On the Achievable Coverage and Uplink Capacity of Machine-Type Communications (MTC) in LTE Release 13

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***Abstract*—LTE Release 13 has introduced coverage enhancement (CE) mode "CE Mode B" to support MTC deployments that require medium-to-large CE, compared to the baseline coverage for LTE voice communications. In this paper, we describe the operation of CE Mode B for the supported physical data and control channels, and study the dimensioning of this mode for each of these channels. We provide link-level simulation results for CE Mode B, which illustrate the possibility of MTC operation at a coupling loss up to 160 dB. Further, we study the achievable uplink capacity in terms of the blocking probability for new scheduling requests. We show that for most of the typical autonomous reporting scenarios, the existing LTE configurations can provide sufficient uplink capacity.**

I. INTRODUCTION

MTC is currently an important focus area in the evolution of cellular networks, and is expected to underpin several new use cases within the networked society [1]. In LTE Release 13, the MTC applications of interest are those that rely on infrequent transmission of relatively small payloads, and may additionally be delay-tolerant compared to the mobile broadband applications. A typical MTC application would require a few transmissions per day of payloads up to a few hundred kilobits, and may be able to relax its delay tolerance up to a few hundred milliseconds for the transmission of each transport block in poor radio conditions.

LTE enhancements for MTC have been introduced in Release 11, 12, and 13, with the three-pronged goal of extending the network coverage to serve MTC deployments in remote radio locations, supporting low-cost/complexity User Equipments (UEs) for large-scale deployment, and increasing the UE battery lifetime for maintenance-free operation up to several years [2] [3]. In LTE Release 13, CE features have been introduced that extend the network coverage by 15 dB or more beyond the coverage for baseline voice communication. The coverage metric of interest is the supported Maximum Coupling Loss (MCL) for which the physical channels have a reasonable performance (e.g., 1% error rate for control channels and 10% Block Error Rate (BLER) for the first hybrid ARQ (HARQ) transmission in case of data channels) [4]. Further from a network perspective, a major MTC goal is to provide sufficient capacity to support a deployment of UEs that is an order or more in number compared to the human-centric UEs within a cell.

In Release 13, a new low-complexity UE category, "Cat-M1", has been introduced that allows a cost reduction up to 80% compared to a Release 8 single-band LTE Cat-1 UE modem. The CE features introduced in Release 13 are supported by Cat-M1 UEs, however, UEs belonging to any other category may take advantage of these features by mimicking the operation of a Cat-M1 UE. In this paper, we use the term "MTC UE" to refer to any UE that uses the Release 13 CE features. Further in conjunction with the CE Mode B that corresponds to medium-to-large CE, this release has specified a complementary "CE Mode A", which corresponds to none-to-medium CE. The MTC UEs always operate in either CE Mode A or CE Mode B, where each mode is configured with a well-defined set of transmission parameters for each physical channel.

In Section II, we discuss the initialization and toggling of the CE modes, and elaborate the CE Mode B operation of the various physical channels. In Section III we outline a few uplink-heavy MTC deployment scenarios and discuss an approach to evaluate the capacity in terms of blocking probability of new uplink scheduing requests. In Section IV, we present link-level simulation results for the error rate and/or throughput performance of supported physical channels in CE Mode B. Further, we evaluate the uplink capacity for each deployment scenario. In Section V, we conclude the paper.

II. CE MODE B DIMENSIONING AND OPERATION

In Release 13, the primary CE mechanism is the repetition of information bits over contiguous uplink/downlink subframes, sometime referred to as "bundling". This techniques is illustrated in Fig. 1, where the control information, the associated data transmission and the subsequent hybrid-ARQ acknowledgements are repeated. The receiver combines the subframes within each bundle coherently (i.e., after channel estimation), either at a symbol level if identical symbols are transmitted in more than one subframe, or at a soft bit level if symbols in the subframes differ in terms of coding, interleaving, cover codes, etc. Additional CE features introduced in this release include support for cross-subframe channel estimation and frequency hopping within a bundle.

For most physical channels, the Downlink Control Information (DCI) contains an index that determines the repetition value to be used from within a configurable set of repetition numbers. This set may be configured on a per-channel and per-CE Mode basis [5][6][7][8]. The allowed values of repetition numbers in CE Mode B are listed in Table I for each supported physical channel.

