A QoS-Based Multi-user Scheduler Applied to Railway Radio-Communications*

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Abstract. This paper investigates what role could play the 3GPP LTE in railway radio-communications. We study a first case of shared infrastructure where the train control traffic is subcontracted to a public land mobile network operator, and a second case of dedicated infrastructure where the LTE-like network only supports the railway communications. We highlight the multi-user scheduler as the key enabler for managing a heterogeneity of sensitive and best effort traffic, and propose a new scheduler that maximizes the best effort traffic throughput while guarantying the sensitive traffic quality of service.

1 Introduction

The history of safety in trains started with the train era. At first, track side signals have been designed and deployed to limit train speed or to require the train to stop; the train driver has to obey to the signal and act accordingly. Soon, the necessity emerged to enforce the control, by designing a system making the train automatically stop in case the driver missed the signal or did not obey to it. The system evolves to in-cabin report of speed and stop signaling. It is however a coarse speed control, with only a few levels of speed limits. Hard blocks definition and enforcement allows controlling distance between trains, to prevent collisions.

With the increased train speed, track-side indications become incompatible with human view and reaction time, leading to the necessity of a better in-cabin signaling report. Hard blocks limit the train density a track is able to handle securely, although the always increasing need of sustainable transports implies higher railways densities. Turning to moving blocks with a high performance safety control provided by an Automatic Train Control (ATC) system (e.g., [6]) becomes a necessity. For example, the US Congress has requested the implementation of PTC (Positive Train Control) systems, as a minimum ATC targeting security issues, by end of 2015 for heavy rail (freight and passenger services) [4]. The CBTC (Communication-Based Train Control) is a more complete version of PTC enhancing security, capacity and sustainability, and is described in the IEEE Std 1474.1-1999 [5].

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A wireless communication between train and ground allows a permanent and fine control. The wireless system can be based on a proprietary radio layer, on a wireless-LAN standard such as IEEE 802.11, or be inherited from cellular area such as GSM-R used in European ERTMS. In addition to vital applications such as CBTC, train operators have identified new needs in their effort to enhance public transports [1], such as Closed Circuit TeleVision (CCTV) and on-board public Internet access. The Quality of Service (QoS) and capacity requirements of these new services will require new wireless telecommunication technologies. This paper investigates the possible role of LTE-like systems in future railway radio-communications.

In Section 2, we compare the advantages and drawbacks of several communication infrastructures for ATC. We also present the typical services of ATC. In Section 3, we make a brief overview of the LTE OFDMA multiple access technique and of scheduling techniques, and propose in Section 4 a throughput maximizing QoS-aware scheduler taking into account the heterogeneity of traffic. In Section 5, we evaluate the impact of transmitting train control traffic in a shared and dedicated infrastructure. Finally, we conclude by giving the pros and cons of shared vs dedicated LTE infrastructures.

2 Automatic Train Control

2.1 Telecommunication Infrastructure for Automatic Train Control: Shared vs Dedicated

The communication infrastructure for train control is usually dedicated, i.e., owned and operated by the train operators. Indeed, they have the will to keep full control and responsibility of the security and safety of the passengers and trains. However, the communication infrastructure represents a significant cost in terms of deployment, operation and maintenance.

The 3GPP LTE is expected to become a worldwide widespread wireless communication toolbox, which could be used outside the Public Land Mobile Network (PLMN) domain of application. Indeed, it fulfills all the needs of modern communication: first by the flexibility and robustness of the LTE physical (PHY) (see, e.g., [7]) and Media Access Control (MAC) layers; and also by its ability to offer in a secure fashion a wide variety of services and applications through an IP-based core network. Thus, a dedicated LTE-like macro-cellular system is a good candidate for the evolution of railway radio-communications. A dedicated bandwidth might be necessary in that case for ensuring a good quality of service for the cell-edge users. A compromise exists between performance, CAPEX, OPEX, and band licensing when comparing such systems to proprietary deployments based, e.g., on 802.11 technologies on ISM bands.

In order to reduce CAPEX and OPEX, it could be envisaged to open the train operator infrastructure to other Public Safety Communications (PSC) services, offering for example an access to police forces in underground stations. In another example, the USA recently imposed LTE for US global PSC[8], which confirms the trend of non specific radio technologies. In a more futuristic approach, the available resource could also be shared with a PLMN operator, but the train control traffic must be prioritized in order to fulfill QoS metrics specific to railway communications. Those metrics are described in Section 2.2 and prioritization is performed via multi-user scheduling, as described in Section 3.

