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Research Article

Dynamic Tradeoff between Energy and Throughput in Wireless 5G Networks

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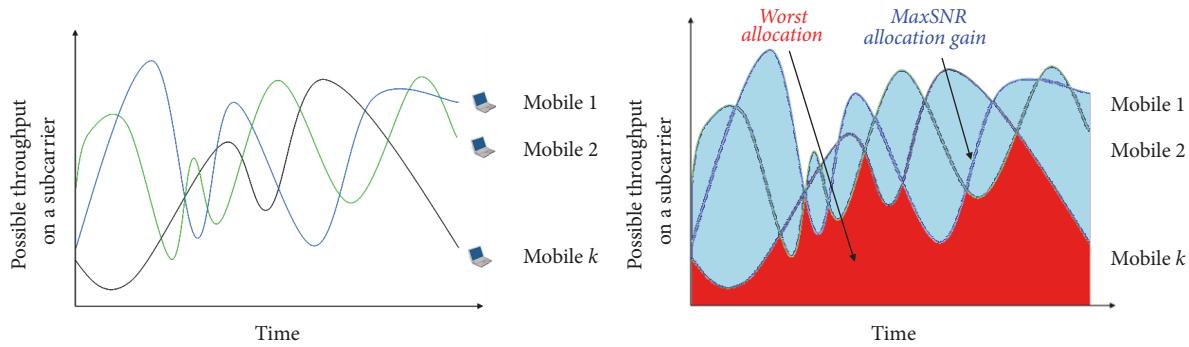
Even though system energy and spectral efficiency are major issues in wireless network, reaching these objectives conjointly seems very difficult and requires the usage of tradeoffs. Moreover, depending on the context, the importance of either varies. In underloaded context, guaranteeing high Quality of Service (QoS) is easily achievable due to large surplus of available radio resources and focus should be put on energy rather than system throughput. On the contrary, in an overloaded context, the lack of available radio resources required that resources allocation algorithms focus on system capacity in order to preserve QoS. Since the major issue of the network is to satisfy users, in this specific case, energy consumption must become lesser important. Many specialized solutions have been proposed that focus either on energy saving or on throughput maximization. They provide high performances, respectively, on their specific network traffic load context, previously described, but are not optimized outside. Other solutions that proposed static tradeoffs provide average performances but can not be fully efficient in all scenarios. In this paper, we propose a Dynamic Tradeoff between energy and throughput efficiency that adapts the scheduler priorities to the network context and particularly to the traffic load. Considering the context, the scheduler is able to adjust its behavior in order to maintain high QoS while reducing as much energy as possible. Performance evaluation will show that the proposed solution succeeds to minimize energy consumption better than energy focused scheduler in underloaded context while being able to reach the same spectral efficiency as throughput oriented scheduler in highly loaded context.

1. Introduction

The constant growing number of users which each are more and more demanding in terms of throughput and delay constraints leads us to develop new resource allocation algorithms that increase spectral efficiency while guaranteeing high fairness. In addition, ensuring high Quality of Experience (QoE) can not be reached without offering a good and sustainable mobility that required new resource allocation strategies which provide low energy consumption in order to increase battery lifetime.

Traditional resource allocation strategies used in wireless networks were originally and primarily designed for the wired context. Consequently, these conventional access methods like Round Robin (RR) and Random Access (RA) are not well adapted to the wireless environment and provide very poor throughput. Intensive research efforts have been given in order to propose throughput efficient schedulers and opportunistic approaches have emerged as the best way. The best known is called Maximum Signal to Noise Ratio (MaxSNR) scheduler [1, 2]. It preferably allocates the resources to the user with the most favourable channel conditions at a given time. It takes benefit of multiuser and frequency diversity in order to maximize the system throughput (Figure 1(b)). However users close to the access point have a better average throughput per Resource Unit (RU) than far users. This induces that, with MaxSNR scheduler, close users have statistically more chances to have access to the medium. In consequence, far users will often obtain radio resources after close users making them overpassing their QoS requirement and being unsatisfied. In order to solve this issue, Proportional Fair (PF) and PF-based algorithms have been proposed [3–8]. The basic principle is to allocate resources to a user when its channel conditions are



(a) Throughput/Resource Unit (RU) variation over the time due to multipath fading

(b) Opportunistic system capacity increase

Figure 1: Benefit of opportunistic scheduling strategies on spectral efficiency and system capacity.

the most favourable with respect to its time average. This approach is more fair than MaxSNR since all users have statistically the same probability to access radio resources. Therefore, PF increases the benefits of multiuser diversity which reinforce the opportunistic resource allocation behavior conducting in spectral efficiency increase. However, all these schedulers have a severe lack in terms of energy management.

In order to offer more battery autonomy to users, solutions focusing on energy have been developed. The Power-based Proportional Fairness (PPF) [9] proposes PF-based scheduler that avoids the inefficient allocations (with low SNR) and delays flows that have high average energy consumption. This slightly increases energy efficiency since this gives access to the medium only to users with good SNR and allows always using higher modulation orders that are the most profitable but potentially could segregate users with high traffic load (that will use more radio resources and consequently use more energy). In addition, the best way to minimize energy consumption is not only to optimize the modulation but mainly to maximize the sleep time. The Opportunistic Energy Aware scheduler (OEA) [10] is built on this principle. It exploits active-sleep mode and channel condition together. While other schedulers can potentially activate all users, the OEA limits this number. This allows compressing the transmission time (i.e., active mode), greedy in energy. Considering the channel condition in the allocation process, only allocations with good modulation are also conserved. T-MAC [11] is another strategy that can be considered as an extreme version of OEA. It only schedules a single user by time slots that strongly maximize sleep time but, by losing multiuser diversity benefit, provide lower throughput. All these energy specialized schedulers lack fairness and have limited spectral efficiency. Therefore this limits their scope of usage to underloaded context. Since energy efficiency guarantee must not evade QoS requirement and the system capacity optimization, new approaches must be developed in order to bring together high spectral efficiency, fairness, and energy consumption minimization whatever considered traffic load.

Previously we had proposed a Fairness-Energy-Throughput Optimized Tradeoff Scheduler (FETOT) [12]. This solution tries to provide the best tradeoff between system capacity and energy efficiency while providing fairness. It takes into account the radio condition in order to avoid bad allocation in terms of throughput. A correction factor on the distance is adequately integrated in the algorithm in order to offer the same high fairness considering far and close users like PF. This scheduler is also built to compress the transmission time but, contrary to the OEA, FETOT is able to take a full benefit on the multiuser diversity thanks to a new tradeoff parameter. The result is that FETOT combined the advantages of MaxSNR, PF, and OEA, respectively, on system capacity, fairness, and energy efficiency. However this tradeoff is static and performances can be enhanced making the tradeoff dynamic and always adapted to the context.

