A queueing approach to the latency of decoupled UL/DL with flexible TDD and asymmetric services

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Abstract—One of the main novelties in 5G is the flexible Time Division Duplex (TDD) frame, which allows adaptation to the latency requirements. However, this flexibility is not sufficient to support heterogeneous latency requirements, in which different traffic instances have different switching requirements between Uplink (UL) and Downlink (DL). This is visible in a traffic mix of enhanced mobile broadband (eMBB) and ultra-reliable low-latency communications (URLLC). In this paper we address this problem through the use of a decoupled UL/DL access, where the UL and the DL of a device are not necessarily served by the same base station. The latency gain over coupled access is quantified in the form of queueing sojourn time in a Rayleigh channel, as well as an upper bound for a priority user.

Index Terms—Two-way communication, decoupled uplink/downlink, latency, URLLC, interactive, flexible TDD

I. INTRODUCTION

The main enhancement of 5G Time Division Duplex (TDD) as compared to 4G is the flexibility in the assignment of the two directions, uplink (UL) and downlink (DL), allowing for a very agile adaptation to the instantaneous traffic variations. Another remarkable feature of 5G is the support of three generic services with vastly heterogeneous requirements (e.g., in the packet sizes): enhanced mobile broadband (eMBB), massive machine-type communications (mMTC) and ultra-reliable low-latency communications (URLLC). The latter will enable the real time interactive applications with two-way traffic, envisioned with the emergence of tactile Internet.

It is well known from queueing theory that waiting in a single line with two available servers is on average better than waiting in separated lines with one server each [1]. The intuition behind is that tasks with a long task in front of the queue shall wait for a long time if only one server is available, whereas having a second server reduces the blocking situations. Translating this principle to a cellular system, we study the gain of decoupling the UL and DL directions under heterogeneous TTI requirements. Decoupled access has been studied in the context of 4G Heterogeneous Networks (HetNets) to improve the average throughput. Having the focus on the user association and the interference, the related literature has used stochastic geometry for the analysis [2].

Several works have looked at the interplay of time slot length versus the switching cost in 4G TDD (see e.g., [3] [4]). Nevertheless, with flexible TDD the switching time is not the bottleneck anymore, because it is rather short especially in indoor scenarios. Another research question has been the possibility of having a link to more than one transmission point from the throughput and reliability perspective, but typically limited to one of the two transmission directions. For example, [5] studies a DL centralized joint cell association and scheduling mechanism for eMBB traffic, based on dynamic cell switching by which users are not always served by the strongest perceived cell.

This letter proposes exploiting the extra diversity of the decoupled access to satisfy low latency requirements, and addresses UL and DL in a unified model. Each slot, of possibly different size in the frequency-time plane, can be assigned to either the UL or DL direction, depending on traffic load and received signal conditions. We use a queueing model for the analysis. The reference example with heterogenous TTI requirements is the mix of eMBB and interactive URLLC devices, as shown on Figure 1. The eMBB device requires long DL transmissions followed by short UL ACKs/NACKs, whereas an interactive process has a stringent latency requirement and sends short UL/DL packets continuously. The coupled and decoupled access are compared in terms of sojourn time, i.e. the queuing time plus the transmission time.

The rest of the letter is organized as follows. In Section II the system model is detailed. In Section III the sojourn time is analyzed. Section IV discusses an upper bound for a priority interactive URLLC user. Conclusions are in Section V.

| Traffic Pattern | UL | DL | UL | DL |
|-----------------|----|----|----|----|
| eMBB user       |    |    |    |    |
| URLLC user      |    |    |    |    |

Fig. 1. Example of traffic patterns of two-way traffic with different TTI requirements: eMBB device and URLLC interactive device. The interactive URLLC device is modeled with some processing time between transmission directions.