In yet another approach, the communication part of the train control could be subcontracted to a PLMN operator. Thus, this would reduce the costs, but raises the issues of quality of service, prioritization of subcontracted services, and responsibility. Indeed, the LTE system capacity could reach its limit if several critical services, such as train control, intelligent transportation systems, smartgrids communications, PSCs, machine type communications (MTCs), are managed by the same PLMN. It becomes the responsibility of the PLMN operator or governmental entities to prioritize such services, which is a rupture with the current way to manage ATCs.

In order to evaluate the pros and cons of shared vs dedicated LTE infrastructure for train communications in terms of performance, we define in next Section the QoS requirements of various train communication applications.

2.2 Services and QoS Metrics for Railway Communication Services

Today's railway communication systems mainly address vital operational services, such as CBTC. In a near future, new services will be required [2]. In a category of applications classified as non-vital operational, we can find CCTV. It can be used to monitor passengers (on-board monitoring), but also to monitor tracks by reporting in advance any obstruction like a car stuck in a level crossing. CCTV is also used to monitor train doors while stopping at a station. Train maintenance, including real-time monitoring from ground and alarm reports, or on-board system configuration before train departure, fall also in the non-vital category, along with on-board passenger information. Multimedia services as Internet access to passengers and on-board television are considered in a third category named comfort applications.

These different types of traffic are very heterogeneous in nature and requirements. CBTC traffic typically requires a bandwidth of 100 kbps, but is a vital application and as such shall be treated with the highest priority. A CCTV camera generates a few - say 1 or 2 - Mbps of data. Applications like train configuration or on-board television program upload behave as bulk file transfers, requiring a high throughput in a rather short period of time. Internet accesses offered to passengers is best-effort and it is admitted today that 20 to 30 simultaneous users can share 1 Mbps of bandwidth [3]. However, Internet usage is evolving rapidly and the acceptable level of Internet access service is likely to be more bandwidth-demanding in the future. Voice services can be split into the operational category for communications dedicated to the train crew or into the comfort class when service is offered to passengers, and should be treated with different priorities. Usually, these different applications are supported by specific communication systems being able to merge them into a unique one would be a definite advantage. Today's communication technologies should be able to support the required bandwidth. They shall be capable of providing the specific QoS required by the various railway services in order to be accepted by train operators. In this paper, we only consider CBTC and CCTV services as prioritized services, and assume that a maximum latency of 50ms is required at the MAC layer. This latency is defined as the time interval between the packet arrival at the base station and its transmission.

3 Multi-user Scheduling in LTE Systems

3.1 An Overview of OFDMA in LTE

In the 3GPP LTE cellular network, the multiple access technique in downlink is based on OFDMA, the time resource being divided into frames comprising ten sub-frames, and the frequency resource within a sub-frame is divided in PRBs (Physical Resource Block). One of the main advantages of the OFDMA technique with respect to more static multiple access techniques such as TDMA, FDMA or CDMA is the ability to dynamically allocate resources to the users according to their QoS requirements and wireless channel quality. The user scheduling decision is at least partially centralized, the 3GPP LTE standard being built under the assumption that the scheduling operation is performed at the base station (eNB) of each cell. A limited amount of information is exchanged between neighboring cells in order to apply inter-cell interference coordination (ICIC) on a long term basis. In future deployments, such as for the 3GPP LTE-Advanced system and beyond, larger coordination and centralization are expected in order to further improve the system performance, in particular at the scheduler level.

The per-cell scheduler collects channel state information (CSI) on the frequency and time selective channel, which is obtained by an uplink feedback of downlink measurements. We consider that the CSI is quantized at the PRB level. One User Equipment's (UE) CSI can be classified as short-term when the channel varies sufficiently slowly in the time domain for the scheduler to have a relevant knowledge of the UE's instantaneous channel realization. When the channel fluctuations in the time domain are quicker than the feedback delay from the UE to the eNB, the scheduler must take the decision based on a long term CSI which usually relates to the Signal to Interference plus Noise Ratio (SINR) averaged over time. As a result of ICIC, the SINR can be frequency selective.

When the UEs are not co-located, they observe frequency selective channels which are different one from each others. This allows in the best case, when the scheduler relies on short-term CSI, to allocate the PRBs providing the best performance to each UE without any conflict. As a result, transmitting the data of each user only on the best sub-carriers of the OFDM channel exploits the frequency diversity. Such an opportunistic frequency scheduling operation is also called a multi-user diversity technique. Unfortunately, in high traffic load, conflicts occurs and must be solved by the scheduler.

