Frequency and Time Spreading for Uplink URLLC Transmission

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***Abstract*—We propose a new transmission scheme for uplink URLLC systems, which can coexist with the eMbb transmission while can still meet the reliability and latency requirements of the URLLC. The proposed scheme spreads the data in both time and frequency domains. The performance of the proposed system is analyzed and closed form expressions are derived. From the analytical results, we optimize the parameters including constellation levels, spreading length and transmit power to maximize the sum rate of the URLLC UE. Simulation results show that the proposed solution significantly improve the performance and the data rate can be up to 8.9 Mpbs in the LTE TDL-C nominal channel with co-existence and achieved URLLC requirements.**

Index Terms—URLLC, ultra-reliable and low latency communications, 5G/B5G, new radio, NR, spreading, co-exist, eMbb.

I. Introduction

Many new applications and services are widely discussed for 5G/B5G wireless communication nowadays. Different applications require one or more characteristics such as low latency, high data rate, high reliability, and better quality of service [1]. 5G is envisaged to support different demands. The International Telecommunication Union (ITU) has defined three application scenarios in 5G, they are enhanced mobile broadband (eMBB), ultra-reliable and low latency communications (URLLC) and massive machine type communications (mMTC) [2]. In these three scenarios, the eMBB service is similar to what we have today but with improved performance; however, URLLC service may be the most challenging since it has to satisfy two contradictory requirements: low latency and ultra-high reliability [3], [4]. Since URLLC data is sporadically inserted in the eMBB traffics, how to configure URLLC data and the eMBB data is a critical problem.

The main challenge mentioned above is how to ensure coexistence of uplink URLLC and eMBB transmissions by avoiding the mutual impact of URLLC and eMBB services and ensuring the latency of one millisecond and the system reliability of 99.999%, which means the quality of service (QoS) of URLLC failed if more than one out of 10^5 packets fails to be delivered within one millisecond [5].

To accommodate sporadic uplink URLLC traffic, there are two types of methods considered. One is grant-based and the other is grant-free transmissions [6]. Although grant-based transmission has higher reliability and spectrum efficiency, it includes additional delay due to scheduling request (SR), base station decoding delay of the SR, transmission of uplink grant, and URLLC user decoding delay of the grant comparing to grant-free transmission [7].

In the grant-free transmission, users can transmit data in an arrive-and-go manner without sending SR from the base station in advance [8]. To make grant-free transmission more spectrum efficient, several vendors proposed a coexistence region for uplink eMBB and URLLC which can support grant-free URLLC transmission, see *e.g.,* [9] and [10].

The main challenge of uplink URLLC transmission is how to satisfy two contradictory requirements: low latency and ultra-high reliability. To meet the strict URLLC requirements, some vendors proposed a dedicated region only for URLLC and some vendors voted for an indication and preemption method [11]. Method of dedicated region only for URLLC can satisfy URLLC requirements but has low spectrum efficiency. On the other hand, methods of indication and preemption lead to larger latency. Even in the coexistence region for uplink eMBB and URLLC, eMBB and URLLC may still use different resource element to avoid interference. This means dedicated resource should be reserved for sporadic URLLC transmission, which may be a resource waste in the URLLC silent period. In [12], the authors proposed a zero-wait-time underlay SR method to transmit SR by spreading the entire channel bandwidth during the uplink data transmissions.

In this study, we propose a time and frequency spreading scheme for uplink URLLC. More specifically, the proposed scheme can coexist with the eMbb devices while can still satisfy the requirements of both ultra reliability and low latency. Unlike the work in [12], we do not spread URLLC SR but URLLC data symbols. In addition, in the proposed scheme, the URLLC data symbols are spread only on a coherent bandwidth and OFDM symbols that can meet the URLLC latency requirement. The reason not to spread the URLLC data on the whole frequency subcarriers is to avoid loss of orthogonality, because the channel is frequency selective. Although spreading URLLC signal only on time domain can solve the frequency selective problem, it leads to large latency and the low latency requirement of the URLLC does not meet in this case. Therefore we propose to spread the signal on both time and frequency domains. Theoretical results of the symbol error rate are derived for the proposed system, and the parameters including the spreading length, constellation level and power allocation are optimized according to the analytical results. Simulation results show that when Coexisting with eMbb UE, the proposed scheme can greatly improve the data rate to 8.9 Mbps; while the one millisecond and 99.999% requirements of the URLLC are still satisfied.

