Fair Preemption for Joint Delay Constrained and Best Effort Traffic Scheduling in Wireless Networks

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Abstract. This paper proposes a preemptive scheduler that takes back resource previously allocated to best effort traffic users for minimizing the drop rate of delay constrained traffic users. An online implementation with low complexity is proposed, where the channel and QoS aware preemption metric takes into account the benefit for the drop rate of the delay constrained traffic and the cost on the fairness of the pre-allocated best effort traffic. By inverting the state of art order of the allocation of delay constrained and best effort traffic, we show that the fairness-throughput tradeoff curve of the best effort traffic is improved with no degradation on the drop rate of the delay constrained traffic. This scheduler is particularly relevant in cellular networks mixing safety-related and non-safety related (data) traffic, such as LTE for trains, tram, buses or cars.

1 Introduction

In the domain of Intelligent Transportation System (ITS), the communication infrastructure for safety applications are often isolated from other communication systems with a specific deployment. On the contrary, the most recent cellular networks provide a large panel of services to a multitude of users, with no strong guarantee of quality of service (QoS). A tram/bus operator might desire to cover a city with a cellular network, for example using the LTE technology, and to take the best benefit of this deployment by offering a large panel of services: safety related (data) traffic for the automatic tram control, CCTV, passenger information, infotainment, and even Internet access provisioning.

In order for the future ITS systems to propose new services to their customers, or for the cellular networks to host safety related services, a step forward must be made in terms of multi-user technologies with a strong guarantee of QoS. The scheduling of an heterogeneity of services with various quality of services is part of the radio resource management (RRM), which is an essential topic in cellular telecommunications (see [1] for a recent survey on RRM for LTE networks). A survey of the most common scheduling problems and technologies is given in [2]. Some multi QoS schedulers have been proposed for wireless networks [3][4], but they do not usually allow a low complexity implementation.

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The choice of the metric to be optimized by the scheduler is crucial and usually divided into two families (see [2] for a complete overview of QoS oriented scheduler types):

- Delay-constrained metrics: the metrics consider the time to deadline of each packet with no considerations on the average transmission rate. This is particularly investigated when several data flows share the same channel.
- Channel-aware metrics: the metrics consider the channel capacity of each user, and optimize the system according to a sum-throughput/fairness trade-off. The scheduling can take benefit of the multi-user diversity, i.e., the statistical independence of fading realizations between resources and users (see, e.g., [5]).

Unlike most data traffics usually provided in cellular networks, the safety related traffic is most of the time periodical, with delay constraints below which the information is deprecated. If no packet is received during a given time window, emergency alarms are activated. For example, in an automatic train control environment, an emergency stop occurs. Thus, the drop rate is the main metric to be optimized and the challenge of the scheduler is to minimize it by allocating one user per resource (at most) by taking into account that each resource brings a different benefit to each user, leading to a channel and delay-aware scheduler. The safety related traffic can be seen as a delay-constrained traffic with very low drop rate requirements.

When all the safety users of the system have the same delay constraint (e.g., 50ms), the system performance is equal to the one of a system where all the packets transmission windows are aligned, which allows a per-block implementation of the scheduler. We will see in this paper that such a per-block definition of the problem naturally leads to converting the delay constraint into a rate constraint which further eases the channel awareness at the scheduler level, as discussed in Section 3. As a remark, the proposed solution also applies to non-equal delay constraints, but this is out of the scope of this paper. Such a goal has already been investigated in the literature [6], but usually arbitrarily combines Delay-constrained and Channel-aware metrics.

This paper is organized as follows: In section 2, we present general results on online utility-based and channel-aware schedulers, that will give the basis for our contribution presented in section 3 and 4. In section 3, we propose a new family of channel and delay aware online schedulers that optimize the drop rate of safety related traffic. In section 4, we propose a new scheduling strategy based on an initial allocation of the best effort traffic, followed by a fair preemption allocation of the safety related traffic, taking into account both the benefit of a resource selection in terms of drop rate and the cost on the best effort traffic. This approach is inspired from our previous work [4], the contribution of this paper allowing to drastically simplify the implementation of the scheduler while providing similar performance. Finally, in section 5, simulation results show the high gain provided by the proposed approach for best effort traffic, while keeping the drop rate of the delay-constrained traffic to its target.

