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Power Control Optimization for Uplink Grant-Free URLLC

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***Abstract*—Ultra-reliable and low latency communication (URLLC) presents the most challenging use cases for fifth generation (5G) mobile networks. Traditionally the focus for mobile broadband has been to optimize the system throughput for high speed data traffic. However the optimization criteria for URLLC should focus on achieving small packets transmissions under strict targets such as 99.999% reliability within 1 ms. Power control is one candidate technology component for improving reliability and latency. In this work we investigate the power control for grant-free URLLC transmissions through extensive system level simulations in a urban outdoor scenario. We initially compare different settings for open loop power control (OLPC) with full and with fractional path loss compensation. Then we evaluate whether power boosting the retransmission can reduce the probability of packets delays under the 1 ms constraint. We also discuss the practical implication of applying power boosting. With full path loss compensation and boosting retransmissions, we show that a URLLC load such as 1200 small packets per second per cell can be achieved in the considered scenario.**

I. Introduction

The fifth generation (5G) radio access technology should support ultra-reliable and low-latency communication (URLLC) use cases, which include applications such as traffic safety, remote tactile control, distribution automation in smart grid, etc. [1]. The third Generation Partnership Project (3GPP) has set strict requirements for URLLC in New Radio (NR), such as 32 bytes packet transmissions to be delivered in $1\,\mathrm{ms}$ with $99.999\,\%$ reliability [2]. It is well established that URLLC will demand enhancements of several technology components to perform well beyond the capabilities of Long-Term-Evolution (LTE) technologies, including link-adaptation, transmission-schemes and power control.

Grant-free (GF) schemes have been considered as a solution for reducing the latency of uplink (UL) initiated transmissions, by skipping the steps of scheduling request and granting [3]. In case of unpredictable traffic, configured resources can be shared by a number of users to reduce waste [4]. GF studies have focused mainly on the massive machine-type communications (mMTC) use cases [5]. In that context, non-orthogonal multiple access (NOMA) is applied to improve the system capacity by serving a massive number of devices.The cost is on the receiver complexity with algorithms that have not been optimized for low latency and ultra reliability. Different candidate schemes for NR are listed in [6], [7]. For URLLC use cases, a system level analysis of GF transmissions considering three different hybrid automatic repeat request (HARQ) schemes is presented in [8].

Power control is an important component for UL transmissions which has not yet been thoroughly studied with the focus on satisfying the strict URLLC requirements. In CDMA systems power control is used to equalize the received power and combat the near-far problem [9]. Standard power control for LTE is defined by 3GPP in [10], known as Fractional Power Control (FPC). FPC combines Open Loop Power Control (OLPC) and closed loop power corrections with fractional path-loss compensation. It allows to reduce the transmit power of cell edge users diminishing their interference on neighbouring cells, at the cost of a lower experienced performance of this users. In general, the goal of FPC is to optimize cell throughput for mobile broadband (MBB) traffic, and its performance is well investigated in e.g. [11], [12].

Traditional FPC optimization criteria focusing on throughput might not be adequate for URLLC given the different targets (latency and reliability) [13]. In this work we first investigate the suitability of LTE alike OLPC for GF URLLC. We aim at optimizing power control settings based on URLLC performance indicators. Further, we evaluate whether a power boosting mechanism for retransmissions is attractive for quickly compensating unexpected Signal-to-Interference-plus-Noise Ratio (SINR) degradations at initial transmissions. Performance is evaluated by means of detailed system level simulations. As in [8], here we use the assumptions for the NR evaluation using cyclic prefix orthogonal frequency division multiplexing (CP-OFDM) and baseline with a minimum mean square error interference rejection combining (MMSE-IRC) receiver to focus particularly on the impact of power control for GF URLLC transmissions.

The rest of the paper is organized as follows: Section II sets the scene of the study. Section III presents an overview of power control strategies and power boosting for URLLC retransmissions. The simulation assumptions are described in section IV. Section V presents the numeric results followed by a discussion in section VI. Finally, section VII brings the main conclusions and some ideas about future work.