II. System Model and Problem Formulation

A. System Model

A block diagram of the proposed UL URLLC system is shown in Fig. 1, in which we assume that there is always an

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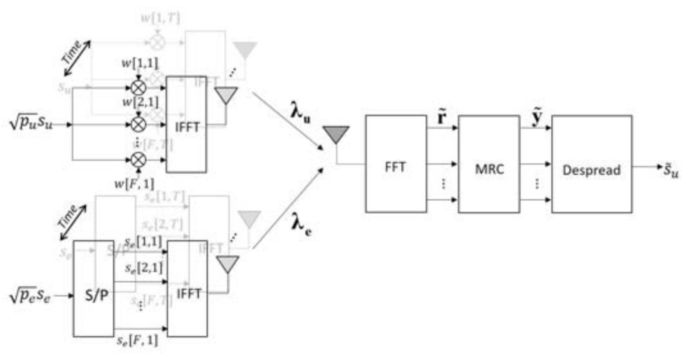

Fig. 1. A block diagram of the proposed UL URLLC system.

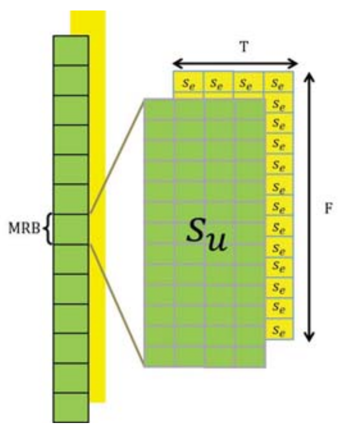

Fig. 2. A co-existing scheme: eMBB overlaps with URLLC in a MRB.

eMbb UE in the background (the worst case). One URLLC symbol is spread in both frequency and time domain with lengths F and T, respectively. The value of F corresponds to the number of subcarriers and the value of T corresponds to the number of OFDM symbol time slots. Both values should be adjusted according to the channel condition. Hence the total spreading length is FT and we define each FT-length spreading block a minimum resource block (MRB), as also shown in Fig. 2, in which one URLLC symbol s_u is spread with length FT and in the background the eMbb data s_e (can be different in individual subcarriers and OFDM symbol time slots) share the same resource with the URLLC spreading data.

Now let us define the signals more specifically as follows: at the transmit side, the URLLC data s_u is spread using a spreading code $w[k,m]$ of length FT in both frequency and time domains[2]. The spread URLLC data in the kth subcarrier and the mth OFDM symbol can be expressed as

$$\sqrt{p_u}s_u w[k,m], \tag{1}$$

where p_u is URLLC transmit power, $\mathrm{E}[|s_u|^2] = 1$ and $|w[k,n]| = 1$. Similarly, the eMBB symbol in the kth subcarrier and mth OFDM symbol can be expressed as

$$\sqrt{p_e}s_e[k,m], \tag{2}$$

[2]Assume that the spreading code $\mathbf{q}$ is used. Then $w[k,m] = q[kT+m]$ or $w[k,m] = q[mF+k]$, for $f = 0,\ 1,\ \cdots, F-1$ and $t = 0,\ 1,\ \cdots, T-1$, depending on which domain the code is put first.

where p_e is the transmitted power for the eMBB user and $\mathrm{E}[|s_e[k,m]|]^2 = 1$.