2 Generalities on Multi-user Scheduling

We consider that the wireless system resource is divided into resource allocation blocks (that we will call *resources* in the rest of the paper) defining elementary square divisions of the frequency and time resource in an OFDM system. We assume that the multi-user scheduler works on a $n_t \times n_f$ time-frequency grid of resource allocation blocks where the total frequency bandwidth is n_f times a resource allocation block bandwidth and the scheduling depth is n_t times a resource allocation block length. Information can be transmitted at rate $r_k(i)$ in downlink to the k-th user on the i-th resource in the time-frequency grid. We assume that this rate can be estimated in advance by taking into account physical layer parameters, and more precisely from the link adaptation strategy, the link quality and the user mobility parameters.

2.1 Utility-Based Scheduling

Let us consider the problem of allocating an average rate R_k to each user k. We focus on a sub-class of schedulers relying on utility functions of the rates, which solve the following optimization problem

$$\max_{\{R_k\}} \sum_k U_k(R_k), \quad s.t. \quad \{R_k\} \in \mathcal{C}$$

where $U_k(.)$ is a concave monotonically increasing function of the rate R_k and $\mathcal{C}$ is the convex set of achievable rates, as defined by the system capacity limits. In other words, this limit can be defined by a resource sharing as follows: The rate of each user is defined as

$$R_k = \sum_{i \in \omega_k} r_k(i), \quad s.t. \quad \bigcup_k \omega_k \subset \Omega \tag{1}$$

where ω_k is the set of resource indexes allocated to user k, and Ω is the set of indexes of the system resources.

This defines a combinatorial optimization problem for which the exhaustive search is most often intractable, and for which many heuristics can be designed.

2.2 Online Scheduling

In this paper, we only address *online schedulers* that do not involve iterative decisions, i.e., we assume that one resource-user allocation is done at each step of the scheduling process. In other words, the rate of the k-th user evolves through the scheduling steps n. It is updated according to the scheduler decision of allocating the $\hat{i}_n$-th resource providing the rate $r_{\hat{k}_n}(\hat{i}_n)$ to the user $\hat{k}_n$, for example according to the averaging rule

$$\forall k, \quad R_k(n+1) = R_k(n) + \frac{1}{n}\left(\delta(\hat{k}_n, k) r_k(\hat{i}_n) - R_k(n)\right)$$

where $\delta(.,.)$ is the Kronecker's delta function indicating which user has been selected by the scheduler. It can be shown that under the utility-based and online scheduler assumption, and by using a Taylor expansion of the utility function $U_k(.)$ around $R_k(n)$, the optimization problem is equivalent to the resource-user selection

$$(\hat{k}_n, \hat{i}_n) = \arg \max_{k,i \in \Omega_n} U_k'(R_k(n)) r_k(i) \tag{2}$$

where Ω_n is the set of free resources at the step n of the scheduler, and where $U_k'(.)$ is the derivative of the utility function $U_k(.)$.

2.3 Channel Aware Scheduling

In the wireless communication domain, the most famous application of online schedulers targets best effort traffic under a full buffer assumption. In other words, the scheduler is resource-oriented and the goal is to find which user to be sent on each resource. In a case of throughput maximization, the user with the best rate should be allocated in each resource at the price of strongly degrading the throughput of the worst channel-quality users. Thus, a fairness metric allows to make a trade-off between the system spectral efficiency, related to the sum throughput, and each user experience. The α-fair utility functions (see [7])

$$\begin{cases} f_\alpha(x) = \frac{x^{1-\alpha}}{1-\alpha}, \quad \alpha \geq 0, \alpha \neq 1 \\ f_\alpha(x) = \log(x), \ \alpha = 1 \\ f_\alpha'(x) = x^{-\alpha} \end{cases}$$

allow to define a family of schedulers with a good throughput/fairness tradeoff [5] by maximizing $\sum_k f_\alpha(R_k(n))$. The resource-user selection criterion of the online scheduler (2) becomes

$$(\hat{k}_n, \hat{i}_n) = \arg \max_{k,i \in \Omega_n} \frac{r_k(i)}{R_k(n)^\alpha} \tag{3}$$

where $\alpha = 1$ falls back to the well know *proportional fair* scheduler.