3.2 QoS-Aware Scheduling in OFDMA Systems

In practice, the resource allocation process is highly connected with the packet fragmentation and retransmission at the radio link control (RLC) layer and with the link adaptation that determines the transmission parameters at the physical layer (PHY). In this paper, we simplify the traffic classification with only two types: Best Effort Traffic (BET) and Sensitive Traffic (ST).

The BET is not associated to any QoS metric such as the latency or the packet error rate. The applications that generate BET are typically web browsing, ftp, file sharing, e-mails and social networks. It is also often considered that the buffers at the RLC are always full, which means that the scheduling decision can be PHY-oriented: the most spectrally efficient resource and transmission scheme are used and the amount of data that can be transmitted is pulled out from the RLC buffers accordingly. When the UEs are at low speed, the short-term CSI feedback can be used in order to take benefit from the multi-user diversity. When the UEs are moving (generally above 20km/h), the scheduler relies on the long-term SINR for deciding on the resource allocation and link adaptation. Three standard schedulers, among a large variety [9][10], are usually considered for PHY-oriented decision on full buffer BET:

– The *round robin* scheduler multiplexes the users on the PRBs. Resource fairness is guaranteed between users, but the multi-user diversity is not exploited which degrades the spectral efficiency.
– The *max-SINR* scheduler allocates a PRB to the user with the best SINR. Resource fairness is not obtained, and the multi-user diversity is exploited, which maximizes the spectral efficiency but not the users throughput.
– The *proportional fair* scheduler makes a compromise between spectral efficiency and fairness by selecting, for each PRB, the user for which the ratio between the instantaneous transmission rate over the average transmission rate is the highest.

The ST is associated with latency, jitter and error rate constraints. We assume that the traffic is periodic, i.e., that the scheduling decision is packet-oriented. In other words, the packets must be sent within a given time window and are pushed out from the RLC to the scheduler. The applications that generate ST are typically VoIP, online gaming and video streaming; train control would be one of them. The resource is usually allocated to ST users in a round robin fashion.

The simplest way to manage such an heterogeneity of traffic is to assign different priority levels to the packets according to their traffic type, and perform the resource allocation starting from the highest priority packets. Unfortunately this does not allow for optimizing the QoS metrics for all users. Indeed, by using a scheduler that first allocates resource for ST users, the degrees of freedom for scheduling BET users are reduced. In extreme cases, ST users are allocated to the highest capacity resource of BET users, which decreases the system spectral efficiency. Another choice of resource might be more optimal and still satisfying the ST QoS constraints. On the contrary, by first allocating resource to BET users without any checking might not allow to fulfill the error rate or latency requirements of ST users.

4 A QoS-Aware Multi-user Scheduler Maximizing Throughput

In this Section, we propose a multi-user frequency scheduler that jointly ensures latency constraints of the ST users and throughput maximization for the BET users. We consider that ST packets are pushed out from the RLC and scheduled in a packet oriented fashion while BET packets are pulled out and scheduled in a PHY-oriented fashion. The main principle of this scheduler is to allocate the best resource to the BET packets first and schedule the ST packets as late as possible in the decision process (not in the time domain) while guaranteeing their QoS with a checking function.

4.1 General Algorithm

The scheduler has a buffer of the frequency/time table of the resource allocation. This table stores, at a given time, the packet index that must be transmitted on a given PRB. It is organized into sub-frames, aligned with the transmission structure defined at the PHY layer. The scheduler has an internal timer synchronized with the PHY layer frame rate. When the time has come to provide the next frame to the PHY layer for transmission, a buffer shifting is performed and a new empty set of PRBs is inserted at the end of the buffer. We assume that the so-called RLC-packets are provided by the RLC buffers, and segmented into packets of one PRB as presented in Section 4.2. We also assume that when one RLC-packet is pushed out from the RLC, it is tagged with a delay constraint related to the latency requirements of the application.

When a new packet belonging to a ST user arrives at the input of the scheduler, it is stored in a ST buffer and a *PRB tagging* function updates a PRB tag table according to the ST QoS. The PRB tagging is updated after each new allocation or after any new buffer shifting after a frame transmission to the PHY layer.

In parallel, before applying a BET scheduling step on one free PRB of the buffer (e.g., with *Round robin*, *max-SINR*, *Proportional fair*), a *Resource Checking* is performed for the buffered ST packets based on the PRB tag tables. It allocates resource for the ST packets only when necessary, i.e., when any new BET allocation would result in resource shortage for ST packets scheduling.

The PRB tagging allows for defining which PRBs that are not already allocated in the scheduler table satisfy the QoS constraint, such as latency, jitter and performance metric. The performance metric can for example be a capacity threshold, or an average error rate being a function of the SINR and packet payload. For each ST packet, the PRB tagging function creates or updates the packet's PRB tag table which stores the indexes of the subset of PRBs satisfying the QoS constraint. The packet is dropped when its table is empty.