Let the channel frequency response for the URLLC UE be $\lambda_\mathbf{u}$, and $\lambda_u[Fk_\Delta + k, Tm_\Delta + m]$ be the frequency response at the $(Fk_\Delta + k)$th subcarrier and the $(Tm_\Delta + m)$th OFDM symbol, where k_Δ and m_Δ are indices of MRB in frequency and time domains, respectively. Similarly, we define the channel frequency response $\lambda_\mathbf{e}$ and $\lambda_e[Fk_\Delta + k, Tm_\Delta + m]$ for the eMBB UE.

At the receive side, the received signal at the $(Fk_\Delta + k)$th subcarrier and the $(Tm_\Delta + m)$th ODFM symbol (after FFT) can be represented by

$$\begin{aligned}&\tilde{r}[Fk_\Delta + k, Tm_\Delta + m]\\ &= \underbrace{\sqrt{p_u}s_u w[k,m]\lambda_u[Fk_\Delta + k, Tm_\Delta + m]}_{\text{desired signal}}\\ &+ \underbrace{\sqrt{p_e}s_e[k,m]\lambda_e[Fk_\Delta + k, Tm_\Delta + m]}_{\text{interference from eMBB}} + \underbrace{n[k,m]}_{\text{noise}},\end{aligned} \tag{3}$$

where $n[k,m]$ is additive white complex Gaussian noise with zero mean and variance ${\sigma_n}^2$. We assume that full channel state information (CSI) is available at the base station and the Maximum Ratio Combining (MRC) is used to coherently combine the received URLLC signals given by

$$\begin{aligned}&\tilde{y}[Fk_\Delta + k, Tm_\Delta + m]\\ &= \tilde{r}[Fk_\Delta + k, Tm_\Delta + m]{\lambda_u}^*[Fk_\Delta + k, Tm_\Delta + m].\end{aligned} \tag{4}$$

The final data $\tilde{s}_u$ is obtained by despreading given by

$$\tilde{s}_u = \sum_{k=1}^{F}\sum_{m=1}^{T}\tilde{y}[Fk_\Delta + k, Tm_\Delta + m]w^*[k,m], \tag{5}$$

Assume that the values F and T of an MRB is properly determined such that each URLLC data s_u experiences approximately flat channel in both time and frequency domain. That is F is within channel coherent bandwidth and T is within channel coherent time. Then from (3) and (4) and the approximation, we have

$$\begin{aligned}\tilde{s}_u \approx\ &\underbrace{\sqrt{p_u}s_u|\lambda_u[k_\Delta]|^2 FT}_{\text{desired signal}}\\ &+ \underbrace{\sqrt{p_e}\lambda_e[k_\Delta]{\lambda_u}^*[k_\Delta]\sum_{k=1}^{F}\sum_{m=1}^{T}s_e[k,m]w^*[k,m]}_{\text{interference from eMBB data, } \mathcal{I}_{eMBB}}\\ &+ \underbrace{{\lambda_u}^*[k_\Delta]\sum_{k=1}^{F}\sum_{m=1}^{T}n[k,m]w^*[k,m]}_{\text{noise, } \mathcal{N}_{noise}},\end{aligned} \tag{6}$$

where we have used the notations $\mathcal{I}_{eMBB}$ and $\mathcal{N}_{noise}$ to denoted the interference and noise after the despreading, respectively.

B. Problem Formulation

To achieve the 10^{-5} error rate criterion of URLLC while maximize the data rate, we formulate the problem as maximizing the sum rate of all MRBs constrained on a objective error probability P_e^o, which is described as follows:

There are several parameters to be optimized in the proposed system. They are spreading length FT, constellation level and power allocation of MRBs. We explain why the value of FT needs to be optimized below: Let the constellation level of the k_Δth MRB be M_{k_Δ} and the power allocation of the k_Δth MRB be p_{k_Δ}. Also, let the symbol error probability of the k_Δth MRB be P_{e,k_Δ}, which is a function of F, T , M_{k_Δ} and p_{k_Δ}. In addition, let N_{MRB} be the number of MRB, which is the number of available subcarriers dividing F, and let N_{sym}^{RB} be the number of OFDM symbols in a resource block. We assume that one resource block lasts for one millisecond. Hence the value N_{sym}^{RB}/T is used to calculate the sum rate in one millisecond. As one may already notice that as the value of T increases, the value of P_{e,k_Δ} decreases while the value N_{sym}^{RB} also decreases. In addition, as F increases, the value of P_{e,k_Δ} decreases while the value N_{MRB} also decreases. Therefore, although increasing the spreading length decreases the error probability and it makes the MRB meets the target error rate easily, the sum rate decreases since the MRB occupies more resource in time and frequency domain. Therefore, there exists an optimal value of FT that maximizes the sum rate for a given target error rate, and we will introduce how to determine this optimal value later. The scenario considered here is that a preferred constellation level is selected and every MRB uses the same constellation level to reduce the broadcasting overhead from the base station to the UEs.

Scenario: Maximize Sum rate for Given Target Symbol Error Rate. Here, M_{k_Δ} is constant for all k_Δ. Thus the problem can be formulated as

$$\begin{aligned} \arg \max_{M,F,T,p_{k_\Delta}} \ & \frac{N_{sym}^{RB}}{T} N'_{MRB} \log_2 M \\ \text{s.t.} \quad & P_{e,k_\Delta}(F,T,M,p_{k_\Delta}) < P_e^o, \\ & \text{Transmit power} = P_T, \end{aligned} \tag{7}$$

where N'_{MRB} is number of MRBs that meet the error rate constraint $P_{e,k_\Delta}(F,T,M,p_{k_\Delta}) < P_{e,target}$. The performance of the proposed system is analyzed in the following section which is used to solve the optimization problem later.

III. Performance Analysis

We first derive an approximated probability density function of the signal to interference and noise ratio (SINR). Then, this SINR is used in expressing the error rate probability.

A. SINR Analysis

To obtain the statistics of the URLLC SINR in individual MRBs, the statistics of received interference are derived, which are introduced in the following Proposition:

Lemma 1. *The distribution of the interference from eMBB UE defined in (6) can be approximated by*

$$\mathcal{I}_{eMBB} \dot{\sim} \mathcal{CN}(0, p_e|\lambda_e[k_\Delta]\lambda_u{}^*[k_\Delta]|^2 FT), \tag{8}$$

and the noise $\mathcal{N}_{noise}$ in (6) has distribution given by

$$\mathcal{N}_{noise} \sim \mathcal{CN}(0, \sigma_n^2 |\lambda_u[k_\Delta]|^2 FT). \tag{9}$$

Proof. Proof is omitted due to page limitation. ■

The interference and noise terms in Lemma 1 can be approximated by a complex Gaussian random variable in the following lemma.

Lemma 2. *The interference ($\mathcal{I}_{eMBB}$) and the noise ($\mathcal{N}_{noise}$) defined in (6) can be treated as an interference plus noise term, denoted by $\mathcal{I}_\mathcal{N}$, and its distribution can be approximated by:*

$$\mathcal{I}_\mathcal{N} \dot{\sim} \mathcal{CN}(0, p_e|\lambda_e[k_\Delta]\lambda_u{}^*[k_\Delta]|^2 FT + \sigma_n{}^2 |\lambda_u[k_\Delta]|^2 FT). \tag{10}$$

Proof. Now $\mathcal{I}_\mathcal{N} = \mathcal{I}_{eMBB} + \mathcal{N}_{noise}$. The proof is trivial that the summation of two complex Gaussian random variables is still complex random variable with variance being the summation of the variances of the two random variables. From (8) and (9), the result in (10) can be obtained. ■

Proposition 1. *The instantaneous received SINR in the k_Δth MRB can be approximated by the following random variable:*

$$SINR[k_\Delta] = \frac{2p_u s_u{}^2 |\lambda_u[k_\Delta]|^4 F^2 T^2}{\alpha[k_\Delta]\chi_2^2}, \tag{11}$$

where χ_2^2 is a Chi-square random with degree of freedom 2 and α is given by

$$\alpha[k_\Delta] = (p_e|\lambda_e[k_\Delta]\lambda_u{}^*[k_\Delta]|^2 FT + \sigma_n{}^2 |\lambda_u[k_\Delta]|^2 FT). \tag{12}$$

