System Level Analysis of VoLTE Capacity with Enhanced Machine Type Communication

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***Abstract*—In this paper, Voice over LTE (VoLTE) capacity for Enhanced Machine Type Communication (eMTC) is evaluated with system level simulations. The study concentrates on a high signal attenuation scenario which is applicable to various VoLTE indoor use cases, for example voice call connectivity for elevator emergency phone. Two semi-persistent scheduling approaches are presented and compared that are designed for keeping the end-to-end packet latencies below the delay budget. Due to physical channel repetitions used with eMTC, favorable conditions for semi-persistent scheduling are limited and thus the presented methods combine both semi-persistent and dynamic scheduling. The results show that signal loss caused by multiple wall penetrations has a significant impact on total VoLTE capacity, with the number of concurrently supported calls in a cell being around 15 with Adaptive Multi-Rate Wideband (AMR-WB) 6.6 kbps codec.**

***Index Terms*—BL/CE, eMTC, IoT, simulation, VoLTE**

I. Introduction

In the past few years, the cellular internet-of-things (CIoT) services have established a stable foothold in the industry as well as in domestic use [1]. This was enabled by the introduction of Enhanced Machine Type Communication (eMTC) and Narrowband Internet of Things (NB-IoT) Low Power Wide-Area Network (LPWAN) technologies in the 4th Generation Long Term Evolution (4G LTE) standard Release 13 [2]. The emergence of devices and applications utilizing these technologies allow a cost-efficient approach to use cases where the requirements are long battery lifetime and extended coverage, while the need for high throughput is more relaxed [3]. Examples of this type of use cases are different sensor deployments and wearables, such as smartwatches. From the aforementioned technologies, eMTC is considered more an extension to normal LTE, introducing improved coverage with a cost of lower operation bandwidth and data rates, while NB-IoT further extends the coverage and, due to very limited bandwidth (200 kHz), is suitable for scenarios with relaxed delay requirements and limited payload size.

In this study, the suitability of eMTC is evaluated for Voice Over LTE (VoLTE) services using system level simulations. The main contribution of the paper is the eMTC VoLTE call capacity evaluation which, to our best knowledge, has not been studied widely earlier. In more detail, the focus is on VoLTE capacity in case the terminal devices face deep signal fades due to extensive wall penetration loss, requiring coverage extension properties from the underlying wireless technology. A good example of such deployment is elevator emergency phone, where the elevator car and shaft may have a significant impact on the signal attenuation. Improved coverage with eMTC is achieved mainly by increasing the number of repetitions which naturally extend the observed end-to-end traffic delay. As a real-time service, VoLTE relies on short packet delivery times, and reaching the stringent delay requirements while at the same time achieving coverage extension becomes a challenging task. In theory, Release 13 eMTC device with a half-duplex transceiver may reach up to 300 kbps bitrate in downlink and 375 kbps in uplink in good channel conditions, which are adequate for voice services. In order to keep the packet delays acceptable in deep coverage, two scheduling methods are presented and compared which utilize semi-persistent allocations, but may rely on dynamic scheduling if required due to the buffer or delay status.

The theoretical maximum bitrates for NB-IoT, with the half-duplex assumption, are 27.2 kbps in downlink and 62.6 kbps in uplink which are inadequate for VoLTE. This limitation becomes evident especially when channel quality and achieved bitrate starts to deteriorate. For this reason, the focus in this paper is only on eMTC.

Although eMTC has been widely studied in various low traffic scenarios, there are limited number of previous studies for real-time services over eMTC. In [4], the authors show that eMTC is capable of carrying VoLTE calls from coverage and delay perspective, however VoLTE capacity is not discussed. In [5], a scheduling algorithm for VoLTE call setup over eMTC is proposed. The study is limited to a single scenario where a non-guaranteed bit rate call delays the VoLTE call setup due to control channel capacity limitation. This likely has only small impact on total VoLTE experience over eMTC, thus the topic discussed in that paper has minor relevance for the capacity study. Voice call capacity in LTE has been studied in various papers. For instance, in [6], authors present Voice-over-IP (VoIP) capacity with different scheduling methods using Adaptive Multi-Rate audio codec. In [7], LTE VoIP capacity is evaluated with system level simulations, considering realistic delay budget and packet error rates.