3 A Channel and Delay Aware Scheduling Metric

Let us consider that several packets are sent to several users, the k-th packet having a delay constraint of ℓ_k resource allocation blocks and a packet with a payload of p_k bits. The definition of the delay constraint in number of resource allocation blocks is convenient but artificial, and can be computed as the time delay constraint divided by the time length of one resource allocation block and multiplied by the number of resource allocation blocks n_f in the total frequency bandwidth. We consider that only one packet is destined to one user within the scheduling window, and multiple packets sent to one user can be seen as multiple packets sent to as many users. If the packet payload cannot be received within the delay constraint, we consider that the packet is not useful for the application and dropped. Thus, the metric of interest that characterizes the efficiency of the scheduler for allocating the delay constrained packets in time is the drop rate. This data traffic definition fits well with many safety related services. The minimal rate at which the packet must be sent for avoiding a drop event at the end of the delay window is $\rho_k = p_k/\ell_k$.

The ratio $R_k(n)/\rho_k$ gives an information whether the current average rate is beyond or behind the rate required for not dropping the packet. Thus, a conversion of the delay constraint into a minimal rate constraint is possible, as in [8]. Several *guaranteed bit rate* schedulers have already been investigated (see, e.g., [9]), but they do not optimize the drop rate of delay constrained users. When the system is overloaded, it is preferable to sacrifice few users for the others not to be dropped. This makes a main difference with the guaranteed bit rate criterion which tries to provide an acceptable rate to all users, that can be below the target rate. Thus, we intend to maximize the number of packets currently scheduled that will not be dropped by choosing the Drop Rate (DR)-related utility function

$$U_k^{(DR)}(R_k(n)) = \mathcal{I}\left(\frac{R_k(n)}{\rho_k}\right)$$

where $\mathcal{I}(.)$ is an indicator function such that $\mathcal{I}(x \geq 1) = 1$ and $\mathcal{I}(x < 1) = 0$. This conversion of the delay constraint into a rate constraint is particularly relevant in the safety scenario where all the safety packets are sent periodically with the same delay window. Additional criteria can be added when the delay windows are not aligned in order to boost the priority of packets close to the deadline (see many examples in [2]).

Advanced algorithms are required for solving the optimization problem (1) with the utility function $U_k^{(DR)}$. However, $U_k^{(DR)}$ being not concave, it cannot directly be applied to online schedulers (2). Thus, we propose to rely on the α-fair utility functions which provide a good behavioral approximation of $\mathcal{I}(.)$. We call β the fairness parameter for the delay constrained traffic, and the utility function $U_k(R_k(n)) = f_\beta(R_k(n)/\rho_k)$ results in the following resource and user selection

$$(\hat{k}_n, \hat{i}_n) = \arg\max_{k,i \in \Omega_n} \left(\frac{\rho_k}{R_k(n)}\right)^{\beta-1} \frac{r_k(i)}{R_k(n)} \tag{4}$$

which can be seen as the product of the proportional fair selection argument $r_k(i)/R_k(n)$ which relates to the channel usage of each user, and a fairness compression of $\rho_k/R_k(n)$ which is the inverse of the estimated packet transmission achievement $R_k(n)/\rho_k$, the priority of users with the lowest transmission achievement values being boosted. An other interpretation is that $\rho_k/R_k(n)$ is proportional to the estimated amount of resource needed until the packet transmission end, with a boost for the users requiring more resource.

When $\beta \to +\infty$, the optimization attempts to maximize the minimum of the transmission achievement $R_k(n)/\rho_k$, which will provide a very low drop rate if the free resource is high enough to schedule all users with their average rate (low load scenario). We observe that the resource and user selection is performed according to $\rho_k/R_k(n)$ which does not take the instantaneous rate $r_k(i)$ into account. We can expect that, as soon as the free amount of resource is not high enough, the drop rate will rise quickly to 100%. Indeed, such scheduler tends to equalize the transmission achievement rate of all users, which most probably results in all packets not reaching their full transmission achievement before deadline when the system is overloaded.

When $\beta = 1$, the selection criterion falls back to the proportional fair's one, which optimizes the resource usage but not the drop rate. However, when the system load is high, rejecting a user with high resource requirements can be beneficial for many others and for the average drop rate among users. This ultimately would be the strategy of the scheduler with $\beta = 0$, where the max-rate strategy is used for each resource allocation and shows the best performance at very high drop rate and system load regions, out of the scope of this paper.