TABLE I
ALLOWED PHYSICAL CHANNEL REPETITION NUMBERS IN CE MODE B.

Physical Channel	Number of Repetitions
Physical Downlink Shared Channel (PDSCH)	[1,2,4,...,2048]
Physical Uplink Shared Channel (PUSCH)	[1,2,4,...,2048]
MTC Physical Downlink Control Channel (MPDCCH)	[1,2,4,...,256]
Physical Uplink Control Channel (PUCCH)	[4,8,16,32]

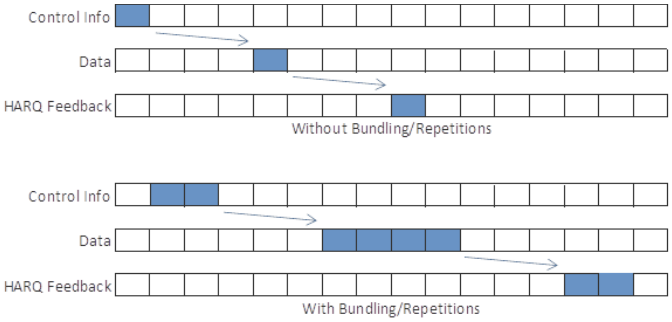

Fig. 1. In Release 13, the main CE feature is the repetition of coded information bits over several contiguous subframes for all supported data and control channels (sometimes referred to as "bundling").

For initial random access, a UE picks the repetition level based on the estimated downlink Reference Signal Received Power (RSRP). If it does not receive a Random Access Response (RAR) from the base station [9], the UE ramps up to the next higher repetition level until it is successful in receiving a RAR, in which case it can transition to the so-called connected mode after some control plane signaling using the Radio Resource Control (RRC) protocol. At each repetition level, the UE may perform up to a configurable maximum number of random access attempts. Further, the UE is allowed to increase the repetition level only up to three times, apart from the attempts made without any repetition. In connected mode, the initial CE mode (i.e., CE Mode A or CE Mode B) can be mapped to the repetition level that results in a successful RAR, and may subsequently be toggled using RRC signaling. In rest of this section, we describe the CE Mode B operation of MTC UEs in connected mode.

In CE Mode B, the spectral efficiency is expected to be low, since several tens or hundreds of repetitions may be required for successful decoding of the information bits at the receiver. This motivates minimizing the overheads associated with control signaling and data transmission, potentially at the cost of reduced flexibility. For control signaling, this is achieved by introducing new formats, whereas for data transmission, large repetition numbers are allowed that support the use of large Transport Block Sizes (TBSs).

Control Signaling: The downlink control signalling for MTC UEs makes use of a new control channel, MPDCCH, introduced in Release 13. MPDCCH is based on the existing LTE EPDCCH and additionally supports DCI mapping over 6 LTE Physical Resource Blocks (PRBs). In CE Mode B, additional DCI formats have been introduced for both uplink as well as downlink scheduling of MTC UEs, which use fewer bits than the corresponding CE Mode A formats.

The uplink control signaling in CE Mode B makes use of the uplink control channel, PUCCH, for downlink HARQ acknowledgements and uplink scheduling requests. However in this mode, there is no periodic or aperiodic downlink channel reporting, since such reports would add a significant signaling overhead. Similarly, the transmission of Sounding Reference Signals (SRS) has also been done away with.

Data Transmission: In CE Mode B, the uplink as well as the downlink data transmissions use a fixed modulation order of 2 (i.e., QPSK). In addition, the maximum supported repetition level is R=2048 to allow a sufficiently low BLER in CE Mode B with the largest supported TBS. For Cat-M1 UEs, the largest supported TBS is restricted to 1000 bits [10], while other UEs in CE may use larger TBS values. Using a large TBS improves the data transmission efficiency by reducing the fraction of bits used for carrying headers and the cyclic redundancy check. However, a large TBS also requires a higher number of repetitions to achieve the BLER target, which increases the latency. This tradeoff needs to be carefully studied while designing scheduling strategies that serve MTC UEs in CE.