II. SYSTEM MODEL

We consider a TDD dense cell deployment with a central baseband pool connected with a fronthaul to a large number of small cells (Remote Radio Heads RRHs) where the RF is located. Being a dense small cell deployments, each device is likely to receive a good or a fair signal quality from more than one cell. The small cells are not necessarily coordinated in their transmission directions, but opportunistically serve the traffic. The small cells are serving eMBB and URLLC devices like the ones in Figure 1. The central unit can quickly decide which device will be served by each cell. In the default scenario (coupled UL/DL) devices are connected to only one RRH but the base station must allocate long DL periods for the
eMBB when scheduled. Preemption can still be used for the small DL packets, but not for the UL, and therefore the overall latency requirement of the interactive user is challenged. The alternative is to allow decoupled UL/DL. Each device can connect to a maximum of two RRHs. Besides the primary cell

where $E$ denotes by $S$ connect to a maximum of two RRHs. Besides the primary cell $P$ with the highest received power, the second one in power, denoted by $S$, is reachable if it is at most $T$ dB below $P$. The devices can be served from any of the two base stations, e.g., receive the DL from the first base station and the UL from the second one. In any case, the devices are half-duplex.

The 5G NR frame has been designed with the premise of providing the necessary flexibility to support a heterogeneity of services and requirements. The main principle is that strict timing relations are avoided. On the same page, the TDD DL/UL scheme is much more flexible than LTE: a slot can contain all DL, all UL, or almost any other DL/UL ratio, and the pattern can be changed in each slot or subframe. The faster TDD turn-around and the self-contained concept, such that data and ACK can be scheduled in the same slot, are enablers for low-latency devices. In spite of the enhancements, we identify a limitation when the TTI requirements are asymmetric, due to the enforced transmission direction.

The lack of coordination in the transmission directions represents a substantial challenge in the form of inter-RRH and inter-device interference. A similar interference problem was addressed in $[6]$, where the notion of interference spin was introduced for the optimization of the two-way scheduling in terms of the sum-rate. The framework can be adapted to be used in our scenario, using the latency as the KPI.

With the focus on the queueing gains, we assume that the inter-RRH interference is ideally cancelled by sending the signal of the DL RRH to the UL RRH, such that it can be subtracted from the received signal. For the inter-device interference, devices with non line of sight (NLOS) can be scheduled together. Alternatively, a parametric approach is also possible, where the average interference level is mapped to a transmission latency. This reduces the inference process to a parameter estimation problem.

A single spectrum with unit bandwidth is assumed. The instantaneous SNR is

\[
\gamma(t) = |h(t)|^2 \frac{E_s}{N_0}
\]

where $E_s$ is the average energy per symbol, $N_0$ the noise power spectral density, and $h(t)$ the complex channel envelope. Considering a block Rayleigh fading channel with Gaussian noise and an average SNR of $\bar{\gamma}$, the SNR is distributed as:

\[
f_\gamma = \frac{1}{\bar{\gamma}} e^{-\gamma/\bar{\gamma}}
\]

### III. Sojourn Time

The analysis of the sojourn time is based on a multiclass M/G/m queue like the one in Figure 2(a) where the traffic is abstracted in two separated queues for small and large packets. The sub-indexes $S$ and $L$ refer to short and long TTIs respectively. To exploit the flexible TDD, there are no separate queues by transmission direction: it is the device traffic imposing the transmission direction. For a fair comparison, the decoupled case is serving the double amount of traffic. The policy within each queue is FIFO. Between queues, short packets have strict priority over long packets. In the coupled UL/DL, see Fig. 2(a), one RRH is serving devices in both directions. The transmission direction is determined by the Head Of Line (HOL) packet. In the decoupled case, the two queues use both RRHs. The queue is conservative, meaning that if the system is not empty, then the server (or at least one of the servers in the decoupled case) is busy. Moreover, there is no loss of work.

Being each arrival process Poisson, the total arrival is also Poisson with rate:

\[
\lambda = \lambda_S + \lambda_L
\]

where the arrival rates are $\lambda_L$ and $\lambda_S$ for the long TTI and short TTI devices, respectively.