The rest of the paper is organized as follows. Section II presents simulation methodology, including explanation of the use cases, simulator and the proposed scheduling control algorithms. In Section III, simulation results are shown and discussed. Finally, Section IV concludes the paper.

II. Methodology

The VoLTE capacity of eMTC is evaluated with quasi-static system level simulations. The proprietary simulator utilized for the study has been used widely for 3rd Generation Partnership Project (3GPP) LTE standardization purposes and calibrated against other companies' results. The implementation of eMTC includes, for example, repetitions, scheduling and processing delays, link-to-system mapping and channel structures for MTC Physical Downlink Control Channel (MPDCCH), Physical Downlink Shared Channel (PDSCH) and Physical Uplink Shared Channel (PUSCH). From the 3GPP release 14 Further Enhanced MTC (FeMTC), terminals deployed in the simulations are utilizing larger Modulation and Coding Scheme (MCS) and transport block sizes for 1.4 MHz narrowband, but otherwise Category M1 (Cat-M1) Bandwidth-Reduced Low-Complexity/Coverage Enhanced (BL/CE) devices deployed in the simulations support features from the release 13.

VoLTE capacity is defined by the maximum number of supported voice calls per sector without exceeding a predefined outage percentage. Outage percentage is determined by the amount of terminals unable to maintain a stable voice call. The quality of the call is specified mainly by the rate of successful voice packet receptions and mouth-to-ear latency, thresholds for which vary slightly depending on the use case. In this study, the maximum allowed total packet error rate (PER) per call is 2 % and delay budget 150 ms. Call load is supported by the cell if at least 95 % of UEs are satisfied.

A. Use cases

The primary use case considered in this paper is a high-attenuation indoor scenario in which the signal fade may be several tens of decibels higher compared to outdoor locations. As discussed earlier, a real-life example of such scenario is an elevator emergency phone deployment. Emergency phone connectivity in elevators is conventionally carried out over wired communication, but also wireless solutions exist, using WiFi, 900 MHz cordless telephone, GSM or LTE. Short range of WiFi can be an issue in high rise buildings, since handovers may not be fully seamless to avoid Quality-of-Service (QoS) degradation. Utilizing low-cost eMTC devices should provide adequate connectivity for the emergency phones, since eMTC has been designed to provide extra coverage for extremely difficult deployments [8]. Because of macro connectivity, the calls are more seamless and generally suffer less from handovers than WiFi. In addition, there is no need for dedicated access points. Regarding LTE, the macro coverage may be insufficient inside the car and would require additional indoor base stations for the elevator use. In light of these facts, eMTC as an elevator emergency phone solution should be a sound alternative to other methods described above. Moreover, the results presented here are applicable to any other high-attenuation deployment.

In addition to the demanding indoor scenario, VoLTE capacity is evaluated in a more relaxed low-attenuation outdoor scenario without wall penetrations, providing additional insight on how the capacity alternates in various networking conditions. There are already voice call appliances that are utilized in outdoor (or low attenuation) conditions, such as LTE based smartwatch phones. Energy-effective eMTC would be preferred in many such portable devices with limited battery life as long as reliable connectivity is guaranteed by the service provider.

B. System model

The assessment is done in a 21-cell hexagonal macro scenario with inter-site distance of 1732 meters and carrier frequency of 900 MHz. The parameters for the scenario are defined in [9], Annex D, and also presented in this section. The wall penetration loss that models fading signal from the macro base station to the terminal receiver inside the building is implemented according to the building penetration loss (BPL) model as defined in [9]. The parameterization is given in Table I.