The uplink coupling loss is expected to be quite high in CE Mode B, therefore the uplink data channel is constrained to 1 or 2 PRBs for sufficiently high power spectral density in this mode. However for a TBS of approximately 1000 bits and 2-PRB allocation, the subframe code rate is larger than 1, which is unsuitable for channel decoding. This may be solved by using a sufficiently large repetition number, which allows transmission of more coded bits by cycling through up to four redundancy versions (RVs), where each RV contains additional code bits. Cycling through the RVs within a bundle reduces the effective code rate of the bundled subframes such that it is possible to obtain reasonably low BLER at the receiver.

III. BLOCKING PROBABILITY OF UPLINK SCHEDULING REQUESTS

An important aspect of MTC deployments within cellular networks is the ability to serve several thousands of MTC UEs within each cell. Here we focus on an uplink-heavy MTC deployment, that comprises a massive number of sensors as a part of a Mobile Autonomous Reporting (MAR) application as defined in [11]. In such deployments, the UEs would be responsible for collecting some local information and periodically transmitting it over the uplink data channel. The radio channel conditions for the MTC UEs may vary significantly depending on their placement, and two typical distributions of MTC UEs with respect to the experienced wall penetration loss are also described in [11]. We consider these scenarios for uplink capacity evaluations in the next section, along with typical MTC UE deployment and payload assumptions for a smart metering solution specified in [4].

To preserve the battery lifetime, it is desirable that the MTC UEs are able to access the uplink radio resources within a reasonably small number of attempts. Therefore in this section, we discuss an approach for evaluating the performance of LTE networks in terms of the blocking probability of uplink scheduling requests. We assume that the UEs are in connected mode, so that they can send scheduling requests, and that each UE requests uplink resources at a uniform interval. If the scheduling request is granted, the UE then proceeds to transmit a fixed amount of data payload over a single PRB allocation and using the configured number of repetitions. For simplicity, we assume a single payload transmission in each attempt, i.e., no HARQ retransmissions are used. Finally, we assume that all the uplink radio resources are available for carrying either scheduling requests, or uplink data transmission.

As in LTE the uplink scheduling requests are not buffered, a pure loss model is an adequate way to model the system. Furthermore, as in real life the UE population within a cell would be finite, one way to model the system would be the Engset's model [12] ($M/M/m/m/k$ in Kendall's notation) where we would have m usable PRBs (corresponding to m parallel servers) with finite number of UEs in the cell k, where $k > m$. The equilibrium distribution of the Engset's model is the truncated binomial distribution. However, especially for MTC use cases where the number k of the devices or UEs in the cell can be considered to be very large, and the probability p of an individual UE to try to access is relatively low so that $\lambda = p \cdot k$ then it can be shown that the binomial distribution can be approximated by the Poisson distribution with mean λ. Thus also the Engset's model can be approximated by the well-known Erlang-B model [12] (i.e. $M/M/m/m$).

Based on above, for modeling the blocking probability P_B of an uplink scheduling request, we use the Erlang-B formula given by

$$P_B = \frac{\frac{E^m}{m!}}{\sum_{i=0}^{m} \frac{E^i}{i!}},$$

where E is the offered traffic in Erlang, and m is the number of identical parallel resources for handling the traffic. In our case, m is the number of uplink PRBs within the LTE system bandwidth. $E = \lambda \cdot h$ where λ is the arrival rate and h is the holding time.

IV. EVALUATIONS OF CE MODE B COVERAGE AND UPLINK CAPACITY

In this section, we provide link-level simulation results for the performance of the physical data and control channels for the Release 13 CE Mode B operation, in terms of their error rates and/or throughput for a range of coupling loss values. The maximum coupling loss at which a given BLER target may be achieved is referred to as the MCL, and is often a useful metric in discussion related to CE and latency. The simulation parameters related to the CE Mode B operation are listed in Table II. Further in this section, we evaluate the blocking probability of uplink scheduling requests for the MTC deployment scenarios discussed in the previous section.