II. Setting the Scene

A. System description

The considered system is a single layer cellular network with synchronized base stations (BSs). The deployed BSs provides coverage to the URLLC user equipments (UEs) which are uniformly distributed in the scenario. The UEs are connected and synchronized to the serving cell. For the GF transmissions, the UEs are configured by radio resource control (RRC) signaling (as Type 1 UL [14]). The semi-static configuration includes time and frequency resource allocation, modulation and coding scheme (MCS), power control settings and HARQ related parameters.

The traffic generated by each UE consists of small packets arriving according to a Poisson process. The transmissions occur in a frame based system like LTE and occurs in transmission time intervals (TTI) of mini-slots with 2 OFDM symbols. These assumptions follows the 3GPP NR URLLC evaluation agreements [6]. Using the $15\,\mathrm{kHz}$ subcarrier spacing, the length of the TTI is $0.143\,\mathrm{ms}$. When a data packet arrives to the UE layer 3 buffer queue, if the queue is empty, it gets immediately passed to the layer 2 HARQ buffer which handles the transmission on GF resources. Prior to a transmission the UE might have to wait for until the start of the next TTI. This waiting time is denoted as frame alignment. If the packet is successfully decoded the BS sends an ACK feedback, otherwise it sends a NACK. After having received and decoded the feedback, the UE can decide to perform a retransmission.

Layer 1 signaling for (re)configuration and other aspects of link adaptation rather than the power control are not considered here, therefore the UE uses the entire pre-configured bandwidth for its UL data transmissions.

B. Problem formulation and Objectives

The objective with power control for the network of URLLC users is to increase the capacity of the system while achieving the URLLC performance requirements. The URLLC performance indicator is the user plane latency and the corresponding reliability of transmitting the packets within a latency target. We adopt the 3GPP baseline reliability target of $1 - 10^{-5}$ with latency of $1\,\mathrm{ms}$ [2].

In the considered system, the GF resource allocation can be shared by multiple UEs which makes the GF transmissions susceptible not only to inter-cell interference, but also to intra-cell interference. Power control is an essential mechanism to manage both intra- and inter-cell interference levels [9].

Given the described network, this means that the use of retransmissions should be minimized in order to keep the latency down. Our hypothesis is that power control settings can be tunned to improve the system performance for GF URLLC transmissions. Also, that power boosting retransmissions can reduce the retransmission probability and hence improve the system capacity for URLLC traffic.

III. Power Control with Power Boosting

In LTE, fractional power control is used to regulate the power level of the received signal at the BS, as well as to limit the inter-cell interference. The transmit power P at the UE is determined by the following expression:

$$P[\mathrm{dBm}] = min\{P_{max}, P_0 + 10log_{10}(M) + \alpha PL + \Delta_{mcs} + f(\Delta_i)\}, \quad (1)$$

where P_{max} is the maximum transmit power, M is the number of assigned Resource Blocks (RBs), P_0 is the target receive power per RB, PL is the downlink path-loss estimate calculated at the UE based on the reference signal power, Δ_{mcs} is a MCS based power offset signaled in the uplink grant, Δ_i is a closed loop correction factor, α is a fractional path-loss compensation factor and $f()$ indicates if closed loop power control are cumulative or absolute commands. The P_0 and α parameters can be cell broadcasted.

The open loop part of the power control is used to compensate for systematic offsets and large scale fading. The effect of the α factor is larger on UEs with higher path-loss which are present at cell-edge, since these UEs are also the ones which contribute the most to the inter-cell interference. The closed loop part of the power control can be used to compensate errors for the UE transmit power and possibly optimize the system performance. The way it is implemented depends on the manufacturer. Closed loop power corrections $f(\Delta_i)$ and Δ_{mcs} will not be further considered in this study.