Proof. Proof is omitted due to page limitation. ■

B. Symbol Error Rate Analysis

Error rate performance directly reflects the reliability of the URLLC system. In Proposition 1, the instantaneous SINRs of individual MRBs are derived, in which the URLLC signal is received with the additive white Gaussian noise consisting of the eMbb interference and the true channel noise. By obtaining the averaged value of SINR in the following lemma, one can evaluate the error rate performance like evaluating the error rate performance in AWGN environments

Proposition 2. *The averaged SINR at the k_Δth MRB can be lower bounded by*

$$\gamma[k_\Delta] \geq \frac{p_u s_u{}^2 |\lambda_u[k_\Delta]|^4 FT}{\alpha[k_\Delta]}, \tag{13}$$

where $\alpha[k_\Delta]$ is defined in (12).

Proof. The instantaneous SINR in Proposition 1 has a random variable in the denominator. This SINR is a convex function of the random variable χ_2^2. Using the Jensen's Inequality that $\mathrm{E}[f(X)] \geq f(\mathrm{E}[X])$, the average SINR can be bounded by

$$\begin{aligned} \gamma[k_\Delta] &= \mathrm{E}\{SINR[k_\Delta]\} \\ &\geq \frac{2p_u s_u{}^2 |\lambda_u[k_\Delta]|^4 FT}{\alpha[k_\Delta]\mathrm{E}\{\chi_2^2\}}. \end{aligned}$$

Using the fact that $\mathrm{E}\{\chi_2^2\} = 2$ leads to the result in (13). ■

In the problem formulation, the SER is constrained to a fixed value to meet the reliability requirement of the URLLC. In Proposition 2, the average SINR for individual MRBs have been derived. Given a objective SER, if the required SINR for a selected M-QAM constellation is known, one can determine a suitable constellation level for the MRB. This is introduced in the following proposition:

Proposition 3. *Given a target SER P_e^o, the minimum required SINR to support a M-QAM constellation is given by*

$$\gamma_M = \frac{M-1}{3}\left[Q^{-1}\left(\frac{1-\sqrt{1-P_e^o}}{2\mu}\right)\right]^2, \qquad (14)$$

where the Q function is defined as

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} exp\left(\frac{-u^2}{2}\right),$$

M' is defined as $\mu = 1 - \frac{1}{\sqrt{M}}$, and $M \in 2^i$ with even i.

Proof. Proof is omitted due to page limitation. ∎

Using the results in Propositions 2 and 3, we can solve the problems defined in (7), introduced in the following section.

IV. Proposed Algorithms

For a fixed power allocation, the problem formulation in (7) can be rewritten as

$$\arg\max_{M,F,T}\left\{\frac{N_{sym}^{RB}}{T}\log_2 M \sum_{k_\Delta=1}^{N_{MRB}} \mathbf{1}\left(P_{e,k_\Delta} < P_e^o\right)\right\}, \qquad (15)$$

where $P_{e,k_\Delta} = P_{e,k_\Delta}(F,T,M)$ is a function of F, T and M and the parenthesis is eliminated to simplify the notation, and $\mathbf{1}(.)$ is the indication function whose value is 1 if the event is true; and is 0 otherwise.

The parameter M, F and T can be determined by exhaustive search using (15), Propositions 2 and 3. For example, for a given objective SER P_e^o, one can verify for a specific parameter setting how many MRBs satisfy $P_{e,k_\Delta} < P_e^o$, which is equivalent to verify whether or not the parameter setting makes the average SINR $\gamma[k_\Delta]$ in Proposition 2 be greater than the required SINR γ_M in Proposition 3 to support the given constellation level specified by the parameter setting. After this procedure, the MRBs that can support the given constellation level should have extra power. Distributing the extra power to the MRBs that cannot support the given constellation level.