TABLE II
SIMULATION PARAMETERS FOR COVERAGE EVALUATIONS

Simulation Parameter	Value
Carrier frequency	2 GHz
System bandwidth	10 MHz
Channel model	EPA
Doppler	1 Hz
Antenna	2x1 (DL), 1x2 (UL)
Antenna correlation	Low
Residual frequency offset	25 Hz
Timing error	None
TBS (data transmission)	936 bits
Base station noise figure	5
UE noise figure	9
Thermal noise density	-174 dBm/Hz
UE transmit power	23 dBm
Base station transmit power	46 dBm

The BLER for the first HARQ transmission and associated throughput for downlink data transmission over PDSCH are shown in Fig. 2 and Fig. 3 respectively, with respect to the coupling loss. With the assumptions used in the link budgets in [4], the baseline MCL for LTE voice communications is 140.7 dB, and thus the 15 dB CE target corresponds to a coupling loss of 155.7 dB. The simulations have been performed for the maximum supported TBS for CE Mode B operation in the downlink, i.e., TBS 936 bits. The PDSCH transmission occupies 6 PRBs, using frequency hopping between the edges of the system bandwidth every 32 ms. Cross-subframe channel estimation is used, with an infinite impulse response that effectively averages the channel over approximately 5 subframes.

From Fig. 2 it can be concluded that 1024 repetitions may be needed in order to achieve 10% BLER target for the first HARQ transmission at coupling loss 160 dB for TBS 936 bits. Using the maximum repetition level, R=2048, it is also possible to achieve BLER levels below 1% for this configuration. The BLER metric can be particularly relevant when considering transmissions of isolated messages, in this case containing 936 bits on the physical layer. For larger data transmissions more extended in time, it may instead be more relevant to consider the achievable throughput, which is depicted in Fig. 3. From the figure it can be concluded that approximately 1.8 kbps can be achieved at coupling loss 160 dB. The optimum repetition level to achieve this throughput is R=128, and the corresponding BLER operating point is around 75%, i.e. considerably higher than the 10% BLER which is often used as a reference target in cellular communication.

The BLER for the first HARQ transmission and associated throughput for uplink data transmission over PUSCH are shown in Fig. 4 and Fig. 5 respectively. The maximum supported uplink TBS in CE Mode B, TBA 936 bits, is used with a 2-PRB PUSCH allocation. The receiver averages the channel estimates over 4 subframes using a sliding window. The PUSCH transmission hops across the system bandwidth every 32 subframes, however, there is no retuning guard interval in these simulations. In practice, each frequency retuning instance

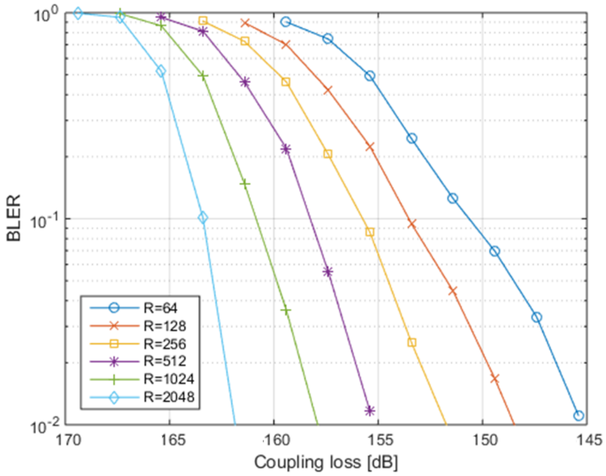

Fig. 2. PDSCH block error rate with 6-PRB allocation and TBS 936 bits, with frequency hopping across the system bandwidth every 32 subframes and cross-subframe channel estimation.

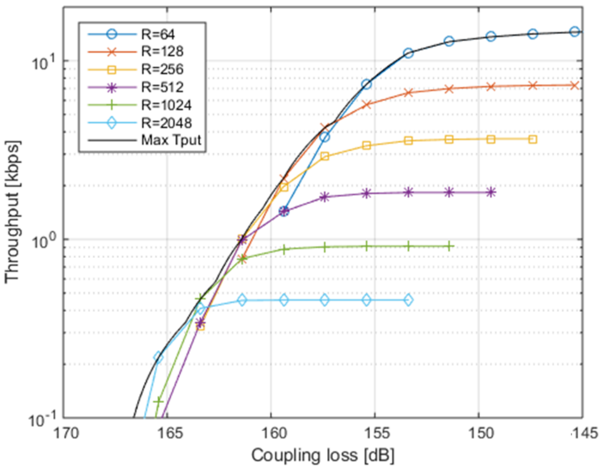

Fig. 3. PDSCH throughput with 6-PRB allocation and TBS 936 bits, with frequency hopping across the system bandwidth every 32 subframes.