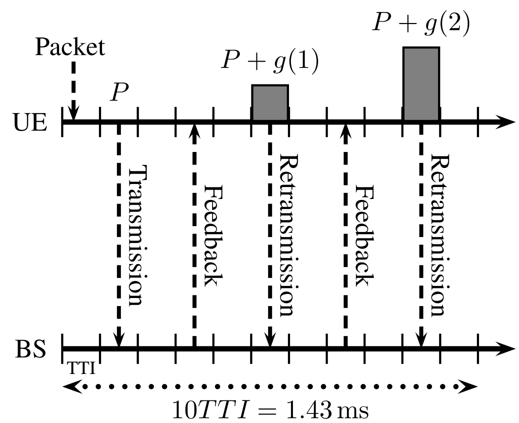


Fig. 1. URLLC Uplink Grant-Free Transmission with Reactive HARQ and Power Boosting for the retransmissions. P is the transmit power without power boosting and $g()$ indicates the requested power boost.

The considered transmission scheme with power boosting is illustrated in Fig. 1. In order to reach the $1\,\mathrm{ms}$ latency budget, there is only time for two transmission attempts. This means that if the packet is not successfully received in the first attempt, it needs to succeed in the retransmission with a very high probability. Besides using soft combining, the success probability of a retransmission can increase by enhancing the signal level and managing the interference. Like in LTE, power control can be used to manage the inter-cell interference. And as in CDMA systems, in case the time-frequency resources are shared by multiple UEs, it can also manage intra-cell interference. To enhance the signal level, power boosting is applied through a mapping function $g(\Delta_{PB})$, where Δ_{PB} is a power boosting index and $g()$ maps the index to a power boosting value PB_{step} in dB and is defined in (3). The considered uplink power control algorithm considered in this study then simplifies from (1) to the following:

$$P[\mathrm{dBm}] = min\{P_{max}, P_0 + 10log_{10}(M) + \alpha PL + g(\Delta_{PB})\}, \quad (2)$$

where $g()$ is defined as:

$$g(\Delta_{PB}) = PB_{step} \cdot \Delta_{PB}. \quad (3)$$

This definition of $g()$ works as power ramping of retransmissions as $\Delta_{PB} = 0$ for the initial transmission and hence increment by 1 for each retransmission. This is also illustrated in Fig. 1, where the value of $g()$ increases at each retransmission attempt. This can be seen as a form of link-adaptation based on the single-bit HARQ feedback. The impact of $g(\Delta_{PB})$ on the transmit power is limited by P_{max}, from (2).

IV. Simulation Methodology

In this work the effect of power control and power boosting for GF URLLC are evaluated using system level simulations. The simulations permit to study effects that would be difficult or even unfeasible to evaluate all together with analytical models. This includes, inter- and intra-cell interference, queuing and the effects of a time-frequency variant channel. The simulation assumptions are summarized in Table I. The used assumptions follow the main guidelines regarding simulation for URLLC defined in [6].

TABLE I
SIMULATION ASSUMPTIONS

Parameters	Assumption
Layout	Hexagonal grid, 7 sites, 3 sectors/site, wrap-around [6]
Propagation scenario	3D Urban Macro (UMa), 500 m ISD
UE distribution	Uniformly distributed outdoor, $3\,\mathrm{km\,h^{-1}}$ UE speed, no handover
Carrier and Bandwidth	4 GHz, 10 MHz (48 RBs) in uplink
PHY numerology	15 kHz sub-carrier spacing, 2 OFDM symbols per TTI, 12 subcarriers/RB
Timing	1 TTI (0.143 ms) to transmit and 1 TTI to process by UE and BS
HARQ configuration	4 TTIs HARQ RTT, 4 SAW channels, maximum 8 HARQ retransmissions
Uplink receiver	MMSE-IRC with 1x2 antenna configuration
Thermal noise density	$-174\,\mathrm{dBm\,Hz^{-1}}$
Receiver noise figure	5 dB
Max UE TX power	23 dBm
Traffic model	FTP Model 3 with 32 B packet and Poisson arrival of 10 PPS per UE
Link adaptation	MCS fixed to QPSK 1/8 and open loop power control
Performance target	1 ms with 10^{-5} outage probability

The system layout is an urban macro-cellular network composed by 7 three-sector sites with 500 meters inter-site distance (ISD) including wrap-around [15]. The BS uses a Minimum Mean Square Error Interference Rejection Combining (MMSE-IRC) receiver with 2 antennas. The IRC receiver is capable of suppress inter- or intra-cell interference from a simultaneous transmission. It is assumed that the receiver can ideally estimate the channel of all superimposed transmissions. However, whether it can successfully decode the transmissions depends on the post-detection SINR after interference rejection. The decoding probability for the applied MCS is given by the link-to-system interface which is based on mutual-information effective SNR mapping (MI-ESM). As in the previous work [8], in this study the UEs are deployed only outdoor.