The PRB tag tables are illustrated in Fig. 1, where three ST packets are considered. The capacity metrics C_1, C_2 and C_3 of the three packets are frequency selective and are assumed constant in time for this example. The frequency allocation is assumed possible when the capacity metric is above a performance threshold. The three considered ST packets have latency constraints of 4, 2 and 6 sub-frames, respectively. Thus, the PRBs for the ST packet P_i are tagged when C_i is larger than the threshold and the sub-frame index in the scheduler buffer satisfies the latency constraint.

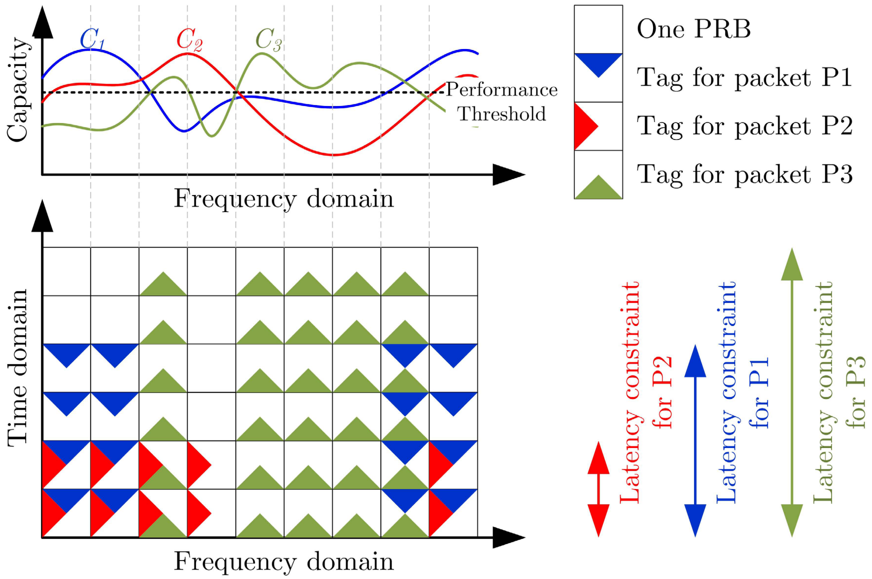

Fig. 1. PRB Tag function for three ST packets

When the future frame is sent from the MAC to the PHY layer for transmission, the PRB tag tables are updated accordingly: the sent PRB indexes are removed from the tables, the PRB indexes are shifted by the number of PRBs by frame, the PRB tagging is performed for the new PRBs inserted at the end of the buffer and the delay constraints associated to the ST packets in the ST buffer are decreased by a time frame duration.

The Resource Checking prevents any resource shortage for ST packets after a future BET packet allocation.

The Algorithm 1 illustrates the resource checking before a BET allocation for a given PRB. Let us assume that N packets are pre-allocated to the given PRB, and their corresponding tag tables $T_{1\leq i\leq N}$ are known. The algorithm first applies

Data: N, $T_{1\leq i\leq N}$ PRB tag tables
for $K \leftarrow 1$ **to** N **do**
  for $\omega \in \Omega(K)$ **do**
    n_t= card $\left(\bigcup_{i\in\omega} T_i\right)$;
    if $n_t = K$ **then**
      call **K-allocation**(ω);
      return *1*;
    end
  end
end
return *0*;

Algorithm 1: Resource Checking algorithm

a loop on an increasing $1 \leq K \leq N$ value. Let $\Omega(K)$ be a set of cardinality $\binom{K}{N}$ comprising all possible index vectors of cardinality K. The algorithm checks, for all possible vectors $\omega \in \Omega(K)$ of K indexes, that the cardinality of the union of the K considered tag tables $T_{i\in\omega}$ is larger than K. If not, the K identified ST packets at stake must be allocated on the K identified PRBs, the *K-allocation* function is called, and the *Resource Checking* is restarted. Whatever PRB is allocated to a BET packet, if the condition is satisfied for all K values and sets of K PRBs, another allocation of the ST packets candidate on this PRB is possible. Thus, the scheduling can process a PRB allocation for the BET traffic while guarantying the QoS of ST traffic.