Similarly, $\mu_L$ and $\mu_S$ denote the service rates. The inverses are the TTI duration (i.e., the service time), $S_S$ and $S_L$ ($S_S << S_L$). The time is discretized, and the minimum scheduling unit is given by the short, fixed TTI duration, $S_S$. eMBB devices (long transmissions) use a discrete adaptation scheme with the range of received SNR divided into $M$ consecutive regions, each of which is associated to a transmission rate within the fading region $(\Gamma_{i-1}, \Gamma_i)$, $i = 1, \ldots, M$. The better the channel quality, the higher the transmission rate. Thus, the service rate can take a value from a discrete set, i.e.,

\[
\mu_L(t) = \mu_i, \quad \Gamma_{i-1} \leq \gamma(t) < \Gamma_i, \quad i = 1, \ldots, M
\]

For Rayleigh channels, the probability of using the $i$th constellation is

\[
p_i = \exp \left( -\frac{\gamma_{i-1}}{\bar{\gamma}} \right) - \exp \left( -\frac{\gamma_i}{\bar{\gamma}} \right)
\]
The first and second moment of the service time are given by

\[ E[S_L] = \frac{1}{\mu_L} = \sum_{i=1}^{M} \frac{p_i}{\mu_i} \]  
\[ E[S_L^2] = \sum_{i=1}^{M} \frac{p_i}{\mu_i^2} \]  

The interaction URLLC devices do not have the possibility of using a closed loop and the transmission rate is fixed, i.e.

\[ \rho = \rho_L + \rho_S = \lambda_L E[S_L] + \lambda_S E[S_S] < 1 \]  

Consider the \( i \)-th data packet arriving to the system with a single server. The sojourn time comprises the queue waiting time, the frame alignment time and the transmission time. If it is a URLLC packet, it must wait in the queue for the residual time until the end of the current packet transmission. If it is an eMBB packet, then it must also wait for the transmission of the URLLC packets arrived during its queueing time.

**Proposition 1.** The average sojourn time of the short and long TTI queues in the multiclass M/G/1 with priorities and discretized time is given by

\[ E[T_{M/G/1}^S] = \frac{\lambda_L E[S_L^2] + \lambda_S E[S_S^2]}{2(1 - \rho)} + \frac{1}{\mu_L} + \frac{1}{2\mu_S} \]  
\[ E[T_{M/G/1}^L] = \frac{\lambda_L E[S_L^2] + \lambda_S E[S_S^2]}{2(1 - \rho)(1 - \rho_S)} + \frac{1}{\mu_L} + \frac{1}{2\mu_S} \]  

The average sojourn time of the short and long TTI queues in the multiclass M/G/2 with priorities and discretized time is approximated by

\[ E[T_{M/G/2}^S] \approx \frac{\lambda_L E[S_L^2] + \lambda_S E[S_S^2]}{(\lambda_L E[S_L] + \lambda_S E[S_S])^2} \cdot \frac{\rho \sqrt{\sigma - 1}}{4\mu_L(1 - \rho)} \]  
\[ + \frac{1}{\mu_S} + \frac{1}{2\mu_S} \]  
\[ E[T_{M/G/2}^L] \approx \frac{\lambda_L E[S_L^2] + \lambda_S E[S_S^2]}{(\lambda_L E[S_L] + \lambda_S E[S_S])^2} \cdot \frac{\rho \sqrt{\sigma - 1}}{4\mu_L(1 - \rho)(1 - \rho_S)} + \frac{1}{\mu_L} + \frac{1}{2\mu_S} \]  

**Proof.** The result for the M/G/1 is a generalization of the Pollaczek-Khinchine formula, by considering the multi-class case, the priority and non-priority classes, and using PASTA and Little’s law. The last term, \( \frac{1}{\mu^2} \), accounts for the frame discretization or the frame alignment, modeled as a uniform random variable \( U \) in \([0, S_S]\).