Thus, this family of schedulers parametrized by β allows for minimizing the drop rate according to the system load. The parameter β can be for example chosen dynamically according to a target drop rate. Alternatively, several instances of the scheduler can be run in parallel with different β values, and a selection can be made on the one providing a drop rate closest to the target. We will see in the simulation results section that a selection between two schedulers with parameters $\beta = 1$ and $\beta = 10$ is very representative of the optimized performance curve. For safety related traffic, the drop rate is usually small and a scheduler with $\beta = 10$ appropriate in all cases. As a remark, in [10], an arbitrary choice of the metric to be optimized has been proposed which is very similar to the $\beta = 2$ case.

4 Fair Preemption Strategy

We now consider that several delay-constrained (DC) users and best effort traffic (BET) users are sharing the same set of resources. In most state of art approaches, the highest priority is served first by a so-called preemptive scheduler, the lowest priority users being allocated on the remaining free resource. In the safety-related context, the DC users are of highest priority compared to the BET users.

In a previous work [4], we have proposed to allocate the BET users until no bottleneck on the resource arise for DC users, guarantying a low drop rate for DC users and maximizing the BET users throughput/fairness tradeoff. The bottleneck checking function can be of high complexity when the number of DC users is high. Also, a pre-processing step involves a segmentation of the DC packets, which introduces a sub-optimality for the BET throughput. Thus, we take a different approach in this paper that keeps the implementation complexity low and does not involve a packet segmentation step.

Let us now consider that a first round of scheduling has been made for the BET users according to the α-fair scheduler with resource-user selection (3). As a result, the j-th resource is allocated to a BET user which gets the rate $v(j)$ on this resource. Then, at the end of the scheduling operation, the fairness metric is $\sum_{k'} f_\alpha(\sum_{j \in \omega'_{k'}} v(j))$, where $\omega'_{k'}$ is the set of resource indexes allocated to BET user k'.

In a second step, we perform the DC scheduler as described in section 3, and modify the resource-user selection by taking into account a cost experienced by the BET users when said resource is preempted by a DC user. We propose to define the cost $c(i)$ of the preemption of the resource i previously allocated to the BET user $k'(i)$ as the loss on the fairness metric, where

$$c(i) = f_\alpha(\sum_{j\in\omega'_{k'(i)}} v_(j)) - f_\alpha(\sum_{j\in\omega'_{k'(i)}} v(j) - v(i))$$

which leads to the following resource-user selection

$$(\hat{k}_n, \hat{i}_n) = \arg\max_{k,i\in\Omega_n} \frac{\left(\frac{\rho_k}{R_k(n)}\right)^{\beta-1} \frac{r_k(i)}{R_k(n)}}{c(i)} \tag{5}$$

This resource-user selection differs from the state of art, that usually combines arbitrarily resource-user selection criteria of QoS and channel aware schedulers (see many examples in [2]). Here, the pre-allocation of the BET traffic allows for precisely evaluating the impact of preemption on the global figure of merit.

5 Simulation Results

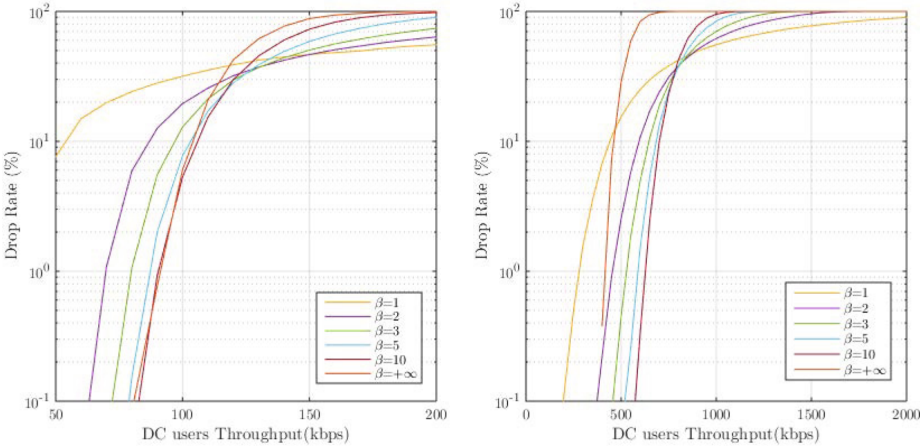
We perform static system level simulations of a multi-cell LTE cellular network with 10MHz bandwidth at 2GHz carrier frequency with nineteen 3-sectors base stations with an hexagonal deployment and 1732m inter-site distance. The antenna diagrams, transmitter and receiver parameters, as well as the path loss model are defined following the case 3 model of 3GPP (see A.2.1.1.1 in [11]). The users locations are selected at random and uniformly within the cell of interest, and Monte-Carlo simulations are performed on the user snapshots and channel realizations. In downlink, the OFDM modulation allows for dividing the time and frequency resource into 50 resource allocation blocks packed in the frequency domain, which are 180kHz-wide and 1ms-long and which carry 168 channel use (i.e., transmission of symbols over one sub-carrier in one OFDM symbol).