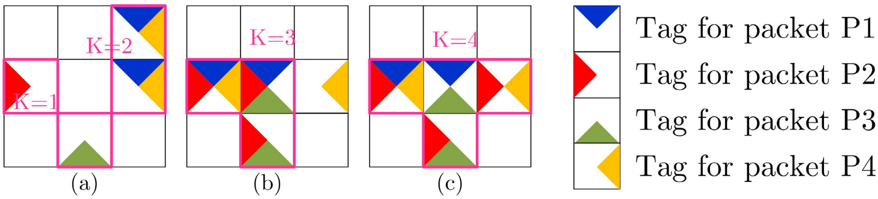

Fig. 2. Examples of resource checking leading to the call of the K-Allocation function

Fig. 2 illustrates three toy examples of the PRB tag tables of four ST packets leading to the call of the *K-allocation* function. In Fig. 2-(a), the *Resource Checking* step with $K = 1$ leads to allocate PRBs for packets 2 and 3. The resource checking for packets 1 and 4 leads to the call of the *K-allocation* with $K = 2$. In Fig. 2-(b), the *K-allocation* function is called after the *Resource Checking* for $K = 3$ and the considered PRBs are allocated for packets 1, 2 and 3. After update of the tables, the packet 4 is allocated after the *Resource Checking* for $K = 1$. In Fig. 2-(c), the *K-allocation* function is called after the *Resource Checking* for $K = 4$ and allocates the 4 PRBs to the 4 packets.

The K-Allocation function assumes that the union of K candidate PRB tag tables contains exactly K PRBs, but that each table has a cardinality lower or equal to K. At least one solution of a possible allocation is found by computing the number m_i of packets that can be allocated to the i-th PRB in the union of the K PRB tag tables. The algorithm loops on the PRBs of the union in the increasing order of m_i. For each PRB i, it allocates a ST packet, the table of which has the lowest cardinality among those containing the i-th PRB, and updates the PRB tag tables and m_i values accordingly. At the end of the algorithm, all K packets are allocated to the K PRBs.

4.2 Packet Segmentation and Optimized Pre-allocation

In the previous Section, we have proposed a scheduler relying on tag tables for ST packets and checking the resource before any PRB allocation for a BET packet. The complexity and performance of the scheduler depends on the packet segmentation into one PRB-length packets, and on the pre-allocation that builds the tag tables.

The packet segmentation divides the ST RLC-packet pushed out from the RLC buffer, and that must be scheduled within the time-frame of the scheduler buffer, into packets of one PRB. The segmentation relies on an allocation metric depending on the expected performance of the transmission at the PHY layer.

When the users are moving at low speed, we consider that the CSI feedback allows to know the channel at the transmitter (closed loop). In that case, we consider the channel capacity as the allocation metric for scheduling. We consider in this paper a packet segmentation based on the payload resulting from a pre-allocation to PRBs in a round robin fashion. Each time a PRB payload (number of bits it can carry) is computed from the channel capacity, it is subtracted from the RLC-packet payload until all RLC-packets are segmented.

For each user moving at high speed, only the SINR is known at the transmitter (open loop). In that case, we consider the average rate obtained from the outage probability as the allocation metric: for ST traffic, we compute the average rate for each SINR such that the outage probability reaches a target QoS of 1e-2; for BET traffic, we find for each SINR the rate R maximizing $(1 - P_o(SINR))R$ where $P_o(SINR)$ is the outage probability of the channel for a given SINR. In this case, all PRBs can carry an identical number of bits, and the ST RLC-packet payload is equally distributed among PRBs.

The optimized pre-allocation limits the cardinality of the tag tables. Indeed, the complexity of the *resource checking* step can become intractable when the cardinality of the union of the tag tables grows. In order to reduce this complexity, we can limit the number of possible pre-allocation and not consider all PRBs that satisfy the QoS constraint for the packet. As a remark, it is sufficient to have one pre-allocation per tag table to satisfy the QoS constraint for the ST packet. Thus, reducing the number of pre-allocation decreases the flexibility in the allocation of the BET packets, and reduces the multi-user diversity for this traffic type. The trade-off between the performance of the BET users and the complexity of the scheduler must be optimized. We propose to limit at maximum the number of possible allocation per tag table, but to maximize the cardinality of the union of the tag tables associated to one PRB. In other words, all users sharing a PRB pre-allocation should not share other PRB pre-allocations. In order to reach this condition, we first apply the RLC-packet segmentation into one PRB-length packets as described above, which defines a payload per packet. Then, we consider that each packet must be pre-allocated to M PRBs. The PRBs are selected sequentially, and for each PRB, we randomly choose one packet, the payload of which is supported by the PRB, if any. We then decrease the number of pre-allocation of this packet by one unit, until all packets are pre-allocated M times. In extreme cases, one packet can be allocated several times to the same PRB. By using this pre-allocation strategy, we manage to have large degrees of freedom in the allocation of BET users. Furthermore, simulation results also show that the *resource checking* has quasi optimal performance even when we limit the search to small values of K (e.g., $K < 3$) and to K equal to the cardinality of the union of the tag tables associated to the considered PRB.