In this paper, we propose a new algorithm Dynamic Tradeoff scheduler (DT) that dynamically adjusts its behavior to the traffic load context. In an underloaded system, radio resources are abundant and the system can easily satisfy all users. Consequently, in these contexts, DT detects the surplus of unused radio resources and orients its scheduling strategy to be energy aware. It makes a better usage of multiuser diversity than OEA that allows to preserve more energy than this specialized algorithm even in its scope of usage. In an overloaded system, radio resources are highly valued and system meets high difficulties to satisfy all users. In these contexts, DT detects the lack of available radio resources and orients its scheduling strategy to increase spectral efficiency in order to withstand the load increase. It offers the same system capacity as PF and outperforms MaxSNR. Between these two extreme contexts, DT takes into account the bandwidth usage ratio to smoothly adapt and adjust its energy-throughput tradeoff to the traffic load. Performance evaluation will show that users are always satisfied with fairness as well as PF while always preserving as much energy as possible.

This paper is constructed as follows: Section 2 presents the system description, Section 3 describes the Dynamic Tradeoff

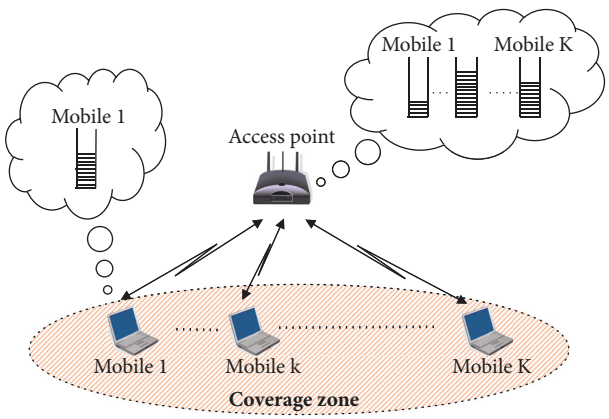


Figure 2: Allocation of radio resources among the set of mobiles situated in the coverage zone of an access point.

algorithm, Section 4 shows performances evaluations, and Section 5 is the conclusion.

2. System Description

We focus on the proper allocation of radio resources among the set of mobiles situated in the coverage zone of an access point (Figure 2). We consider a centralized approach. The packets originating from the backhaul network are buffered in the access point which schedules the downlink transmissions. In the uplink, the mobiles signal their traffic backlog to the access point which builds the uplink resource mapping.

We assume that the physical layer is operated using the structure described in Figure 3 which ensures a good compatibility with the OFDM based transmission mode of the IEEE 802.16-2004 [13, 14]. The total available bandwidth is divided into subfrequency bands or subcarriers. The radio resource is further divided into the time domain in frames. Each frame is itself divided into time slots (TS) of constant duration. The time slot duration is an integer multiple of the OFDM symbol duration. The number of subcarriers is chosen so that the width of each subfrequency band is inferior to the coherence bandwidth of the channel. Moreover, the frame duration is fixed to a value much smaller than the coherence time (inverse of the Doppler spread) of the channel. With these assumptions, the transmission on each subcarrier is subject to flat fading with a channel state that can be considered static during each frame.

The elementary Resource Unit (RU) is defined as any (subcarrier, time slot) pair. Each of these RUs may be allocated to any mobile with a specific modulation order. Transmissions performed on different RUs by different mobiles have independent channel state variations [15]. On each RU, the modulation scheme is QAM with a modulation order adapted to the channel state between the access point and the mobile to which it is allocated. This provides the flexible resource allocation framework required for opportunistic scheduling.

The system is operated using time division duplexing with four subframes: the *downlink feedback subframe*, the *downlink data subframe*, the *uplink contention subframe*, and the *uplink data subframe*. The uplink and downlink data subframes are used for transmission of user data. In the downlink feedback subframe, the access point sends control information towards its mobiles. This control information is used for signalling to each mobile to which RU(s) has been allocated in the next uplink and downlink data subframes, the modulation order selected for each of these RUs, and the recommended emission power in the uplink. In the uplink contention subframe, the active mobiles send their current traffic backlog and information elements such as QoS measures and transmit power. The uplink contention subframe is also used by the mobiles for establishing their connections. This frame structure supposes a perfect time and frequency synchronization between the mobiles and the access point as described in [16]. Therefore, each frame starts with a long preamble used for synchronization purposes. Additional preambles may also be used in the frame.

3. Dynamic Tradeoff Scheduler

The DT scheduling algorithm relies on weights that set the dynamic priorities for allocating the radio resources. These weights are built in order to satisfy three major objectives that are explained separately in the following: system capacity maximization, fairness, and energy consumption minimization. Then we will present a calibration of the function that adds an ability for the scheduler to adequately tune the multiuser diversity usage considering the context and relative objectives, merging previous weights in a balanced DT solution.

3.1. System Throughput Maximization. The DT scheduler optimizes the system throughput in a MAC/PHY opportunistic approach. Data integrity requirements of users are enforced considering each user independently, adapting the modulation and the transmit power to the user specific channel state. At each frame allocation, the scheduler computes the maximum number of bits $q_{k,n}$ that can be transmitted in a TS of subcarrier n if assigned to user k while keeping below its Bit Error Rate target ($BER_{target,k}$), for all k and all n:

$$q_{k,n} \leq \left\lfloor \log_2\left(1 + \frac{3P \times T_s \times (1/d_k)^{\beta} \times \alpha_{k,n}^2}{2N_0\left[\operatorname{erfc}^{-1}\left(BER_{target,k}/2\right)\right]^2}\right)\right\rfloor, \quad (1)$$

where P is the transmission power, N_0 is the spectral density of noise, T_s is the OFDM symbol duration, d_k is the distance to the access point of the user k, and $\alpha_{k,n}^2$ represents the flat fading experienced by this user on subcarrier n. In the following, $\alpha_{k,n}$ is Rayleigh distributed with an expectation equal to unity. The exponent β corresponds to the experienced path loss and goes from 2 to 4 considering environment density level. Due to multipath fading, the potential number of bits that a user can transmit on a RU will fluctuate around this value over the time.