The system is evaluated at different loads by varying the number of UEs deployed in the network. Each UE generate a small packet of 32 Bytes following a Poisson arrival process with an average of 10 packets per second (PPS). Multiple drops of Monte Carlo simulations are conducted. At each drop the UEs are uniformly deployed in the network and stay connected until the end of the simulation. Initial random access procedures, control signaling errors and reference signal overhead are not considered.

The physical layer numerology and frame structure is inline with 3GPP NR evaluation agreements and uses CP-OFDM with mini-slots of 2 OFDM symbols [6] for transmissions in short TTI (0.143 ms). Grant-free transmissions use all available 48 resource blocks (RB) in a bandwidth of 10 MHz, to transmit the small packet with MCS fixed to QPSK 1/8. The transmissions duration and the processing time are assumed to take 1 TTI, giving a round-trip time (RTT) of 4 TTIs as the time between one transmission can be followed by a retransmission. As in [16], the simulation time is configured to collect at least 5×10^6 samples from several drops to ensure sufficient confidence level on the 10^{-5} quantile.

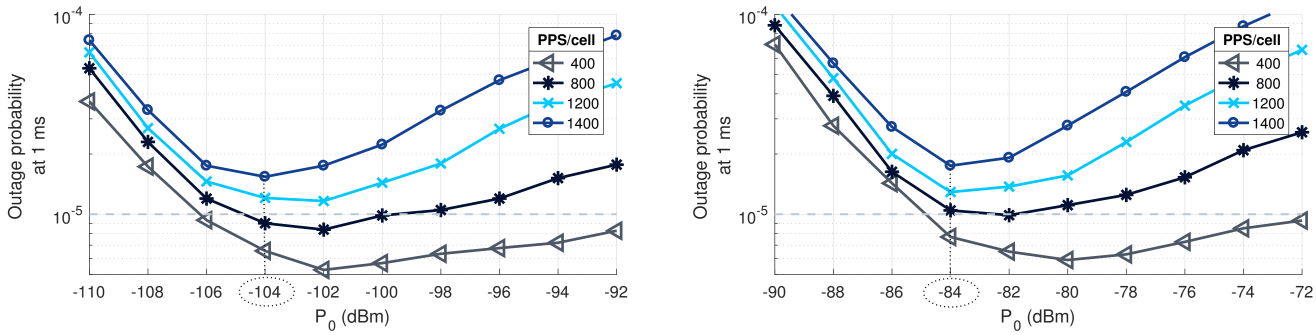
V. Results

The evaluation is done in two steps: First by focusing on the OLPC parameters P_0 and α, where P_0 is chosen to optimize URLLC performance indicators and secondly, evaluating the gains of using power boosting, which includes selecting suitable PB_{step} values.

A. Power control settings

We start by analyzing the OLPC settings for α and P_0 which can satisfy URLLC performance requirements. Fig. 2 shows the outage probability, namely the probability that the transmissions in the system does not succeed within 1 ms latency target, as a function of P_0. Fig. 2a is with full path-loss compensation ($\alpha = 1$) and Fig. 2b is with fractional path-loss compensation ($\alpha = 0.8$). Four different loads are being considered and are defined as the average packet generation rate per second per cell.