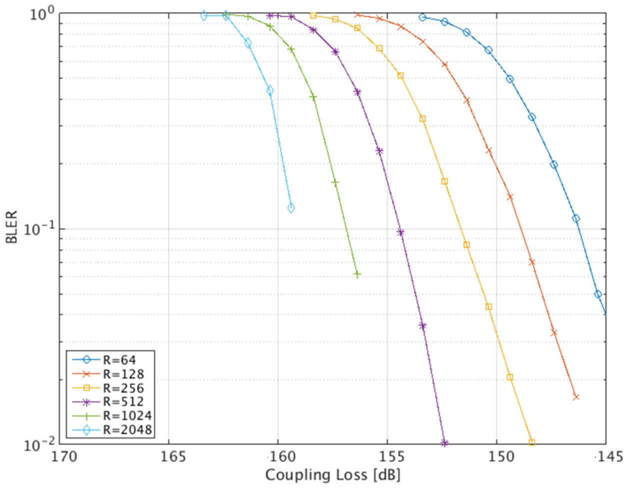

Fig. 4. PUSCH block error rate for the first HARQ transmission, with 2-PRB allocation and TBS 936 bits. The channel estimates are averaged over 4 subframes, and the PUSCH transmission hops across the system bandwidth every 32 subframes. Cross-subframe channel estimation is used with a sliding window filter spanning 4 subframes.

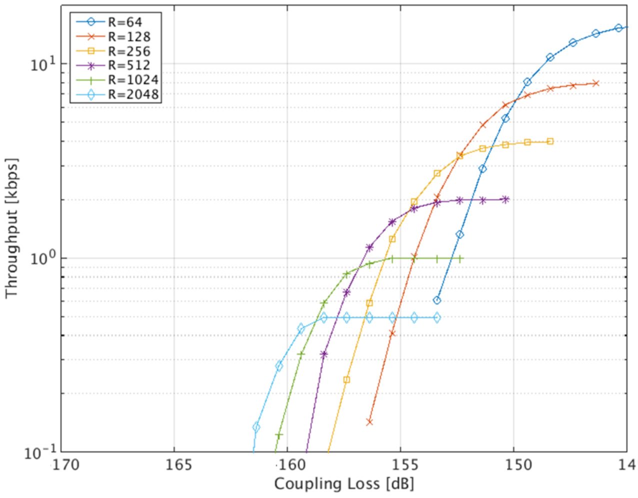

Fig. 5. PUSCH throughput with 2-PRB allocation and TBS 936 bits, frequency hopping across the system bandwidth every 32 SF. Cross-subframe channel estimation is used with a sliding window filter spanning 4 subframes.

will incur a guard interval of 2 OFDM symbols, which is expected to lead to a slight degradation in performance. It is observed that at a coupling loss of 160 dB, the maximum repetition level, R=2048, provides a sufficiently low BLER of less than 30% for the first HARQ transmission, and a throughput of approximately 350 bps.

The BLER performance of the downlink control channel MPDCCH is depicted in Fig. 6. No frequency hopping is applied in these simulations, which in practice may further improve the performance by 2-3 dBs. The maximum possible allocation, 6 PRBs, and maximum aggregation level 24 have been used. From the figure it can be concluded that for a coupling loss of 160 dB, it is feasible to achieve lower than 1% BLER with R=256, even without frequency hopping.

