assumes four receive and two transmit antennas at the base station and +4 dB downlink PSD boosting*

10 References

[1] "Coverage Analysis of LTE-M Category-M1" V1.0 Jan 2017, https://sierrawireless.com/-/media/iot/pdf/LTE-M-White-Paper

[2] TR 45.820 V13.1.0, "Cellular system support for ultra-low complexity and low throughput Internet of Things (CIoT)"

[3] TR 38.913 V14.3.0, "Study on scenarios and requirements for next generation access technologies"

[4] Draft version of Report ITU-R Mxxxx "Guidelines for evaluation of radio interface technologies for IMT-2020", https://www.itu.int/md/R15-SG05-C-0056/en

[5] Recommendation ITU-R M.2083 - "IMT Vision - Framework and overall objectives of the future development of IMT for 2020 and beyond", https://www.itu.int/rec/R-REC-M.2083

[6] Report ITU-R M2410-0 – "Minimum requirements related to technical performance for IMT-2020 radio interface(s)", https://www.itu.int/pub/R-REP-M.2410

[7] RP-150492, Rel 13 3GPP Work Item Description "Further LTE Physical Layer Enhancements for MTC"

[8] RP-170532, Rel 14 3GPP Work Item Description "Further Enhanced MTC for LTE"

[9] RP-171441, Rel 14 3GPP Work Item Summary "Summary for WI Further Enhanced MTC for LTE"

[10] RP-171427, Rel 15 3GPP Work Item Description "Even Further Enhanced MTC for LTE

CONTACTS

Sierra Wireless	Gus Vos (Editor)	gvos@sierrawireless.com
Ericsson	Johan Bergman	johan.bergman@ericsson.com
Altair	Yigal Bitran	yigal@altair-semi.com
Sony	Martin Beale	martin.beale@sony.com
Virtuosys	Mark Cannon	mark.cannon@virtuosys.com
AT&T	Robert Holden	rholden@att.com
Verizon	Yee Sin Chan	yeesin.chan@verizonwireless.com
Sequans	Guillaume Vivier	gvivier@sequans.com
Orange	Ronan Le Bras	ronan.lebras@orange.com
KDDI	Toshiyasu Wakayama	to-wakayama@kddi.com
Nokia	Rapeepat Ratasuk	rapeepat.ratasuk@nokia-bell-labs.com
NTT DOCOMO	Naoto Okubo	ookubona@nttdocomo.com
KT	Kyujin Park	kyujin.park@kt.com
SoftBank	Yosuke Akimoto	yosuke.akimoto@g.softbank.co.jp
SK Telecom	Sangmin Lee	lesam821@sk.com
Telenor	Sofia Tropé	sofia.trope@telenor.com
KPN	Frank Mertz	frank.mertz@kpn.com