The result for the M/G/2 is a generalization of the approximated result in [7] for GI/Gs,

\[ E[W_{M/G/2}] \approx \frac{1 + C_S^2}{2} \rho \sqrt{\frac{\sigma(\sigma + 1)}{2\mu(1 - \rho}}} \]  

where \( C_S^2 \) is the coefficient of variation of the service process.

Then, we use the observation in [8],

\[ E[W_{M/G/1}^{\text{prior}}] \approx \frac{E[W_{M/G/1}^{\text{non-prior}}]}{E[W_{M/G/1}^{\text{prior}}]} \]  

IV. UPPER BOUND OF THE CYCLE TIME: PRIORITY DEVICE

We have studied the average gains for URLLC as a homogeneous service with FIFO policy among URLLC packets. Next, we give an upper bound of the latency distribution of the decoupled access by considering the highest priority two-way URLLC device. The interactive traffic is modeled with some processing time \( t_{\text{proc}} \) in between the transmission directions, and TTI length \( S_S \). In the background, there is broadband traffic with a maximum long TTI \( S_L \) and no strict latency requirement. The interactive device has scheduling priority over any other device.

The two-way traffic is decomposed in UL-DL cycles, from the arrival instant of a UL packet to the reception of the following DL packet. Figure [4] shows an example of the round trip time with decoupled access. The processing time \( t_{\text{proc}} \) and the transmission time \( S_S \) add to the total cycle time. Moreover, both directions might find the RRHs busy, and the user has to
wait the residual time $t_{res}$, i.e., the time til one of the RRHs is available. The cycle time is written

$$t_{cycle} = 2 \cdot (S_g + t_{res}) + t_{proc} \quad (16)$$

Assuming the same constant $S_g$ and $t_{proc}$ for the coupled and the decoupled access, the only randomness in equation (16) comes from the residual time. In our scenario, $t_{res}$ is confined to the interval $(0, S_L)$. In the coupled scheme, the residual time in each base station follows a generic distribution $G$ between 0 and $S_L$ (the longest possible TTI duration for eMBB traffic). We call this random variable $X_i \sim G(0, S_L)$, were $i$ is the RRH id. In the decoupled case, the residual time is the minimum between the residual times of the two RRHs,

$$Y \sim \min(X_1, X_2) \quad (17)$$

**Remark 1.** The CDF of the residual time in the decoupled access is given by the minimum between the residual times of the two RRHs, therefore

$$F_Y(y) = Pr \{ Y \leq y \} = 1 - [1 - F_{X_i}(y)]^2 \quad (18)$$

**Remark 2.** Regardless of the distribution, the CDF of $Y$ is lower than the CDF of $X_i$, and therefore the latency of the decoupled access is always better than the coupled case.

Figure 5 plots the CDF for the exemplary case of an exponential distribution, which corresponds to the residual time of an M/M/1 queue in the coupled access. The CDF yields,

$$F_Y(y) = 1 - e^{-2\lambda y} \quad \forall 0 \leq y \leq S_L \quad (19)$$

**V. CONCLUSIONS**

We have investigated the latency gains of an interactive URLLC device when using flexible TDD and a decoupled UL/DL access. The priority URLLC traffic is multiplexed with eMBB traffic, which usually requires much longer TTIs and adaptation to the instantaneous channel quality. The flexible TDD frame in 5G NR is the basis for the analysis. The problem is addressed from a queueing perspective, with the heterogeneous requirements and the Rayleigh channel variations captured in the model. The results show the latency improvements of the decoupled access, which are remarkable when the load increases. An upper bound of a priority user completes the analysis giving insight of the two-way round trip time. We have identified and quantified the potential of decoupling the two transmission directions, setting the basis for future work. Next steps include refining the model to include the impact of the interference and the scheduling.

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