We further assume that the supported QAM modulation orders are limited such that q belongs to the set $S = \{0, 2, 4, \ldots, q_{max}\}$. Hence, the maximum number of bits $m_{k,n}$

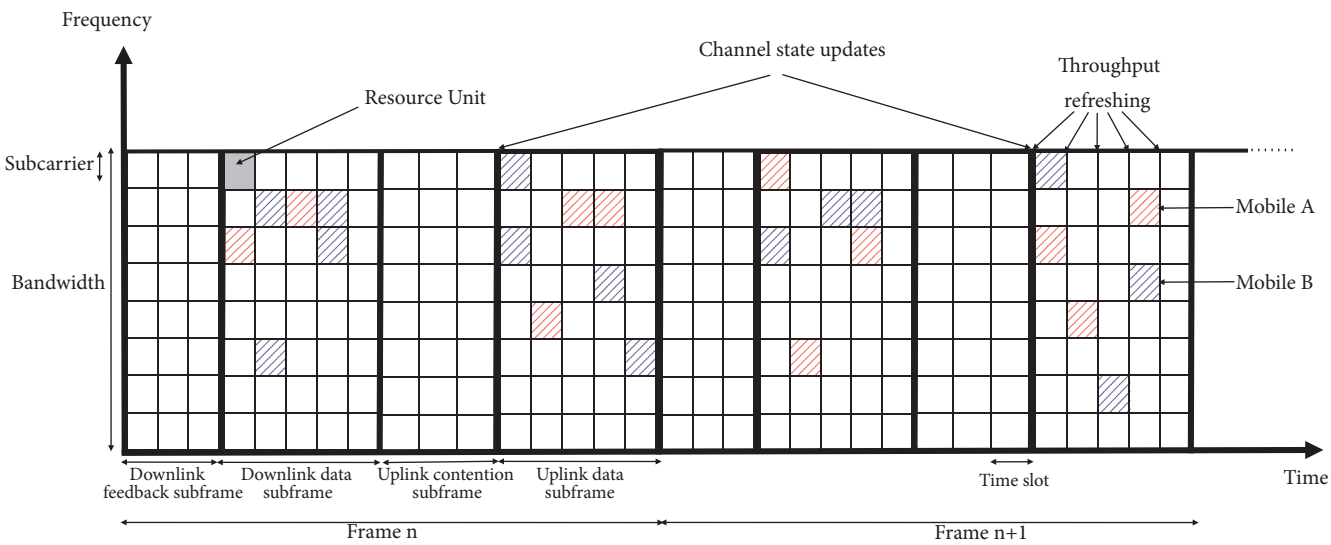


Figure 3: DT frame structure in TDD mode.

that will be transmitted on a TS of subcarrier n if this RU is allocated to the user k is

$$m_{k,n} = \max\{q \in S,\ q \leq q_{k,n}\}. \quad (2)$$

MaxSNR based schemes allocate the RU to the user which has the greatest $m_{k,n}$ values. This strategy maximizes the system capacity at short time scale but is highly unfair considering users far to the access point that are often delaying out of their delay requirement. In order to provide more fairness considering users locations while preserving the system throughput maximization, a fairness parameter is introduced in DT.

3.2. Fairness Guarantee. DT integrates in its scheduling process the fairness parameter proposed in [8]. Called "Compensation Factor" (CF_k), this parameter takes into account the current path loss impact on the average achievable bit rate of mobile k:

$$CF_k = \frac{b_{ref}}{b_k}. \quad (3)$$

b_{ref} is a reference number of bits that may be transmitted on a subcarrier considering a reference free space path loss a_{ref} for a reference distance d_{ref} to the access point and a multipath fading equal to unity:

$$b_{ref} = \log_2\left(1 + \frac{3P_{max} \times T_s \times a_{ref}}{2N_0\left[\mathrm{erfc}^{-1}\left(BER_{target}/2\right)\right]^2}\right). \quad (4)$$

b_k represents the same quantity but considering a distance d_k to the access point:

$$b_k = \log_2\left(1 + \frac{3P_{max} \times T_s \times a_{ref} \times \left(d_{ref}/d_k\right)^{\beta}}{2N_0\left[\mathrm{erfc}^{-1}\left(BER_{target}/2\right)\right]^2}\right), \quad (5)$$

with β the experienced path loss exponent.

Adequately combining and taking into account both $m_{k,n}$ and CF_k in the allocation process ($m_{k,n} * CF_k$), DT considers all mobiles virtually at the same position in the scheduling decision. CF_k adequately compensates the lower spectral efficiency of far mobiles bringing high fairness in the allocation process. An equal throughput can be provided to each mobile while keeping the MaxSNR opportunistic scheduling advantages thanks to the $m_{k,n}$ parameters which take into account the channel state. Moreover, in contrast with MaxSNR which satisfy much faster the mobiles which are close to the access point, DT keeps more mobiles active but with a relatively low traffic backlog. Satisfaction of delay constraints is more uniform and, by better preserving the multiuser diversity, a more efficient usage of the bandwidth has been highlighted. This jointly ensures fairness and system throughput maximization. If two mobiles have an equal priority for RU, this one is given to the mobile which has the highest buffer occupancy further strengthening fairness. At this step, DT optimizes the throughput and guarantee high fairness but highly suffers of an inefficient energy management as the same level as PF. In order to provide energy consumption minimization while preserving the system throughput maximization and fairness, an energy parameter is introduced.

3.3. Energy Consumption Minimization. The third major objective of the DT is to provide efficient energy management in addition to the system throughput optimization and fairness. Existing opportunistic resource mapping (as MaxSNR or PF for example) basically overexploits multiuser diversity which induces horizontal allocation. Indeed, due to flat fading during a frame, often the same user strictly experienced the greatest channel condition on each TS of a given subcarrier. Consequently, with classical opportunistic schedulers, the same user often receives all the TS of a subcarrier and needs to stay in active mode during a long time. We can potentially have one different selected user on each available subcarrier. Consequently, during all TS, many

selected users can not be set in sleep mode. They consume a lot of power to transmit few bit during a long time (with many allocated TS but on few subcarriers).

The DT scheduler integrates a modified version of the energy efficient OEA solution [10], keeping its energy benefit without its fairness and system capacity failure. Energy consumption is minimized particularly by increasing the sleeping mode duration. In order to achieve this goal, DT extends the classical OEA opportunistic cross-layer design to obtain a new vertical opportunistic resource mapping. When a user is in active mode, DT tries, like OEA, to benefit from its activation in order to compress its time of activity and to transmit more bit per "used" TS. Like this, DT allows to significantly increase sleeping mode duration and energy preservation. Originally, OEA scheduler computed an "energy transmission cost" (ETC_k) parameter (in Watt). It is based on the energy cost of user k to transmit on a RU:

$$ETC_k = A_k * Cn_k + (1 - A_k) * (C_k + Cn_k). \quad (6)$$

When the user k is in active mode, $A_k = 1$ otherwise $A_k = 0$ (i.e., sleep mode). In addition, Cn_k and C_k are two constants (in Watt). C_k represents the energy needed to wake up the user k from the sleep mode to the active mode. Cn_k represents the energy needed to transmit on a nth allocated subcarrier. The energy cost to transmit on the first RU (C_k) is higher than the cost to transmit on n^{th} (Cn_k) since the cost to move to sleep mode to active mode and transmit is greatly higher than just transmit some supplementary bits while user is already active.