The comparison of fractional and full path-loss compensation is done in two different ranges of P_0 found by an initial sampling of a large P_0 range. It was found that $\alpha = 0.8$ provided the best performance for $-90\,\mathrm{dBm} \leq P_0 \leq -72\,\mathrm{dBm}$,



(a) Full path-loss compensation ($\alpha = 1.0$)

(b) Fractional path-loss compensation ($\alpha = 0.8$)

Fig. 2. Outage probability at $1\,\mathrm{ms}$ as a function P_0 for different traffic loads.

while for $\alpha = 1$ the best range of P_0 is $-110\,\mathrm{dBm} \leq P_0 \leq -92\,\mathrm{dBm}$, i.e. $20\,\mathrm{dB}$ offset.

The best choice of P_0 is the one that provides the lowest outage probability. This is load dependent and varies less than $4\,\mathrm{dB}$ for the considered loads. It is also clear that the outage probability slope is steeper for P_0 values smaller than the optimum rather than higher. The penalty of being offset from the optimum P_0 becomes more significant when the load increases, meaning that particular for higher loads, it is critical to use a P_0 as close to the optimum as possible.

Comparing Fig. 2a and Fig. 2b it can be noted that the outage is slightly more sensitive to the P_0 setting for fractional path-loss compensation than for full path-loss compensation. This is due to the higher penalty to cell edge devices caused by fractional path-loss compensation, so operating with optimum P_0 setting becomes more critical in this case.

The choice of P_0 used throughout the rest of the paper is the one that provides the lowest outage probability for the highest considered load (1400 PPS). This is selected to be $P_0 = -104\,\mathrm{dBm}$ for $\alpha = 1$ and $P_0 = -84\,\mathrm{dBm}$ for $\alpha = 0.8$.

Previous work done on LTE, such as the one presented in [17], shows that the optimum setting of P_0 for the system performance in terms of coverage and throughput is load dependent. Taking the differences in scenarios and assumptions into account, this tendency is also present in our results, but not as significant as presented in [17]. This is expected to be due to the lack of link-adaptation with adaptive transmission bandwidth, given that the resources allocation and MCS are fixed for the pre-configured GF transmissions.

In the previous work on GF URLLC transmissions schemes [8], similar assumptions were used, but did not consider power control optimizations. The settings used was fractional power control and $P_0 = -85\,\mathrm{dBm}$ with a resulting outage capacity of 400 PPS/cell. In this paper achieves, with the optimized power control parameters, an outage probability at at least 800 PPS/cell corresponding to a $100\,\%$ gain. This is even without using power boosted retransmissions. This underlines that deviating from the optimal P_0, particularly when using fractional path-loss compensation, can considerably impact the URLLC network performance.

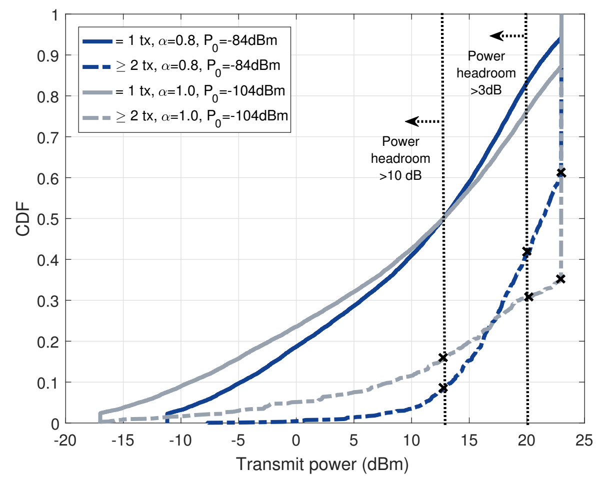


Fig. 3. CDF of the transmit power according number of required transmissions and power control setting (load of 800 PPS/cell).

TABLE II
POWER HEADROOM FOR BOOSTING RETRANSMISSIONS

	Headroom for retransmissions		
	>0 dB	**>3 dB**	**>10 dB**
$\alpha = 0.8, P_0 = -84\,\mathrm{dBm}$	61%	41%	8%
$\alpha = 1.0, P_0 = -104\,\mathrm{dBm}$	35%	31%	16%

B. Power boosting evaluation

Fig. 3 shows the Cumulative Distribution Function (CDF) of used transmit power for packets that were decoded using only one transmission (solid lines) and using more than one transmission (dashed lines), for both fractional and full path-loss compensation with the found optimal P_0 values. The load is 800 PPS per cell which is performing close to the acceptable baseline outage for URLLC (as seen in Fig. 2).