TABLE I: Building penetration loss model parameters

Parameter	Value
Number of floors	10
External wall loss min	{4, 11, 19} dB
External wall loss max	{11, 19, 23} dB
External wall class probability	{0.5, 0.45, 0.05}
Number of internal walls	{1, 2, 3, 4}
Number of internal wall probability	{0.266, 0.266, 0.266, 0.202}
Internal wall loss	4-10 dB, uniform distribution

Regarding the suitability of the penetration model for the elevator emergency phone use case, in [10], the signal attenuation in a lift shaft for a 900MHz system was measured approximately 14 dB higher compared to free space propagation, whereas in a lift car the attenuation was 35 to 39 dB higher depending on the number of persons inside the car. The median loss provided by the BPL model is approximately 22.5 dB and the maximum around 48.5 dB, covering the empirically measured values as well as additional loss caused by internal and external building walls.

The calculated penetration loss is added to the baseline path loss which results in a maximum coupling loss (MCL, loss between terminal and serving eNodeB) of around 156 dB in the indoor scenario. This is close to the maximum theoretical link budget target for eMTC presented in [8]. Such a high loss scale will enable utilization of the full range of link adaptation capabilities in terms of power control, modulation and coding scheme selection and repetition levels, thereby providing insight on how the system performs in deep coverage conditions. The highest number of repetitions for downlink control channel (MPDCCH) and data channels (PDSCH and PUSCH) is limited to eight in order to fit a single packet transmission within 20 milliseconds which is the inter-arrival period of a voice packet during a talk spurt. With such a low number of repetitions it is challenging to maintain the Block Error Rate (BLER) target for the first Hybrid Automatic Repeat Request (HARQ) transmission for terminals with low coupling gain. The target BLER of the data channels is set to relaxed 10 % in order to reduce the allocation sizes as the available bandwidth is limited, and rely on HARQ retransmissions that should allow correct reception of a packet in most cases. Alternatively, BLER target could be set to 2 %, but that would cause link adaptation to end up using more robust MCS, more frequency resources and/or repetitions. The outdoor scenario does not have high path loss links and in practice repetitions are not required to reach the BLER target. MPDCCH is modeled error-free, although repetitions and aggregation level are selected according to the channel quality and Coverage Enhancement (CE) level that depends on the Reference Signal Received Power (RSRP).

Traffic model used in the simulations is a realistic two-way voice call model that supports talk spurt and silence indicator (SID) traffic in downlink and uplink. Caller traffic generator at the UE side initiates the call while the responder generator is located at the network side. An average talk spurt length is three seconds with 0.5 second post-talk silence before the roles between the talker and listener are switched. Adaptive Multi-Rate Wideband (AMR-WB, [11]) codec with bitrates 6.6, 8.85 and 12.65 kbps are used.

User plane UE and eNB protocol stacks include Physical (PHY), Medium Access Control (MAC), Radio Link Control (RLC) and simplified Packet Data Convergence Protocol (PDCP) layers. Evolved Packet Core (EPC) and IP network are not implemented, but modeled as a constant delay of 30 ms before the received packet reaches the peer application/traffic generator.

Half-duplex 1x1 antenna terminals (eNodeBs have 2x2 antennas, Interference Rejection Combining receiver) are dropped within a cell coverage in random locations in the beginning of the simulation and multiple simulation drops with different seed are run in order to obtain enough samples. Mobility and handovers of the terminal devices are disabled, but fast fading is calculated based on Extended Typical Urban 3 km/h (ETU-3kmph) channel model.

Although the theoretical data rates offered by eMTC are adequate for VoLTE call for single user, the number of multiplexed calls can be very high, which likely makes the limited bandwidth the bottleneck for VoLTE capacity. Presumably, operators do not want to dedicate an extensive part of their frequency resources for IoT, but for legacy traffic. Therefore it is reasonable to assume a single narrowband of six physical resource blocks (PRBs) to be available for eMTC per cell. Thus, the capacity evaluation in this paper is done with one narrowband. VoLTE capacity is directly proportional to the number of deployed narrowbands and therefore capacity can be easily up-scaled by adding more narrowbands.

Some additional performance gain in the form of higher frequency diversity, even with single narrowband, could be achieved by narrowband hopping where the narrowband location dynamically changes in frequency, but the hopping is not enabled in current simulations.

Legacy LTE User Equipment (UE) devices are not created in the simulations. Therefore, to produce interference between cells and eMTC UEs and to avoid optimistic networking conditions, narrowbands used in different cells overlap in frequency.