The performance of the uplink control channel, PUCCH, is shown in Fig. 7 in terms of the ratio of positive acknowledgements (ACKs) that are mis-detected. The PUCCH receiver detects the absence of any valid transmission (i.e., DTX detection). The threshold for DTX detection is fixed separately for each repetition level such that the probability of for false detecting a DTX as a negative acknowledgement (NACK) is less than 1%. The receiver does not use cross-subframe channel estimation, which in practice may improve the performance further by 2-3 dBs. The PUCCH transmission hops across the system bandwidth every 2 subframes, however, the impact of retuning guard interval is ignored in these simulations. It is observed that at a coupling loss of 160 dB, the maximum repetition level R=32 provides an ACK Miss Ratio of approximately 10%, which could be further lowered

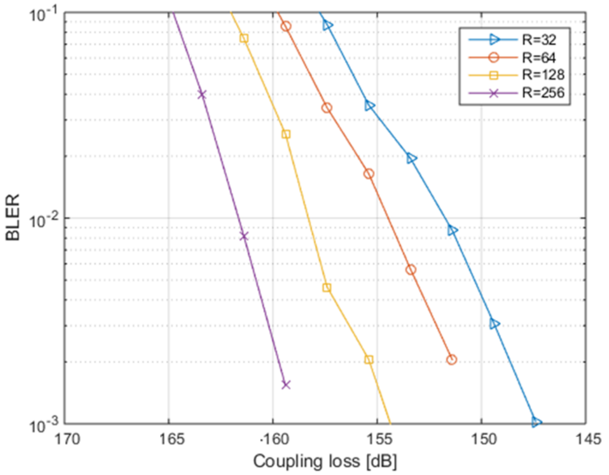

Fig. 6. MPDCCH block error rate for DCI format 6-1B used in CE Mode B, without frequency hopping and using all available resource elements in 6 PRBs.

to below 3% with 3 dB gains from cross-subframe channel estimation.

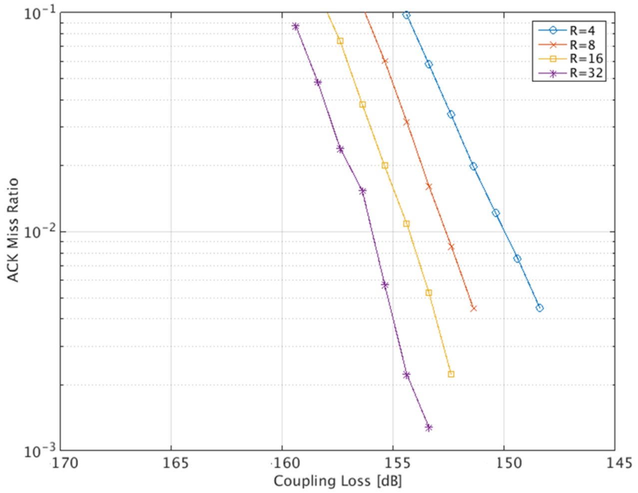

Fig. 7. PUCCH ACK Miss Ratio for Format 1A, with DTX detection used and the false alarm rate fixed at 1%. Single-subframe channel estimation is used and the PUCCH transmission hops across the system bandwidth every 2 subframes.

Finally, we evaluate the uplink capacity in terms of the blocking probabilities for different system bandwidths. The uplink packet size is obtained as 1000 bits from [4], and we add a further 200 bits to accommodate the headers and the scheduling request. This implies that 1.2 kilobits need to transmitted in the uplink in each reporting instance. We assume that the mean coupling loss in an outdoor environment is 5 dB better than the baseline coverage of 140.7 dB in [4], i.e., the outdoor coupling loss is 135.7 dB. We use the building penetration loss model of [11] to determine the distribution of MTC UEs placed indoors, and the corresponding mean coupling loss values in Table III. Further for each coupling loss value, we obtain the uplink throughput from Fig. 5.

TABLE III
PERIODIC MOBILE AUTONOMOUS REPORTING SCENARIOS.

Total Uplink Transmission per Reporting Instance: 1.2 kilobits					
Penetration Loss [dB]	Mean Coupling Loss [dB]	Tput [kbps]	Transmit Time [ms]	Device Distribution	
				Scen. 1	Scen. 2
4-11	143.2	25	48	0.19	0.20
11-19	150.2	6.2	193	0.49	0.40
19-23	156.7	1.1	1090	0.07	0.20
>23	160	0.35	3429	0.15	0.20

From Table III, the mean time required for uplink transmission in each reporting instance can be obtained as $h^{\text{Scenario 1}} = 0.19\times48+0.49\times193+0.07\times1090+0.15\times3429 = 694.34$ ms, and $h^{\text{Scenario 2}} = 0.20\times48+0.40\times193+0.20\times1090+0.20\times3429 = 990.60$ ms respectively. We plot the blocking probabilities for each scenario Fig.8 in terms of the mean uplink scheduling request rate, when the uplink system bandwidth is 10 MHz, 5 MHz, or 1.4 MHz.