First of all it is noted that, for packets succeeding in one transmission, the probability of using full transmit power is relatively small for both $\alpha = 0.8$ ($\leq 6\,\%$) and $\alpha = 1$ ($\leq 13\,\%$). However, for packets requiring 2 or more transmissions ($\geq 2tx$), the probability of using full transmit power increases to 39 % and 65 % of the cases for $\alpha = 0.8$ and $\alpha = 1$, respectively. This observation matches the intuition that fractional power control allows for a larger power headroom, especially for devices with higher path-loss, i.e. close to the cell edge.

The intention with power boosting is to use some, or all, of the power headroom available after initial transmission, to increase the SINR on the retransmissions. Table II shows the fractions of retransmissions occurrences which have different ranges of power headroom. For instance, taking the case with full path-loss compensation, an aggressive boosting step of 10 dB can be fully applied on approximately 16 % of the retransmission occurrences. While in a moderate configuration, with $PB_{step} = 3$ dB, approximately 31 % of the retransmissions occurrences are boosted with limited step. This can prevent UEs very close to the BS to transmit with very high power. The referred boosting steps of 3 dB and 10 dB are evaluated as values of PB_{step} along with 0 for reference and P_{max} which will cause maximum transmit power for the retransmissions.

It is worth mentioning that, in practice, a very high transmission power from a UE that is closer to the BS can increase the adjacent channel interference. A very strong signal can also overshoot the receiver and suppress the detection of other simultaneous GF transmissions in the same channel. However, such effects are not considered in this study. For this reason, the maximum PB_{step} value is included for completeness of the two extremes of power boosting (0 and P_{max}).

C. Performance summary

Having determined a optimal P_0 for fractional and full path-loss compensation and a set of values for PB_{step} it is time to evaluate the resultant performance for the different power control configurations. Fig. 4 shows the Complementary Cumulative Distribution Function (CCDF) of the one-way latency as a function of PB_{step} for a load of 1200 PPS/cell. The offset between 0 and ~ 0.3 ms is caused by the transmission and processing time. The slope which follows the initial step at 0.4 ms is caused by frame alignment which is a uniform random variable of maximum length of 1 TTI. The steps are caused by the HARQ RTT between the transmissions.

It can be noted that there is just sufficient time for one retransmission in the 1 ms latency budget to reach 10^{-5} outage probability. We can also see, after the slope of the initial transmission, that the retransmission slope starts below the 10^{-3} quantile. This indicates that retransmissions occur very rarely and that power boosting has a very low impact on the interference level.

It is observed that the power boosting reduces the tails of the latency distribution in the very low quantile, i.e. in the region where the performance of the retransmission is observed. The boost of 3 dB has the lowest impact on the tail, while boosting to maximum power does not present a visible difference compared to $PB_{step} = 10$ dB.

Fig. 5 shows the achieved outage probabilities at 1 ms as a function of the load for the different α, P_0 and PB_{step}.

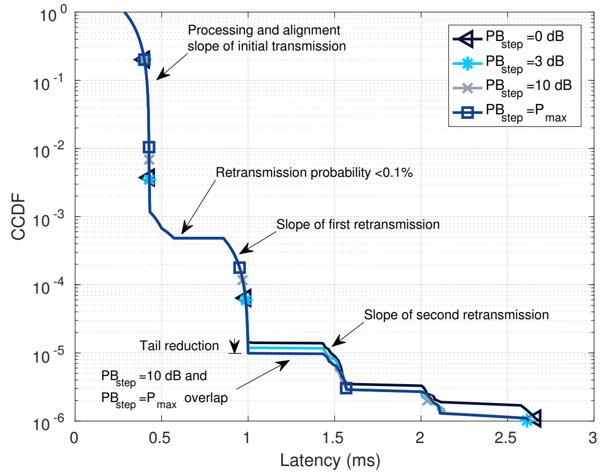


Fig. 4. Latency CCDFs with 1200 PPS/cell.