More specifically, the power allocation is conducted as follows: Each time, pick up the MRB that has the most extra power and distribute the power to the MRB that needs the least power to achieve the given constellation level. Repeat this power distribution procedure until that there is no extra power left or all MRBs achieve the given constellation level. Note that the power allocation increases the sum rate because some MRBs that originally cannot support the given constellation level can support it now thanks to the proposed gain swapping.

After power allocation, one knows the achievable data rate using (15) for this specific parameter setting with its power allocation. Conducting the same procedure for all combinations of the parameters, one knows the highest achievable rate and determine the optimal parameter setting for constellation level, spreading length and the power allocation.

It is worth pointing out that since the numbers of constellation levels and the spreading length are finite, conducting exhaustive search is still affordable. Taking practical URLLC systems for instance, the maximum value of T should be selected so that the time spreading latency is smaller than 1 ms, which is around 14 OFDM symbols in LTE standard, and the maximum value of F should be selected such that the frequency spreading is within the coherent bandwidth. Also, the supported constellation levels for LTE are BPSK, 4-QAM, 16-QAM, 64-QAM, 128-QAM. Therefore, the number of possible combinations is feasible.

Algorithm 1: Solution for Scenario

Input: $\boldsymbol{\lambda_u} \in \mathcal{C}^{1\times N_{tot}}$, $\boldsymbol{\lambda_e} \in \mathcal{C}^{1\times N_{tot}}$, constellation sets $\mathcal{M}$, spreading length sets $\mathcal{F}$ and $\mathcal{T}$, and target SER P_e^o.

Output: Best constellation M_{opt}, best spreading length T_{opt} and F_{opt}, and best sum-rate R_{opt}.

for $t \in \mathcal{T}$ **do**
  for $f \in \mathcal{F}$ **do**
    Calculate number of MRB $N_{MRB} = N_{tot}/f$ according to f. Cluster the N_{tot} subcarriers into N_{MRB} subbands and use the approximation in (6). Then the frequency response of the subbands become $\boldsymbol{\lambda_u} \in \mathcal{C}^{1\times N_{MRB}}$ and $\boldsymbol{\lambda_e} \in \mathcal{C}^{1\times N_{MRB}}$.
    Calculate SINR $\gamma[k_\Delta]$ for individual MRBs using Proposition 2.
    for $m \leq length(\mathcal{M})$ **do**
      Calculate the minimum required SINR γ_m to support constellation level m using Proposition 3. Calculate sum-rate via summing up the MRBs whose SINR are greater than γ_m, *i.e.*, $S_m = sum(\mathbf{1}(\gamma[k_\Delta] > \gamma_m))\log_2(\mathcal{M}_m)\frac{N_{sym}^{RB}}{t}$
    end for
    $[R_{t,f}, M_{t,f}] = \arg\max_{m\in\mathcal{M}} S_m$
  end for
end for
$[R_{opt}, T_{opt}, F_{opt}] = \arg\max_{t\in\mathcal{T}, f\in\mathcal{F}} R_{t,f}$,
$M_{opt} = M_{T_{opt},F_{opt}}$

V. Simulation Results

In this section, simulation results are provided to verify the analytical results as well as demonstrate the advantage of the proposed systems and algorithms. Simulations were done using the following settings. In 5G New Radio (NR), there are various transmission bandwidths and subcarrier spacings (SPS) (see [13]). We chose the configuration with SPS 15kHz and bandwidth 50MHz, this corresponding to 270 resource blocks and each resource block contains 12 subcarriers. Thus there are total 3240 subcarriers. To contain these 3240 subcarriers, we used 4096 point FFT with 856 zero padding in the simulation. PN sequence was used for the time and frequency spreading. The power of URLLC power and eMBB power is $1:1$ unless specifically mentioned.

The channel that we used is the TDL-C model [14] which is usually used in LTE. The scaled delays can be obtained by:

$$\tau_{scaled} = \tau_{TDLC} \cdot DS_{desired},$$

where τ_{TDLC} is the normalized delay in the TDL-C model, τ_{scaled} is the new delay (in [ns]), and $DS_{desired}$ is the wanted delay spread (in [ns]). The $DS_{desired}$ that we used is the very short delay and nominal delay spreads.