5 System Level Simulations

In this Section we consider the downlink of a macro-cellular LTE system at 2GHz. We consider a uniform and random deployment of UEs in a static multi-cell system-level simulator following the 3GPP case 3 parameters [11]. The small-scale Rayleigh channels are the ITU 6-path Typical Urban channel model. In all simulations, ideal channel estimation and measurements feedback are assumed. We consider a 10MHz bandwidth divided into 50 PRBs of 12 sub-carriers, with a sub-carrier spacing of 15 kHz. In time domain, the smallest unit is the slot composed of 7 OFDM symbols. One sub-frame of 1 ms has to 2 slots. The channel is considered quasi-static for non-moving UEs. We make 1000 snapshots of UEs positions, comprising N_{BET} UEs with a BET traffic and N_{ST} UEs with a ST traffic (trains in our case). The BET traffic satisfies the full buffer assumption, and the ST traffic has a MAC latency constraint of 50ms. We consider three possible data rates: 100kbps for CBTC-like traffic, 1Mbps for CCTV, and 4Mbps for CCTV with several video streams.

First, we will consider a shared infrastructure where $N_{BET} = 20$ regular PLMN LTE users per cell, for each snapshot, use a BET service. We assume that several trains lie in the cell, and use ST services.

In Fig. 3, we first consider the case with no ST traffic as the reference performance. Then, we consider that two trains at low speed receive downlink communications with a throughput of 4Mbps each. We consider here an extreme case in order to illustrate the gains obtained by the proposed scheduler. In some of the snapshots, the 10MHz LTE capacity is not sufficient to support the ST throughput. This happens when the trains are located at the cell edge and require a too large number of resource. In average, 7% of the ST packets are dropped and BET

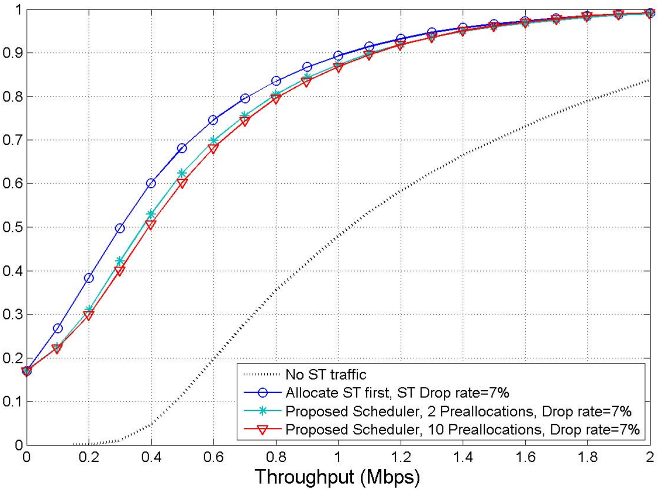

Fig. 3. Comparison of the c.d.f of the BET users throughput, 20 BET users per cell, 2 low-speed ST users with 4Mbps traffic

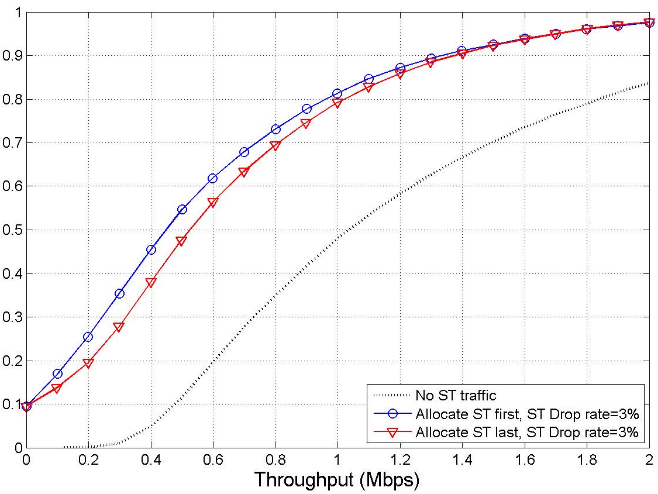

Fig. 4. Comparison of the c.d.f of the BET users throughput, 20 BET users per cell, 2 high-speed ST users with 1Mbps traffic

users are not served in 18% of the cases. When using the state of the art priority-based scheduling, a large loss is observed on the BET users. When maximizing the throughput with the proposed QoS-aware scheduler, the BET throughput is improved with respect to the state of the art. This illustrates that, by allocating the ST packets only when necessary, the BET scheduler has more degrees of