ETC_k is used in OEA scheduler but has the negative side effect to highly reduce the usage done of the multiuser diversity. This drastically and negatively impacts the OEA system capacity optimization. In order to keep its energy minimization properties while fixing this throughput issue, DT integrates a modified ETC_k parameter that we called "Throughput-Energy Tradeoff" parameter TET_k:

$$TET_k = A_k * Cn_k + (1 - A_k) * \left(\frac{C_k}{MD} + Cn_k\right), \quad (7)$$

where MD is a multiuser diversity factor. The higher MD is, the more the system increases the number of active users at the same time, intensifying the multiuser usage and consequently the global system throughput at the expense of the energy consumption (infinite MD value makes TET_k constant and induces DT similar to a PF resource allocation). On the contrary, low MD value makes DT decreasing the number of active users at the same time, reducing energy consumption at the expense of the multiuser diversity usage that provides a resource allocation close to OEA scheduling (excepting that this version is strongly more fair due to Section 3.2). After large performance evaluation studies we found that $MD = 10$ provides a very efficient static tradeoff between energy consumption minimization and spectral efficiency. These works had led to a proposition of a new scheduler called FETOT in [12]. It allowed making an adequate usage of the multiuser diversity in order to provide the same system capacity as MaxSNR, same fairness as PF, and an energy minimization very close to the OEA results. However, we are convinced that the usage of a static MD value is not optimal. Even if FETOT provides a very good static overall tradeoff, this can be highly improved with a solution able to adapt and tune the MD (and consequently the tradeoff) to the network traffic load context. Indeed, in very low traffic load context, energy minimization must be the only objective. With the increase of the traffic load, more attention must be done on spectral efficiency in adequate tradeoff. In high traffic load, to improve spectral efficiency becomes the primary goal in order to continue to satisfy users and energy minimization priority must be relegated. The main contribution of this paper is to propose a new scheduler that combined all previously described parameters and used a dynamic MD parameter to adapt priority to the context.

3.4. DT Merging of Priorities. The DT scheduler allocates the radio resource n to the mobile k that has the greatest $DT_{k,n}$ value such as

$$DT_{k,n} = \frac{m_{k,n} * CF_k}{A_k * Cn_k + (1 - A_k) * (Cn_k/MD + Cn_k)} \quad (8)$$

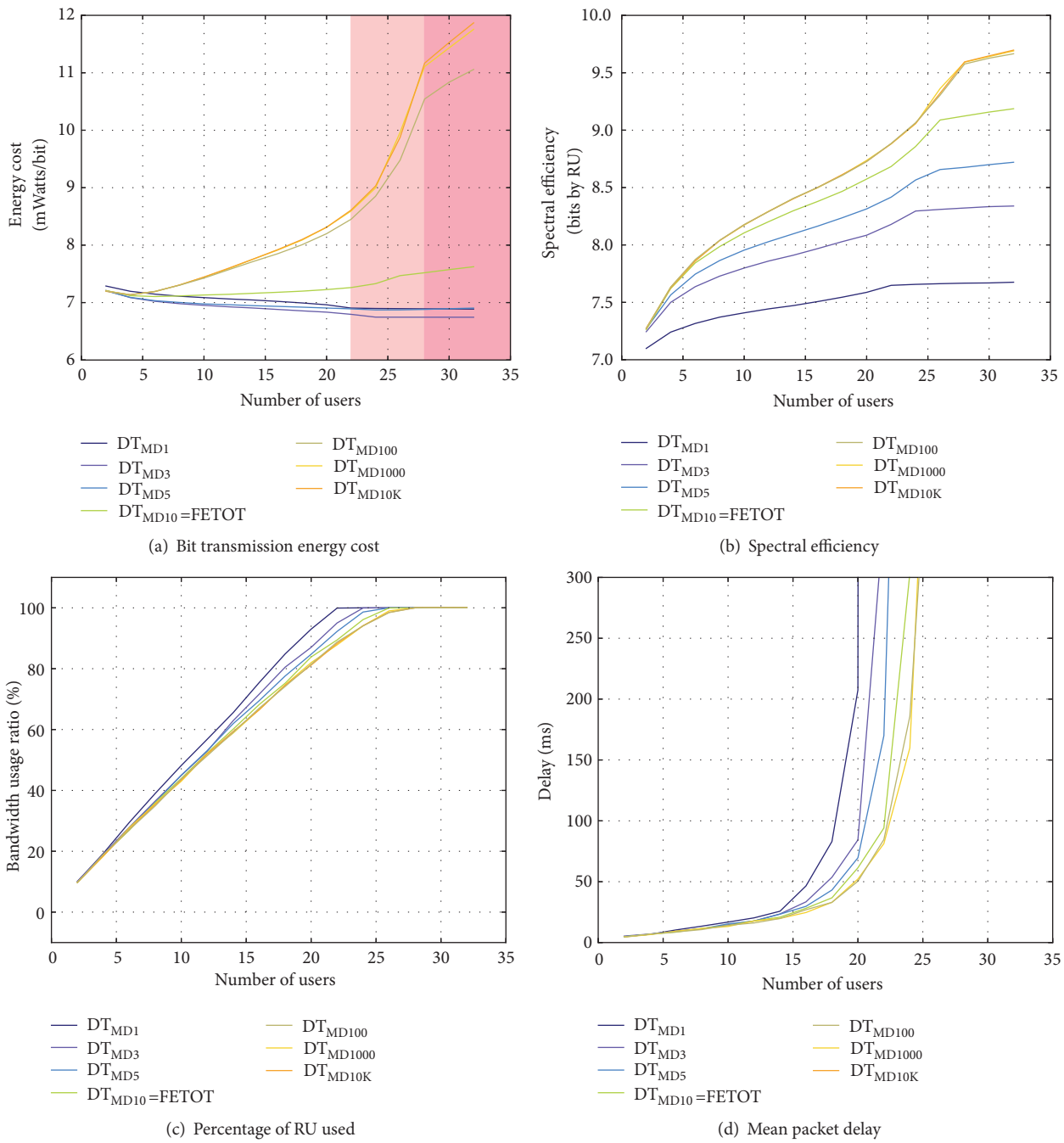
Taking into account $m_{k,n}$ allows optimizing system capacity avoiding unprofitable radio resource allocation, CF_k allows staying fair in the allocation process regarding user location, and the other parameter allows fighting versus energy waste. Particularly, by adjusting the multiuser diversity usage thanks to good function of MD, DT could select the minimum number of users per timeslot to have a good energy efficiency while respecting the QoS requirements. However when the system is more loaded, DT could increase the multiuser diversity thanks to a higher value of MD in order to obtain a better spectral efficiency to support the load.