The small-scale fading follows an ITU 6-path Typical Urban channel model. We consider that one user is either subject to a *fast link adaptation* strategy where we assume that perfect Channel State Information is available at the transmitter, or to a *slow link adaptation* strategy where we assume that no Channel State Information is available at the transmitter. Fast link adaptation applies to low mobility users, while the slow link adaptation applies to high speed users. The rate obtained with a fast link adaptation on a given resource is estimated by the Shannon capacity limit according to the instantaneous signal to noise ratio experienced on each sub-carrier. The rate obtained with a slow link adaptation on a given resource is estimated by the highest value $R(1 - P_{out}(R, SINR))$, where $P_{out}(R, SINR)$ is the outage probability for a transmission on the given resource at rate R with no channel state information knowledge at the transmitter but the long-term SINR (i.e, averaged over the fast fading). Usually, the long-term SINR is assumed constant in time and frequency, which involves that all the resources have the same rate for a given user.

We consider two classes of users. Firstly, the eNB scheduler receives *delay constrained (DC)* packets every 50ms with a fixed payload defined according to a given throughput. We assume for simplicity that all DC users/packets are received by the scheduler at the beginning of a 50ms-long window, which defines a scenario where a safety related server manages several users and wishes to send safety packets to each of them every $50ms$. Secondly, the eNB scheduler has buffers for data to be transmitted to *Best Effort Traffic (BET)* users, and we assume that the buffers always have enough data to serve said users (a.k.a. full buffer assumption). The scheduler works on blocks of $50 \times 50 = 2500$ resource allocation blocks in a block-wise fashion both for DC and BET users.

First, we evaluate the efficiency of the *Channel and delay aware scheduling* strategy proposed in Section 3. The number of DC users is 30 and no BET users are present in the system. All the DC users have the same throughput, and thus same packet payload. Fig. 1 shows the drop rate, i.e., the proportion of DC packets that could not be completely sent within the 50ms constraint length, as a function of each DC user throughput, when the DC users have a high or low mobility and subject to a slow or fast link adaptation, respectively. The performance of the proposed scheduler is shown for different parameters β. The simulation results confirm that larger β values perform better for lower drop rates and smaller load (lower DC traffic user throughput). When the DC users have a high mobility, for $\beta \to +\infty$, a max-min scheduling decision is performed on the portion of payload already transmitted by each user, and provides the best performance at low load. This criterion does not take into account the instantaneous rate given by each resource. This is not detrimental in the slow link adaptation case since all the resource of the same user have the same rate, which is also the average rate playing a role in the portion of payload already transmitted. For $\beta = 1$, the scheduler falls back to a proportional fair scheduler that allows for providing a lower drop rate when the system is highly loaded. When the DC users have a low mobility, all the DC users have a sufficiently low speed to allow a fast link adaptation strategy. We observe the same behavior as for the high mobility, except for the $\beta \to +\infty$ performance, which is significantly worse than with $\beta = 10$ for relatively small values of the drop rate (around 1%). This is explained by the observation that the $\beta \to +\infty$ scheduler does not take into account the instantaneous rate of each resource, which varies because of the channel frequency selectivity and independence between users. Thus, it does not take benefit from the multi-user diversity which is one key gain factor for multi-user OFDM systems. Thus, a sufficiently large value β (e.g., $\beta = 10$) takes into account both the delay constraint through the portion of payload already transmitted, and the channel-aware user fairness through the proportional fair metric (see (4)).