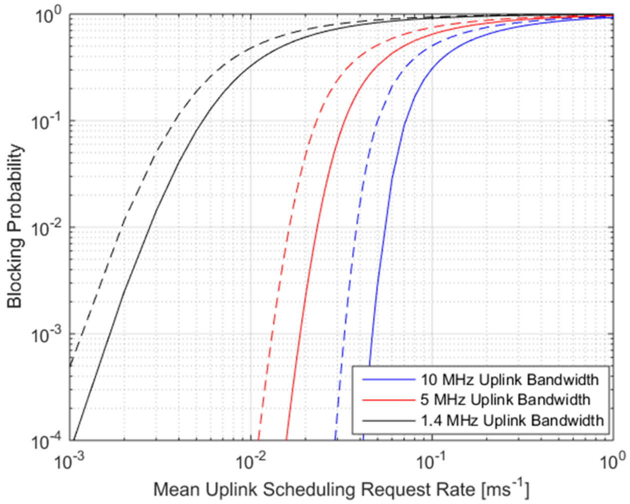

Fig. 8. Blocking probability for different available uplink bandwidths. The solid and dashed lines correspond to Scen. 1 and Scen. 2 of Table III, with mean uplink transmission times $h^{\text{Scenario 1}} = 663.05$ ms and $h^{\text{Scenario 2}} = 910.20$ ms respectively.

In [4], a typical MTC deployment for smart meters in an urban area was identified as comprising between 2778 (London, Dense Urban) and 18051 (Tokyo, Urban) MTC UEs in each cell. The mean reporting interval was specified being as seldom as once every 3600s (i.e., 1 hour), or as frequent as 300s (i.e., 5 minutes). From these values, we calculate three uplink scheduling request rates that are respectively low, 0.0008 ms^{-1} (London, Dense Urban, 3600s), intermediate, 0.005 ms^{-1} (Tokyo, Urban, 3600s), and high, 0.06 ms^{-1} (Tokyo, Urban, 300s). The blocking probabilities for these configurations are obtained from Fig. 8 and tabulated in Table IV. We observe that for a reporting interval of 1 hour, even the smallest evaluated system bandwidth of 1.4 MHz is sufficient to provide a low blocking probability for for most scenarios and deployment densities.

TABLE IV
BLOCKING PROBABILITY FOR NEW UPLINK SCHEDULING REQUESTS

Uplink Bandwidth	Uplink Scheduling Request Arrival Rate $0.0008\ \text{ms}^{-1}$ Scen.1	$0.0008\ \text{ms}^{-1}$ Scen.2	$0.005\ \text{ms}^{-1}$ Scen.1	$0.005\ \text{ms}^{-1}$ Scen.2	$0.06\ \text{ms}^{-1}$ Scen.1	$0.06\ \text{ms}^{-1}$ Scen.2
10 MHz	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	0.03	0.2
5 MHz	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	0.4	0.6
1.4 MHz	$< 10^{-4}$	$\approx 10^{-4}$	≈ 0.08	≈ 0.18	≈ 0.9	≈ 0.9

V. CONCLUSIONS

The features introduced as a part of CE Mode B in LTE Release 13 allow the operation of MTC UEs up to 160 dB, with reasonable performance in terms of the throughput and error rates of the physical channels. This corresponds to a coverage extension of almost 20 dB compared to the coverage of baseline voice communications in LTE, and will facilitate large-scale MTC deployments.

Further, we take into consideration the relatively lower throughput observed in case of the UEs operating in CE and show that the current LTE configurations are well-equipped to handle several thousand MTC UEs in each cell for uplink reporting scenarios in urban areas. However, the uplink capacity of such networks might be strained for extreme scenarios that correspond to dense deployments of MTC UEs along with frequent reporting.

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