The main simulation parameters are listed Table II, which mainly follow the assumptions presented in [9].

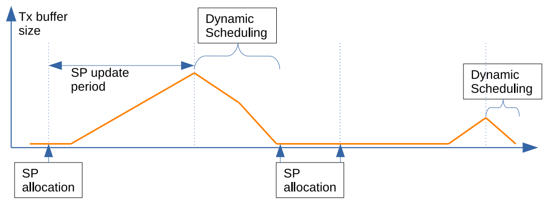
TABLE II: Simulation parameters

Parameter	Value
Scenario	Hexagonal macro, 21 cells with wraparound
Carrier frequency	900 MHz
Path loss model	L=120.9+37.6*log10(R), R in km
Channel model	ETU-3kmph
Slow fading	Correlated log-normal
Bandwidth	1 narrowband (6 PRBs)
eMTC VoLTE UEs per cell	1, 5, 10, 15, 20, 30, 35
Packet size	
AMR-WB 6.6 kbps	20 bytes (17B data+3B ROHC)
AMR-WB 8.85 kbps	26 bytes (23B data+3B ROHC)
AMR-WB 12.65 kbps	35 bytes (32B data+3B ROHC)
SID	16 bytes (13B data+3B ROHC)
Packet arrival period	20 ms (talk spurt), 160 ms (SID)
PDU fragmentation	Disabled
eNodeB Tx power	46 dBm
Maximum UE Tx power	23 dBm

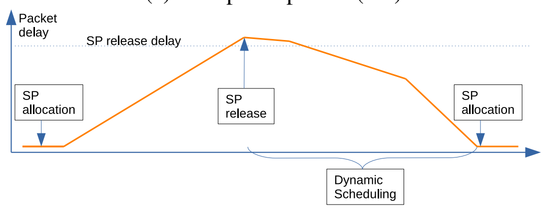
C. Resource Control

Baseline scheduler in downlink (DL) and uplink (UL) is round robin with semi-persistent scheduling possible during a talk spurt. A semi-persistent (SP) allocation repeating every 20 milliseconds is allowed if the transmission buffer contains only one packet at the time of scheduling in which case the allocation can be optimized for that single packet size. In case the transmission buffer contains multiple packets, dynamic scheduling is performed that allows emptying the buffer whenever there are free resources. With SP allocation enabled, packets may start to pile up if the new packet cannot be delivered every 20 ms, for instance due to reception errors. Piling up of packets becomes an issue once the end-to-end (E2E) delay of packets near the delay budget, as packet discards become more frequent. Two approaches to tackle the delay budget violation issue are introduced and compared with the simulations, namely introduction of semi-persistent update period and semi-persistent release delay. Both methods are described below and depicted in Figure 1.

- **SP update period (*UP*)** – Every *UP* milliseconds, old SP allocation is released and a new allocation is assigned to UE via Downlink Control Information (DCI) message over MPDCCH. The new allocation may or may not be semi-persistent, depending on the number of packets in the transmission buffer. The benefit of updating the allocation periodically is two-fold. First, it prevents delay budget violation by performing dynamic scheduling for all buffered packets before creating a new SP allocation. Second, periodic link adaptation allows optimizing the



(a) SP update period (UP)



(b) SP release delay (RD)

Fig. 1: Semi-persistent scheduling update methods

MCS and allocation size. Frequent updates, however, curtail the overhead reduction which is why semi-persistent scheduling is used in the first place. The following *UP* values are simulated: $UP = \{60, 100, 400\}$ milliseconds.

- **SP release delay (*RD*)** – SP allocation is released if buffering delay of the head-of-line packet reaches the threshold *RD* and a new allocation is created, again either semi-persistent or dynamic. Once a semi-persistent scheduling is done, the allocation remains until the packet delay increases above the threshold and the allocation is released. It is likely that the buffer size has increased when the release must be done, which leads to dynamic scheduling until the next semi-persistent allocation is possible. Simulated values: $RD = \{50, 80\}$ milliseconds.

Both methods rely on UE reporting its buffer status to eNB. The report can be piggybacked with uplink data or HARQ acknowledgment report and therefore does not impose high additional overhead in uplink.