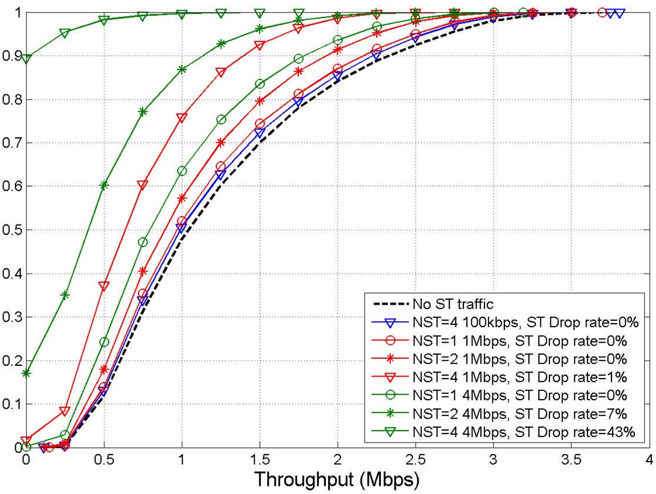

Fig. 5. Comparison of the c.d.f of the BET users throughput, 20 BET users per cell, and low-speed ST users

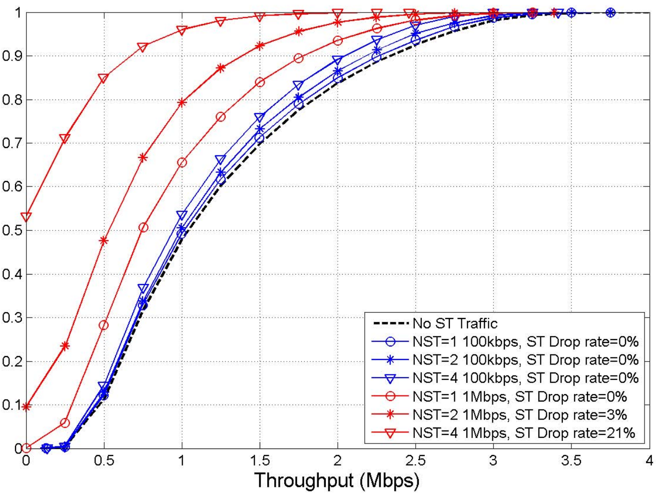

Fig. 6. Comparison of the c.d.f of the BET users throughput, 20 BET users per cell, and high-speed ST users

freedom. We consider two cases with $M = 2$ and $M = 10$ pre-allocations per ST packet. We observe that two pre-allocations are sufficient to reach the maximum throughput constrained by the ST QoS, which drastically limits the proposed scheduler complexity. Finally, we also see from the optimized BET throughput that the main factor of degradation of the BET users is the resource loss, and not the multi-user diversity loss. In Fig. 4, we consider that two trains at high speed receive downlink communications with a throughput of 1Mbps each. In

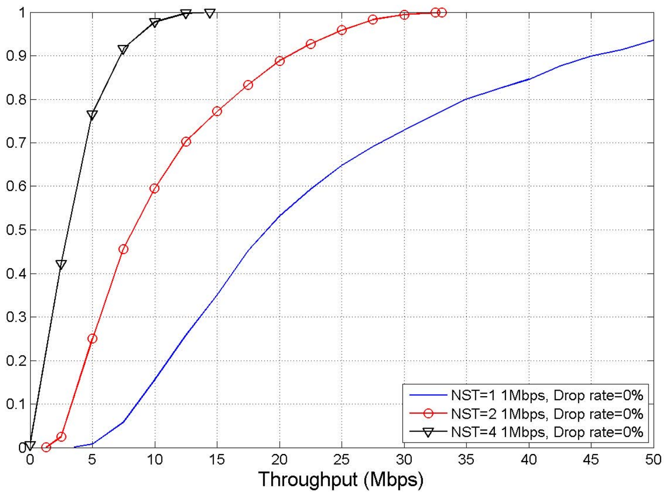

Fig. 7. Comparison of the c.d.f of the on-board BET throughput, with low-speed ST users