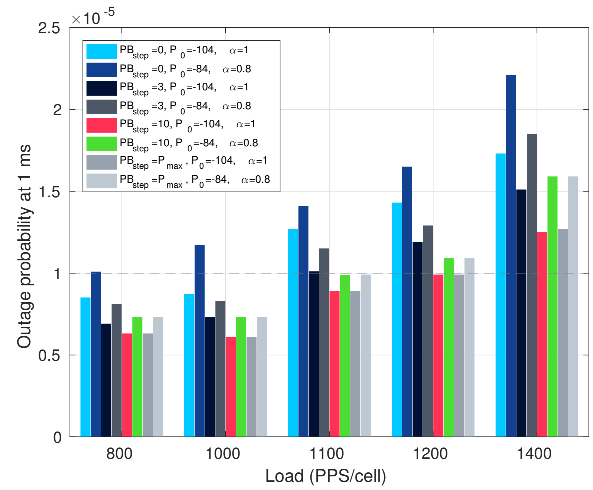


Fig. 5. Outage at 1 ms for different power control configurations.

This figure shows clearly that without power boosting the outage capacity is close to 800 PPS/cell for fractional path-loss compensation in accordance to the observations from Fig. 2. While with optimal power control setting $\alpha = 1$, $P_0 = -104$ dBm and power boosting with $PB_{step} = 10$ dB, a load of 1200 PPS/cell is achievable. The $PB_{step} = 3$ dB approaches an achievable load of 1100 PPS/cell. It can be seen that full path-loss compensation is generally providing the lowest outage probabilities.

Also for higher loads such as 1400 PPS/cell, the use of fractional path-loss compensation seems not beneficial, which is likely due to the higher failure probability of packets transmitted from the cell edge. It can be also seen that $PB_{step} = 10$ dB and $PB_{step} = P_{max}$ provides similar performance in all the cases, making the smaller step preferable in practice to lower co-channel and adjacent channel interference.

VI. Discussion

In this work we considered GF parameters with fixed MCS configured by higher layers (e.g. RRC). We observed that optimum power control setting is slightly sensitive to the traffic load. A possible inclusion of link adaptation with fast reconfiguration by layer 1 signaling (e.g. Type 2 option in [14]) can modify the allocation bandwidth according to the channel conditions. Then load adaptive power control algorithms like in [17] can be beneficial for network performance.

In GF transmission the control signaling issues for initial transmission are avoided, nevertheless the reliability of the feedback can still impact on the reactive retransmission. With power boosted retransmission, ACK/NACK false alarms can be more harmful due to possible extra interference from the provoked and boosted retransmissions. Enhancements for the feedback reliability as proposed in [18] can be employed to mitigate such issues.

As in [8], this paper assumes that the BS is capable of doing blind detection of the UEs. Orthogonal reference signals could be used for the channel estimation and UE identification. In a practical implementations the reference signal overhead and its reliability should be taken into account. More complex reception mechanisms could be applied to achieve higher GF URLLC loads. This can include NOMA schemes, and advanced receivers with higher number of antennas for improved interference suppression capabilities.

VII. Conclusion

Motivated by the new requirements given for URLLC in 5G, in this paper we studied uplink power control configurations particularly for grant-free transmissions. In order to meet the strict latency and reliability constraints power control should be optimized for URLLC. Further we studied power boosting of retransmissions and evaluated this through extensive system level simulations. Based on the observations, the take-away messages from this study are;

1) Full path-loss compensation shows better performance and less sensitivity to the choice of P_0 than fractional path-loss compensation.
2) The network performance significantly improves by using optimized power control settings. The system capacity doubles, compared with previous work.
3) The use of power boosting of retransmissions is capable of providing a further outage capacity gain of $20\,\%$.

We emphasize that the success rate of the initial transmission should be high, such that retransmissions occur with a low probability, hence minimizing the excessive interference caused by boosting. Future studies will consider the impact of the feedback errors and the performance of the system with more advanced receivers including higher number of receiver antennas to further improve the URLLC network performance.

Acknowledgment

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