RD and *UP* could be active concurrently, in which case *RD* would act as a fallback that guarantees that delay budget is not exceeded. It would be activated only if for some reason packets accumulate fast in the transmission buffer before the next update occasion. Presumably it is most effective when *UP* is relatively long. In order to save space, results for the combined *RD* and *UP* evaluation are not included in the paper, as we observed that there is insignificant benefit from enabling both at the same time.

Scheduler selects an optimal allocation based on the buffer size and link information, such as CQI in downlink. The frequency allocation size is dynamically chosen based on the buffer size and selected MCS. In uplink, the number of PRBs may be limited by the transmission power that is regulated by the standardized power control algorithm [12]. Multiplexing UEs within the same narrowband in both uplink and downlink is possible in case one UE does not consume the whole 6 PRB narrowband. SPS is used only during a talk spurt. Dynamic scheduling is performed for SID.

As a remainder, maximum delay budget is set to 150 milliseconds which is the maximum tolerated E2E delay before packet is discarded at the receiver and counted in outage statistics. *RD* must be considerably shorter than that since the total packet delivery time includes, in addition to buffering, also transmission, processing and core network delays. The longest tolerable buffering delay in uplink is around 110 milliseconds when 30 millisecond core network delay is assumed, although that would not allow any HARQ retransmissions. When *RD* is disabled, such condition should be managed if *UP* is short, i.e. $UP = \{60, 100\}$.

III. Results

A. High-attenuation Indoor Scenario

Figure 2 shows the call outage probability with different *UP* lengths when *RD* is disabled, i.e. scheduler performs continuous adaptation to buffer and link states every predefined *UP* period. The black dashed line at 0.05 indicates the level under which the call load is assumed supported by the network. The number of concurrently supported calls per cell is from

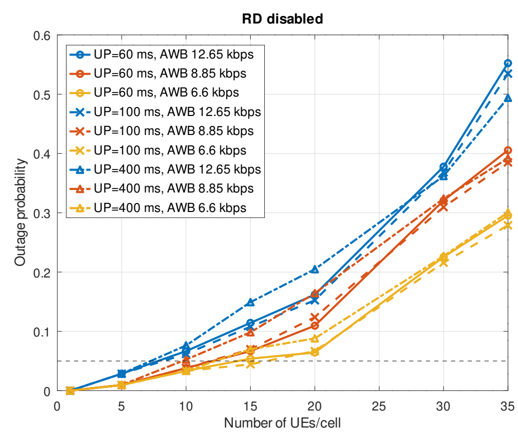


Fig. 2: VoLTE call outage ratio, BPL=Enabled, RD=Disabled.

around 7 to 15, depending on the AMR codec. Different *UP* values have minor impact on the capacity, but also on outage probability at higher loads. It is likely that UEs in bad channel conditions require substantial number of repetitions and still their first HARQ transmission is prone to failure. Since HARQ retransmissions are always scheduled dynamically over MPDCCH (by using the same transport block size and MCS of the original transmission), the overhead reduction and interference gain become smaller. Higher retransmission rate, together with long transmissions due to repetitions, may finally lead to growing transmission buffer and eventually packets become discarded due to exceeded delay budget. For these reasons, different *UP* may have only minor effect on the total capacity, although for UEs with low path loss a longer *UP* could be beneficial.

In order to verify the increased load on MPDCCH due to retransmissions and also to show the impact of *UP* on resource consumption, the average number of allocated PRBs in downlink and uplink is presented in Figure 3 for AMR-WB 12.65 kbps codec. The figure shows how the uplink