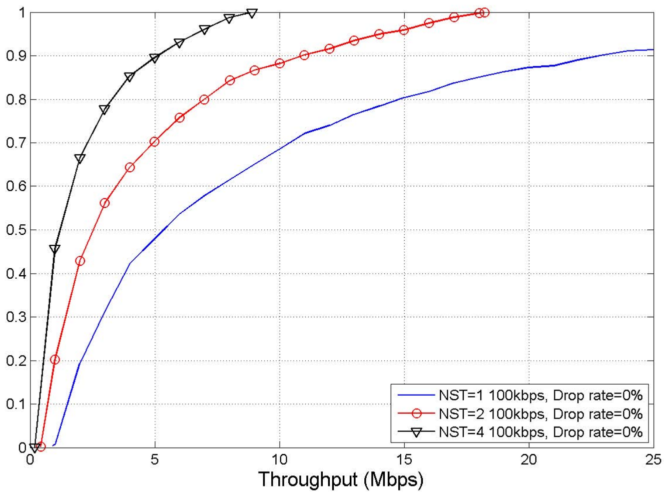

Fig. 8. Comparison of the c.d.f of the on-board BET throughput, with high-speed ST users

average, 3% of the ST packets are dropped and BET users are not served in 10% of the cases. When the allocation metric for the ST traffic is based on the wideband SINR, no PRB is better than another in the latency window. The QoS-aware scheduler is simplified to an allocation of all ST packets that fills the buffer as late as possible in the decision process. As for the low-speed case, a gain of 20% on the BET throughput is observed with respect to the state of art, and the resource taken for ST traffic has the main impact on the loss. We have shown that the proposed QoS-aware scheduler optimizes the BET throughput, with a reduced complexity when used along with an optimized packet segmentation and pre-allocation. By using such an optimized scheduler, we guarantee that the conclusions taken on the impact of the train communications to the PLMN users are relevant. For an even better case study, ICIC techniques should be taken into account. It has to be noted that in many low ST load scenarii, the proposed scheduler shows no gain with respect to the state of the art.

In Fig. 5, we consider 1, 2 or 4 low-speed trains with ST throughput of 100kbps CBTC, 1Mbps CCTV or 4Mbps (high quality or several) HQ-CCTV. First, the CBTC at 100kbps has no impact on the BET throughput for four trains, and this is also the case for one and two trains in the cell which are not plotted on the figure. When the trains use CCTV at 1Mbps, the impact on the BET traffic becomes non negligible with two trains and very important with four trains. The results clearly show that the 10MHz LTE capacity cannot support HQ-CCTV at 4Mbps. In Fig. 6, we consider 1, 2 or 4 high-speed trains with ST throughput of 100kbps (CBTC) and 1Mbps (CCTV). We can see that the impact of the CBTC traffic, even for trains at high speed which consumes more resource, is limited. However, the impact of CCTV is non negligible, even for one train. In conclusion of Fig. 5 and Fig. 6, a 10MHz LTE system can support CBTC with a guaranteed QoS for up to four trains with a negligible impact on the PLMN LTE users. When the train approaches the stations at lower speed and requires CCTV services, the impact on the PLMN LTE users becomes large.

We now consider a dedicated LTE network, where the only users are trains. We assume that the leftover resource is used for non critical traffic, such as on-board Internet access, and place a BET user in each train.

In Fig. 7, we consider that several low-speed trains are using CCTV, and observe the cdf of the throughput for the on-board BET user. The ST packets are never dropped, which shows that the QoS is guaranteed. The on-board BET throughput suffers from the resource sharing between several trains. From the assumption that twenty users can share a 1Mbps Internet access with a good experience, when four low speed trains are considered, an average throughput of 5Mbps can be shared between hundred users per train. In Fig. 8, we consider that several high-speed trains are using CCTV, and observe the cdf of the throughput for the on-board BET user. Since the BET users are also high-speed, we use the wideband SINR-based allocation metric. The BET throughput is drastically reduced with respect to the low-speed case, a loss factor of around four is due to the non-exploitation of the channel knowledge at the transmitter (open loop). When four low speed trains are considered, an average throughput of 1Mbps can be shared between only twenty users per train with a correct Internet experience. In conclusion of Fig. 7 and Fig. 8, a dedicated 10MHz LTE system can support CBTC and CCTV services with a guaranteed QoS. Non critical traffic can also be provided on-board, with a significant throughput at low speed and a reduced yet correct one at high speed.

6 Conclusions

In this paper, we have shown that the CBTC service can be provided with guaranteed QoS and no impact on the PLMN users of a shared infrastructure. The CCTV or other high throughput services, even when only activated at low speed, have a strong impact on the PLMN users' throughput. In a dedicated infrastructure scenario, we have shown that the sensitive traffic's QoS is always guaranteed, and that additional throughput can be offered on-board, especially at low speed. Thus, the dedicated LTE infrastructure is a potential candidate for the future needs of railway communications, and should be compared with proprietary deployments in terms of deployment costs, OAM, and performance.

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