3.5. Study of the Multiuser Diversity Factor. The multiuser diversity has an important impact on the load resistance and on the energy consumption. Finding an efficient way to adapt its usage to the context thanks to a well-tuned MD factor is challenging:

(i) The first step would be to determine the extremes values of the MD which correspond the best to extreme configurations: when the system is clearly underloaded, the only concern is the energy consumption, and when the system is largely overloaded, the main focus has to be on the QoS requirements.

(ii) The second step is to find a smooth and adequate transition between those two extremes values based on adapted inputs.

3.5.1. Study of Different Static MD Values in order to Detect the More Efficient in Extreme Scenarios. Figure 4 shows the performances of preliminary versions of DT using static value of MD factor. For different traffic loads it shows the energy transmission cost per bit (Figure 4(a)), the spectral efficiency (Figure 4(b)), the bandwidth usage ratio (bandwidth usage ratio of the number of allocated resource units divided by the total number of radio resource units in the system, in average, per frame) (Figure 4(c)), and the packet delay (Figure 4(d)).



(a) Bit transmission energy cost

(b) Spectral efficiency

(c) Percentage of RU used

(d) Mean packet delay

Figure 4: System capacity and spectral efficiency study obtained with different static *MD* values.

In a noncongested system (i.e., when delay and bandwidth usage ratio are low, here with a number of users < 15 users), the focus should exclusively be put on the energy efficiency. As we can see in Figure 4(a) a value too big of *MD* (>10) induces excessive consumption due to several users simultaneously active on same time slots. However choosing the smallest value is not a good option either. Indeed if the *MD* is too small, opportunistic behavior is drastically reduced, and the spectral efficiency (Figure 4(b)) is not good enough to evacuate the necessary amount of information in a short time. Even if the scheduler could appear to be more energy efficient due to a drastically limited number of active user at the same time, it is not at long time scale since users will transmit during longer periods due to very low spectral efficiency. Consequently, in extreme and very low loaded context, $MD = 3$ seems to be the most adequate value in order to reach the minimization energy consumption objective (Figure 4(a)).

In a congested system (i.e., when delay is high, bandwidth usage ratio very close or equal to 100 %, here with a number of users > 20 users), the focus should exclusively be put on the spectral efficiency since the priority is to maintain a good level of QoS. Concerning bandwidth usage ratio, Figure 4(c) underlines that all *MD* values superior or equal to 100 allow better withstanding extreme traffic loads providing same spectral efficiency (Figure 4(b)) and best delays (Figure 4(d)). However, having a look at the energy efficiency (Figure 4(a)), we notice a slight advantage to $MD = 100$ over superior value that drive us to consider MD value around 100 as the most adequate values in this extreme highly loaded context.

3.5.2. Dynamic MD Function Calibration. Originally in previous works (FETOT) [12], we show that a fixed *MD* value set at 10 could represent an average good tradeoff. However it is not the best suitable solution for extreme cases as shown above. Adaptive solution can be developed to outperform FETOT in those situations with a dynamic usage of multiuser diversity that can be obtained thanks to a dynamic *MD* according to the context and particularly to the traffic load (that should define the scheduler priorities/goals). We propose in DT to define *MD* as an increasing function of the bandwidth usage ratio. This parameter simply and accurately informs on the state of the system and on the difficulties or not for the scheduler to maintain the QoS to user. Low bandwidth usage ratio values, inducing low MD value (MD=3), underline to DT to focus on energy. High bandwidth usage ratio, which required to focus on spectral efficiency, will induce high MD value (MD around 100) that will improve multiuser diversity usage. In order to link these two extremes, we proposed an heuristic:

$$MD_x = C + \beta x^{\alpha} \tag{9}$$

where x is the bandwidth usage ratio, C is a constant that defined the starting value of the MD function when the system is underloaded, and β corresponds to the other extreme when the system is overloaded. In the following, we set C to 3 and β to 100 according to Section 3.5.1. The parameter α allows setting the reactivity of the function to the traffic load variation. An appropriate calibration of α is highly important.

3.5.3. Studies of α. It is important that the MD function gives low values when bandwidth usage ratio is low. Since QoS is easily guaranteed, DT has to limit the multiuser diversity usage in order to focus on energy consumption minimization. When traffic load increases, MD function must increase its output in adequation with the difficulties met by the scheduler to conserve high QoS. Figure 6 represents *MD* variation depending on traffic load (measured with the bandwidth usage ratio) for different value of α. As we can notice in this figure, the α parameter directly impacts how this *MD* value will increase from the traffic load. If α is set equal to 1, the *MD* function is linear and multiuser diversity usage will be constantly increased with the bandwidth usage ratio. It is not optimal since no QoS difficulties are met with low bandwidth usage ratio values and problems are experienced only when we they come closer to 100%. On the contrary, high value of α (typically $\alpha = 40$) makes MD function growing too late in order to satisfy the QoS. Indeed, in realistic scenario, with the variability of the traffic, even with an average measurable bandwidth usage ratio inferior to 100% but close to this limit, temporary short term congestion can occur decreasing QoS. In these cases multiuser diversity usage must be intensified and this can be done by DT scheduler if MD function is well calibrated. Detecting when MD function must begin to grow is a difficult task and relies on the elasticity of the traffic. In order to define the best value of α we decide to evaluate all possible α values performances in extensive simulations (Figure 5). We used the more realistic traffic models (MPEG-4, Voice, Videoconference, etc.) that highly complicate the task of the schedulers.