Experiment: Performance evaluation of proposed solutions. In this experiment, the solution for the target scenario was evaluated. Fig. 3 shows the performance for different settings. The curve without mark corresponds to the proposed solution and the solid-square curve corresponds to fixed constellation to 4-QAM and spreading length to 24, which has been verified to have good performance if one fixed all the parameters without any selection. From the figure, at a given target SER 10^{-5}, the sum-rate raises from original $2.1Mbps$ to $7.8Mbps$ by applying the proposed solution, which is a 370% increase in the nominal delay spread case.

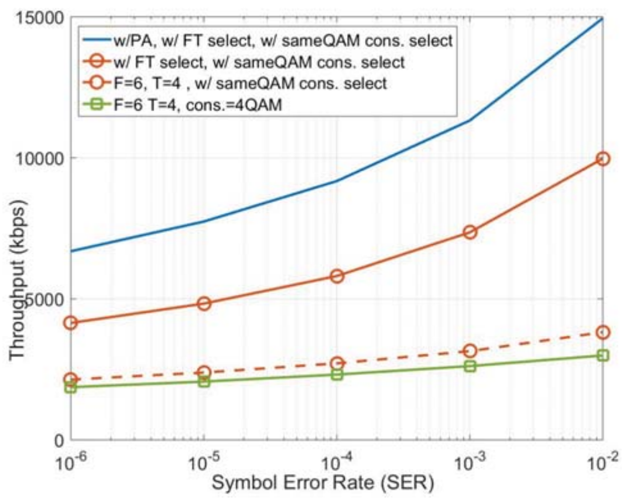

Fig. 3. Sum-rate improvement using proposed solution for target scenario with nominal delay spread TDL-C channel.

Fig. 4 shows the performance for the TDL-C channel with very short delay spread. Observe that at a target SER 10^{-5}, the sum-rate raises from original $2.1Mbps$ to $8.9Mbps$ using the proposed solution for scenario 1. Comparing Figs. 3 and 4, the performance improvement for the proposed solution is more pronounced when the delay spread is short. This is not surprising because short delay spread leads to more flat frequency response. Hence the spreading length FT can be reduced and this increases the sum rate.

VI. Conclusions

We have proposed a new time and frequency spreading scheme for uplink URLLC transmission, which can coexist with the eMbb UE in the background, so that there is no need to reserve a dedicated resource for the URLLC UEs. The performance of the proposed system has been analyzed. Based on the closed-form theoretical results, we have proposed algorithms to optimize the parameters including spreading length, constellation level and the power allocation. Simulation results have shown that the proposed scheme and algorithm can significantly increase the transmission data rate; at the same time the demanding requirements of low latency and ultra-reliability of the URLLC can still be satisfied.

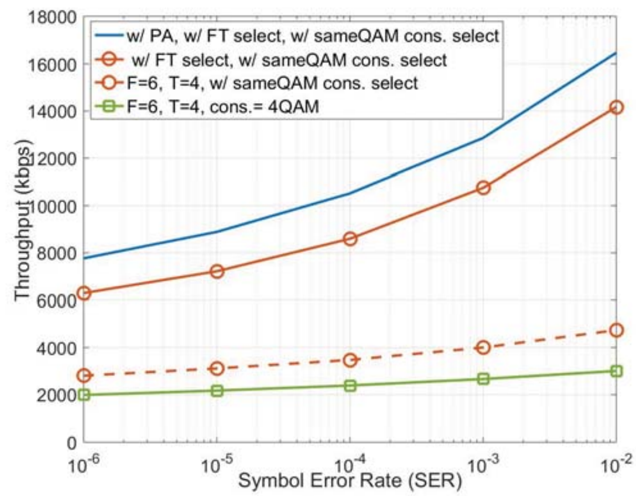

Fig. 4. Sum-rate improvement using proposed solution for target scenario with very short delay spread TDL-C channel.

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