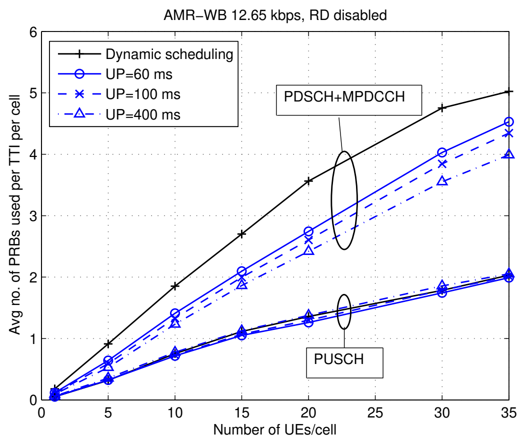


Fig. 3: Average number of consumed PRBs for VoLTE per TTI per cell

usage rate is much lower than that of downlink (combined PDSCH and MPDCCH) which translates to greatly lower interference in uplink. The gap between uplink and downlink is mainly explained by MPDCCH utilization that reserves a significant part of DL resources. For comparison of resource usage gain from SPS, the figure shows also the PRB usage when using only dynamic scheduling, representing the upper bound resource consumption level.

DL resource usage with SPS approaches relatively close to dynamic scheduling, which is another indication that semi-persistent allocation is often not sufficient and must be switched to dynamic scheduling. Another observation from the figure is that the mean PRB usage is in general not saturated close to the maximum of 6 PRBs with the simulated load levels [1]. This means that the network could occupy more calls from the resource perspective, but call capacity is limited by decoding errors at physical layer. Indeed, the capacity is reduced mainly by terminals at worst locations with coupling loss well beyond 140 dB. In fact, the allowed packet drop rate of 2 % permits only few decoding errors during the call which is hard to achieve in extreme conditions without sacrificing a significant amount of resources in frequency or time. There are cases in the simulations when the fast fading and interference conditions are unfavorable and the SINR of the first repetition falls clearly below -20 dB, although the minimum geometry factor (G-factor), i.e. the ratio between the maximum wanted signal power over total maximum interference power plus noise power, is approximately -13 dB. Recovering from such a low SINR would require remarkably larger number of repetitions than what is used in the simulations.

If the transmission of single transport block exceeds the voice packet inter-arrival time, there is a high probability that eventually the delay budget is compromised. Even if the delay budget allows increased number of repetitions, it would elevate the total system interference and reduce the available physical layer resources from other UEs. Instead of scheduling higher number of repetitions in order to provide reliable connectivity towards the devices with most extreme channel conditions, it may be better to aim for lower interference and utilization of different diversity methods. For example, narrowband hopping would protect from deep attenuation pits, but that would require either larger bandwidth dedicated for eMTC (i.e. multiple 1.4 MHz narrowbands or 5 MHz wideband in case of FeMTC) or dynamically changing single narrowband.

Figure 4 depicts the VoLTE capacity for *RD* lengths 50 ms and 80 ms when *UP* is disabled. In terms of number of sup-

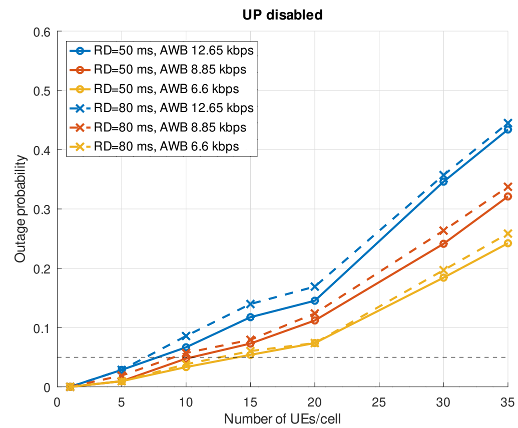


Fig. 4: VoLTE call outage ratio, BPL=Enabled, UP=Disabled.

ported calls per cell, using release period for semi-persistent allocation does not improve the performance compared to the allocation update method shown earlier. However, for higher loads outage probabilities are 5 to 10 % lower, which is the result from reduced MPDCCH usage and thereby lower DL interference and higher resource availability for PDSCH. *RD*=50 ms provides slightly better results compared to 80 ms threshold since it allows earlier reaction to packet congestion at the transmitter.