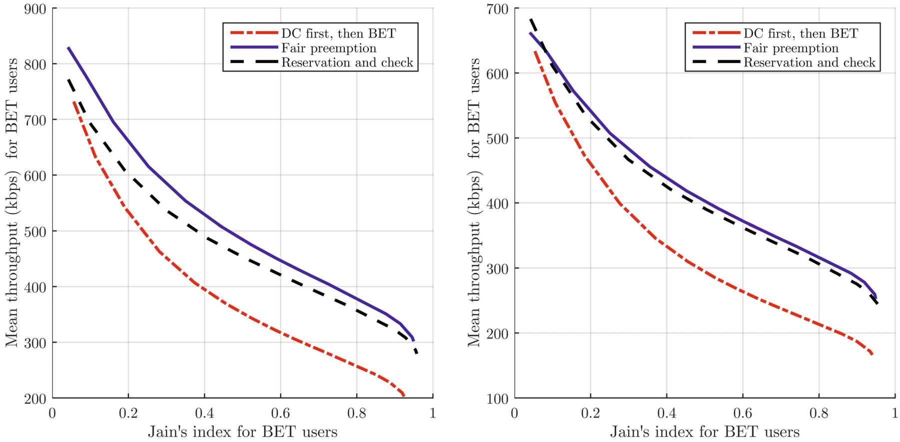
This paper targets safety related traffic with a low drop rate requirement. Thus, in the following, we set $\beta = 10$ as the parameter for scheduling the DC users. Admission control mechanisms can be used for controlling the system load and rejecting users that would endanger the QoS requirement of the DC users.



High Mobility case. Low Mobility case.

Fig. 1. Drop Rate as a function of each of the 30 DC users throughput for different values of the parameter β of the channel and delay aware scheduler. The throughput is linearly related to the system load. Larger β values provide lower drop rate when the system is close to full load.

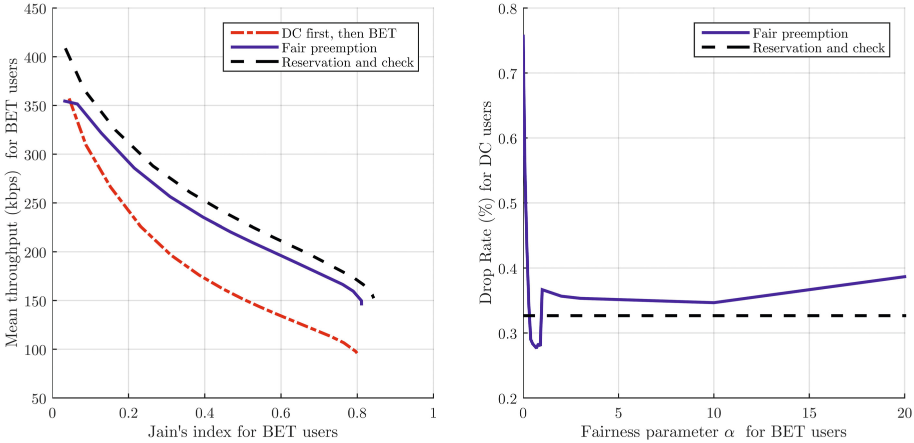
Fig. 2 shows the compromise between the mean throughput and Jain's fairness index (see, e.g., [5]) for 30 BET users. High mobility and Low mobility are considered for 30 DC users. Their throughput is tuned to the limit that gives a quasi-null drop rate. The state of art approach is named *DC first, then BET*, and first allocates the DC traffic with an online scheduler using the metric (4). Then, it allocates the BET according to the metric (3) on the remaining free resource, with a variable parameter α that impacts the fairness-throughput compromise. The proposed approach is named *Fair Preemption* and first allocates the BET on all resources of the considered window of resource allocation blocks according to the metric (3) with a variable parameter α; then allocates the DC traffic with an online scheduler using the metric (5). The *Fair Preemption* strategy highly improves the performance of BET users with no loss (null drop rate) for DC users. For the sake of comparison, we also have plotted the *Reservation and check* scheduler as presented in our previous work [4] comprising: a segmentation of the packets into smaller sub-packets according to the average user rate, a tagging of all resources that can carry each sub-packet, and an online BET scheduling with a check that no bottleneck occurs on the DC traffic. The packet segmentation and the high complexity of the checking function when many sub-packets are considered are the main drawbacks of this approach. For the simulations, we have limited the checking function to a random selection of 100 checks among the set of all possible checks, which explains that the throughput of BET for the *Reservation and check* can be outperformed by the *Fair Preemption*, especially for the high mobility scenario where all resources can carry the same rate. As a remark, the drop rate of *Reservation and check* is always equal to the one of



High Mobility DC users with 70kbps Throughput.