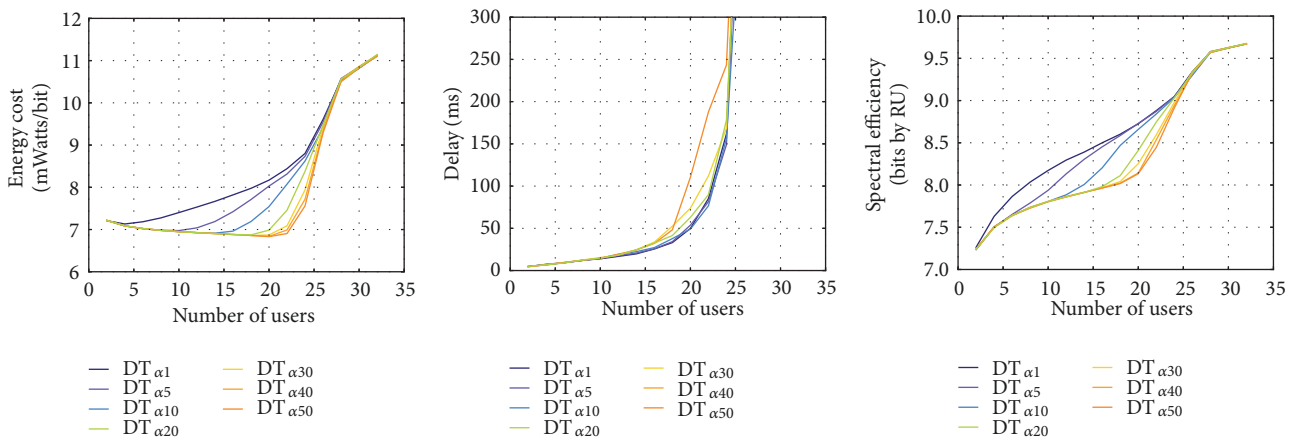
Figure 5(a) shows the impact of α regarding the energy efficiency. It is the most important objective for all the left part of the figure since delays are very low (Figure 5(b)). Choosing a small α value such as 1 has a very bad impact on the energy consumption that increases quickly. This is due to the fact that the algorithm is too much reactive on the traffic load increase, uselessly exploits a supplementary of multiuser diversity, and futilely tries to focus on the QoS. Indeed, the same very good values of delay are obtained for all α values inferior or equal to 20 (Figure 5(b)). Higher values than 20 increase MD too late and provide worst delay, and lower values provide same delay but more energy consumption. If we consider that a final goal is to be able to maintain the best QoS while minimizing energy as much as possible, the most suitable α value for the MD function is 20.

4. Performance Evaluations

4.1. Context and Simulation Setup. Performance evaluation results are obtained using discrete event simulations. In the simulations, we assume C_k and Cn_k are fixed, respectively, equal to 110.2 mW and 46.8 mW, for all k in accordance with measured hardware consumption. The BER target is taken equal to 10^{-3}. We also consider that all users run realistic Variable Bit Rate applications [17] that generate high volume of data with high sporadicity and require tight delay constraints which substantially complicate the task of the scheduler. In order to study the influence of the distance of users on the scheduling performances, a first half of mobiles is situated close to the access point and has a mean $m_{k,n}$ equal to 8 bits. The second half is more far from the access point such as their mean $m_{k,n}$ equal to 6 bits. All performance criteria are done studying the influence of the traffic load. This one varies adding users 2 by 2 (each time, 1 close user and 1 far user).

4.2. Simulation Results

4.2.1. Spectral Efficiency and Throughput. Figure 7(a) shows the spectral efficiency obtained with each scheduler for different traffic load in the system. Since RR does not take into account radio conditions and therefore is not opportunistic, it does not take any advantage of multiuser diversity and its spectral efficiency is constant and low. State-of-the-art energy focused schedulers (T-MAC, OEA) drastically limit the usage



(a) Bit transmission energy cost (b) Mean packet delay (c) Spectral efficiency

Figure 5: Study of α on system capacity and delay.

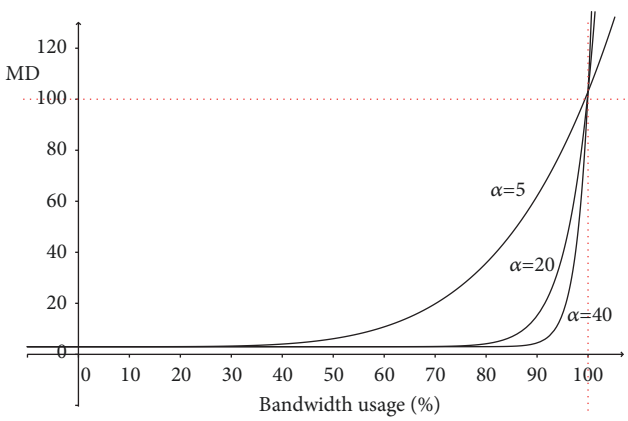


Figure 6: Variation of *MD* according to α value.

of the multiuser diversity in their allocation process offering slightly better results. On the contrary MaxSNR, highly opportunist, provides a large gain. However, as explained in Section 3.1, MaxSNR has a lack on fairness and is not able to take all the benefits of the multiuser diversity and is highly outperformed by PF. FETOT makes a tradeoff between energy and throughput providing spectral efficiency results close to MaxSNR.

Thanks to its dynamic MD parameter based on the bandwidth usage ratio, DT has lesser spectral efficiency in low traffic load context using a moderate usage of the multiuser diversity focusing its efforts on energy. However, when it becomes necessary (i.e., system approach congestion (Figure 7(b))), its MD factor adequately increases and raises the DT usage of the multiuser diversity improving the spectral efficiency at the same level as PF reaching the same overall maximum system capacity (Figure 7(b)).

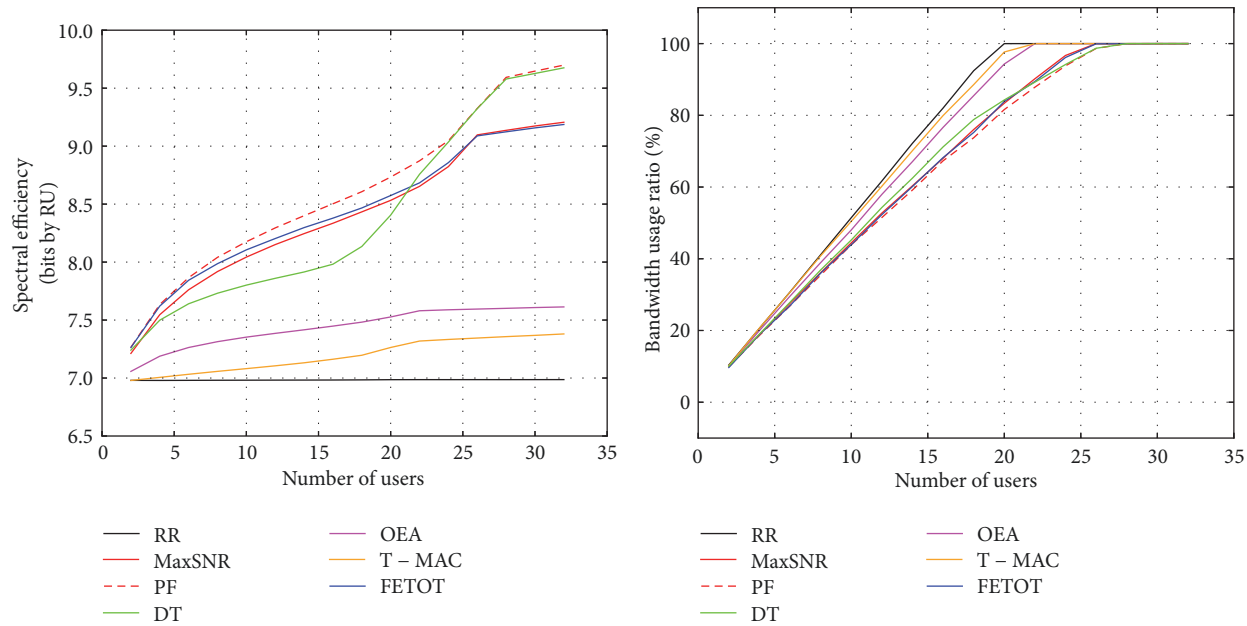
4.2.2. Delay and Fairness. A major QoS key performance indicator is the latency. Figure 8(a) represents the mean packet delay experienced in the system in milliseconds according to the number of users showing the traffic load. We can notice that 2 groups emerged:

(i) First, RR, T-MAC, and OEA have the worst results. Having a low spectral efficiency (Figure 7(a)), they failed to support a large amount of traffic load with good QoS.

(ii) Secondary, MaxSNR, PF, FETOT, and DT are able to better sustain higher load increase with acceptable delay.

Figure 8(b) focuses on fairness computed thanks to the Jain's fairness index applied on mean packet delay. (With n defined as the current number of users in the system, Jain's fairness index can vary between $1/n$ and 1, respectively, associated with the most unfair scheduling to the most fair.) T-MAC, OEA, and MaxSNR significantly penalize user far from the access point and have decreasingly fairness results with the traffic load increase. On the contrary more fair solutions as RR, PF, FETOT, and DT achieve to reach an high fairness. Note that after congestion fairness cannot be guaranteed since global mean packet delay is infinite. Consequently the capacity of these schedulers to maintain high fairness is directly related to their spectral efficiency and when they have no longer available radio resources, fairness disappeared. (Note that when the system capacity is highly overpassed, Jain's fairness index can increase due to comparison of close but unacceptable huge value of delay.) Respectively, the most fair schedulers are consequently PF, DT, FETOT, RR, MaxSNR, OEA, and T-MAC.

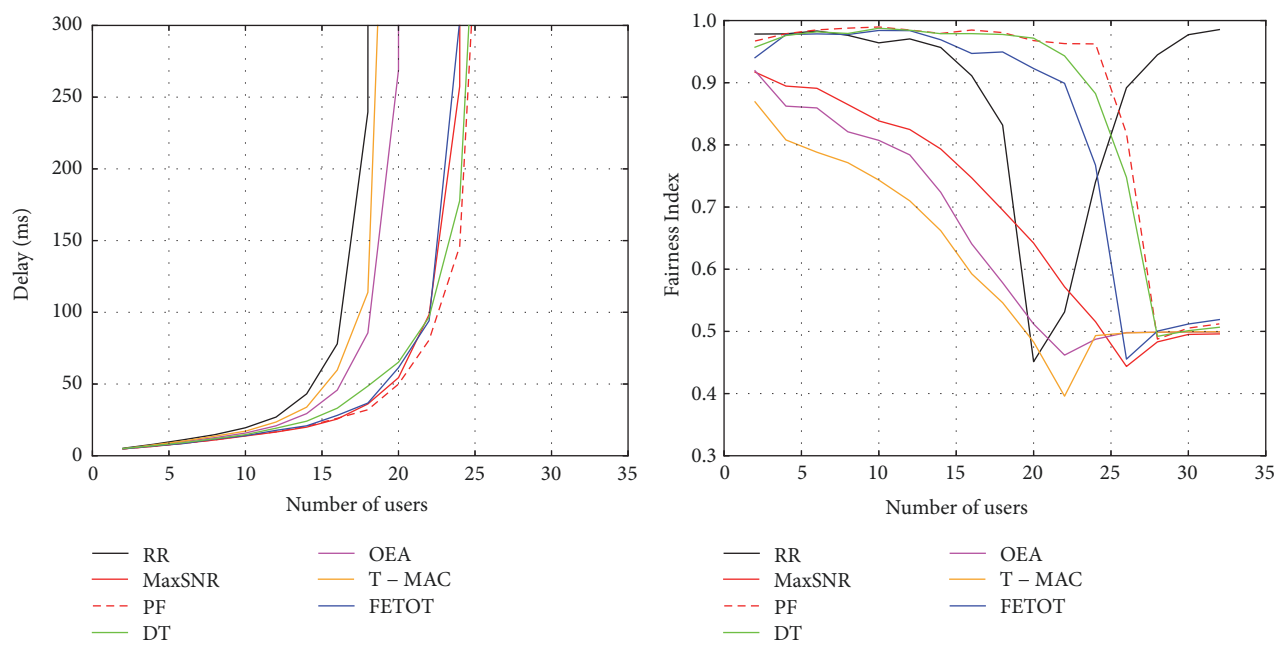
4.2.3. Energy Consumption. Figure 9 shows the abilities of each scheduler to be energy efficient. RR widely provides the worst results. This is due to its nonopportunistic behavior that makes possible highly inefficient resource allocation in terms of bit per RU and corresponding to a significant energy and RU wastes. In addition, due to a cycling user selection, many users can be simultaneously activated (Figure 9(d)) increasing again the energy waste (with more of 20 users, the system is overloaded and RR fails to provide the sufficient amount of RUs required by each user; they are often forced to stay in sleep mode even with data to transmit due to the lack of RUs; more often in forced sleep mode, the users consumed



(a) Spectral efficiency

(b) Percentage of RU used

Figure 7: Schedulers system capacity study.