B. Low-attenuation Outdoor Scenario

Call capacity in the low-attenuation scenario is presented in Figure 5 for different *UP* values. As expected, the absolute capacity is clearly higher now in more relaxed networking environment, with peak capacity beyond the highest simulated load level of 35 UEs per cell. Assuming the relative capacities with different bitrates are similar to those in the previous scenario, the peak capacity with 6.6 kbps in the outdoor case would settle at around 40 UEs/cell. In contrast to the high-attenuation scenario, now the gain from SPS is more evident as BLER target can be reached in most cases, thus HARQ retransmissions are more sparse and MPDCCH interference is clearly lower. Different SP allocation update periods affect only little, behavior seen also in the indoor scenario. Only

[1]The saturation is slightly visible only at 30 to 35 UEs/cell, downlink with dynamic scheduling. It was observed that the system capacity will be restrained once the mean consumption starts to approach 5 PRBs.

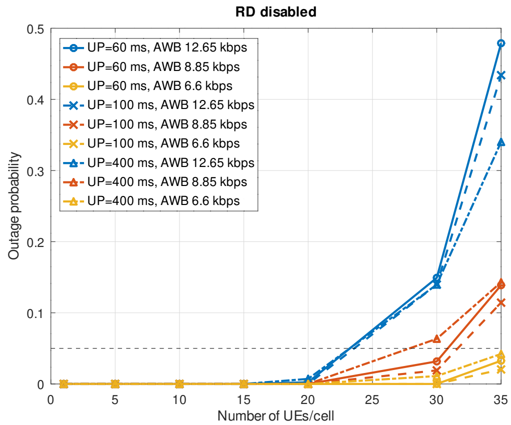


Fig. 5: VoLTE call outage ratio, BPL=Disabled, RD=Disabled.

with the highest bitrate, capacity improves towards longer *UP*, indicating that short update periods have negative effect due to extra overhead and interference. Thus, a longer *UP* is recommended in case when the devices are stationary. Short update period could be more suitable when mobility is present, resulting in need for adaptation to faster channel fluctuation.

Figure 6 shows the outage ratios for the two *RD* durations. Absolute supported capacity levels are similar to the allocation

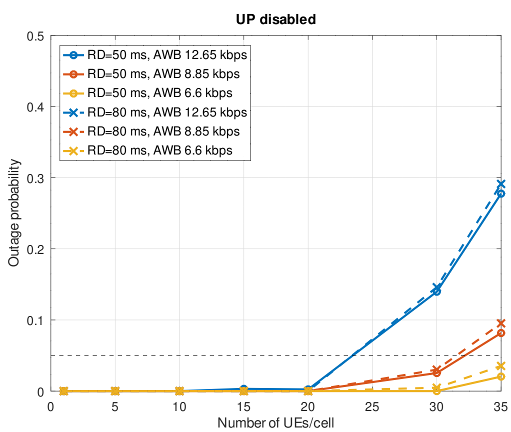


Fig. 6: VoLTE call outage ratio, BPL=Disabled, UP=Disabled.

update scheme in Figure 5. Again, higher loads have slightly lower outage ratio using *RD* approach compared to *UP*. In case the call capacity definition would be relaxed from 95 % UE satisfactory level or if a higher PER or a longer delay budget were allowed, the number of supported calls might be increased, but the impact would be very small.

IV. Conclusions

The capacity of VoLTE over eMTC is analyzed in this paper using system level simulations. The main focus is on the capacity evaluation in an indoor scenario where devices experience difficult channel conditions due to significant wall penetration loss. Additional insight of the capacity in varying network conditions is provided in a more relaxed outdoor scenario. In the former, cells are able to maintain up to approximately 15 concurrent calls that fulfill the strict delay and packet error requirements. This is achieved by deploying single 1.4 MHz narrowband in each cell. It was observed that the benefit of SPS and related allocation methods presented in the paper decrease in high signal attenuation deployment due to repetitions and increasing number of HARQ retransmissions.

In the outdoor scenario, where retransmission rates are lower, the estimated capacity reaches up to 40 concurrent calls. When comparing the SPS allocation methods, although both provided approximately the same call capacity, it is recommended to avoid frequent allocation updates. Even though periodically updated allocations provide rapid adaptation to buffer and link alterations, they also consume considerable amount of downlink resources and add interference to the system. A better approach is instead to drop the old semi-persistent allocation and re-schedule only if the head-of-line buffering delay starts to increase.

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