Low Mobility DC users with 500kbps Throughput.

Fig. 2. Compromise between the mean throughput and Jain's fairness index for BET users. The 30 delay constrained users have a high (left figure) or low (right figure) mobility while the 30 BET users have a low mobility. The drop rate of DC users is null. The proposed scheduler with a fair preemption approach always outperforms the state of art approach. The parameter α is the fairness parameter used for the BET scheduling.



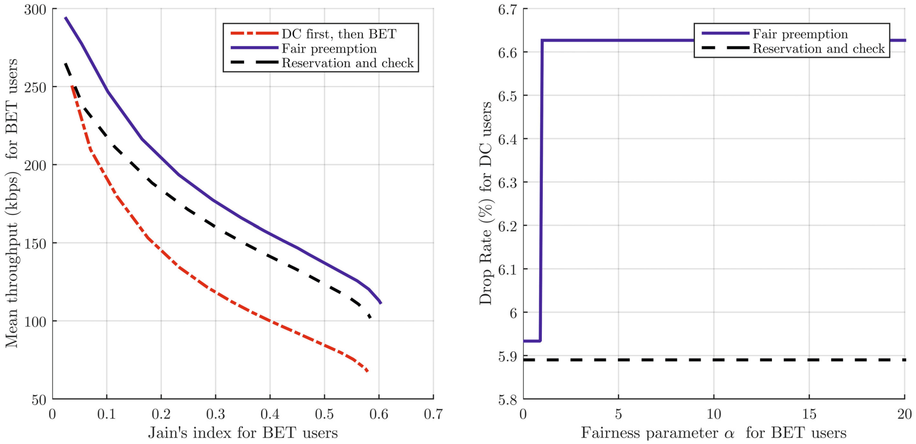
Compromise between the mean throughput and Jain's fairness index for BET users.

Drop Rate of DC users as a function of the fairness parameter used for the BET scheduling α.

Fig. 3. The 30 delay constrained and 30 BET users have a low mobility. The throughput of DC users is 600kbps. The proposed scheduler with a fair preemption approach always provides improved BET performance with a similar drop rate for DC users.

DC first, then BET. The complexity of the proposed *Fair Preemption* is similar to the one of *DC first, then BET*.

In Fig. 3, in order to show that the drop rate and the BET throughput fairness are optimized altogether by our proposed scheduler, low mobility DC users are considered with a throughput of 600kbps that overloads the system for a portion of snapshots of users positions and leads to a non-null (yet low) drop rate. We observe that the drop rate is similar for the three strategies (the drop rate of *DC first, then BET* and *Reservation and check* are equal), while the *Fair Preemption* strategy highly improves the performance of BET users with respect to the *DC first, then BET*, with much lower complexity than *Reservation and check*. The same observation is made in Fig. 4, where the *DC* users have a high mobility and a throughput of $100kbps$ that leads to overloading for some snapshots, and for which the *Fair Preemption* marginally increases the drop rate with respect to the BET throughput improvement.



Compromise between the mean throughput and Jain's fairness index for BET users.

Drop Rate of DC users as a function of the fairness parameter used for the BET scheduling α.

Fig. 4. The 30 delay constrained users have a high mobility. The throughput of DC users is 100kbps. The proposed scheduler with a fair preemption approach always provides improved BET performance with a similar drop rate for DC users.

6 Conclusion

In this paper, we have first proposed a channel and delay-aware scheduler that allows for optimizing the drop rate of safety related traffic, even when the wireless system is highly loaded. Then, we have presented a new preemption approach where the lowest priority (best effort) users are scheduled first, and some allocated resources taken back by a second step of high priority (delay constrained) scheduling, that takes into account both the delay constraints of the priority users and the throughput fairness of the best effort users. Future ITS networks mixing safety and non-safety services with an LTE-like wireless communication system will be particularly relevant applications of the results presented in this paper.

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