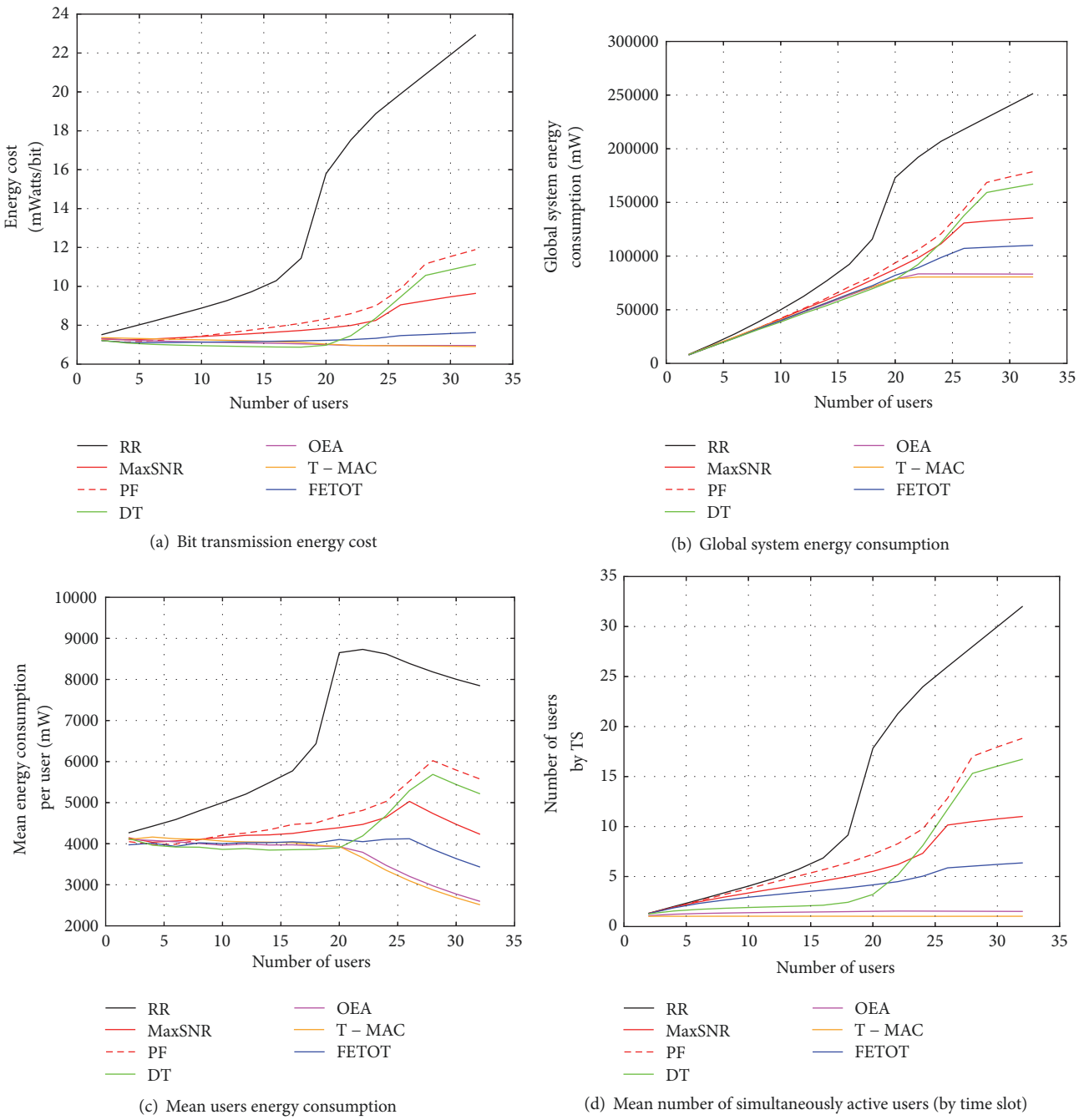


(a) Mean packet delay

(b) Jain's fairness index

Figure 8: Schedulers abilities to guarantee high Quality of Service.

less energy over the time; this explains why, with more than 20 users, the RR curve decreases (Figure 9(c))) since more users pay the high transmission activation price C_k. Limiting the usage of the multiuser diversity to a low value whatever the context (Figure 9(d)), T-MAC and OEA provide very good energy consumption (Figure 9(c)). Note that these good results must be put into perspectives. Indeed, those solutions continue to search to minimize energy consumption even when traffic loads increase and this stubborn behavior conducts these schedulers to quickly reach congestion (Figure 7(b)) with high delay (Figure 8(a)). On the contrary, PF, fully exploiting the multiuser diversity (Figure 9(d)), consumes more energy (Figure 9(c)) but less than RR thanks to strongly better spectral efficiency. Focusing on MaxSNR, its energy results are slightly better than PF. Indeed, this scheduler has a tendency to segregate a part of users (far from



(a) Bit transmission energy cost

(b) Global system energy consumption

(c) Mean users energy consumption

(d) Mean number of simultaneously active users (by time slot)

Figure 9: Scheduler energy efficiency.

the access point) and consequently obtains reduced benefits of multiuser diversity usage. This is a weakness in order to improve spectral efficiency but an advantage to increase user sleep duration. FETOT provides better energy efficiency than MaxSNR, very close to OEA, when the traffic load is low (below 20 users). Using an adequate static tradeoff, energy consumption stays reasonable even when traffic reaches higher value but, when necessary and contrary to OEA, this is less done at the expense of spectral efficiency that stays close to MaxSNR (Figure 7(a)).

Considering underloaded contexts (number of users inferior to 20), guaranteeing high Quality of Service (QoS) is easily achievable by DT (Figure 8(a)) due to large surplus of available radio resource units (Figure 7(b)) and focus should be put on energy rather than system throughput. Figures 9(a), 9(b), and 9(c) underline that DT is the scheduler that better optimizes the multiuser diversity usage in this context. Few users are simultaneously activated per time slot (close to T-Mac and OEA (Figure 9(d))) but, contrary to the specialized state-of-the-art energy aware schedulers, DT provides an

adequate spectral efficiency forbidden inefficient resource allocation. This combination allows to better compress the transmission time and therefore better optimize energy consumption. Considering highly loaded context (number of users superior to 20), the lack of available radio resources (Figure 7(b)) required that schedulers focus on system capacity in order to preserve QoS. Energy consumption must become a lesser priority. In this context, DT behavior slightly sacrifices energy in order to sustain the network viability and then favours high spectral efficiency that reaches values close to PF (Figure 7(a)) which provides acceptable delay as long as possible (close to PF).

5. Conclusion

Reaching both low system energy consumption and high spectral efficiency is very difficult tasks in wireless network. Specialized solutions as MaxSNR, PF, or T-MAC have been well designed to well answer one of these criteria failing to the second. Other solutions propose static tradeoffs that provide good average results on these two metrics without success outperforming specialized scheduler in their focused domain. In this paper, we underline that the network objectives must be dependant of the context and particularly to the traffic load. In underloaded context, guaranteeing high Quality of Service (QoS) is easily achievable due to large surplus of available radio resources and the focus must be put on energy rather than system throughput. On the contrary, in a highly traffic loaded context, the lack of available radio resources required that resources allocation algorithms focus on system capacity in order to preserve QoS and satisfy users; thus energy consumption must become lesser important. The main contribution of this paper is to propose a Dynamic Tradeoff (DT) scheduler able to tune its priorities and the multiuser usage benefit according to the network traffic load context. It provides a better energy efficiency than specialized energy aware scheduler when it is feasible while providing the same spectral efficiency and delays as throughput oriented scheduler when it is required. This is achieved with a fairness special attention that is also guarantee. Future works could focus on other metrics like mean packet delay in order to adapt the multiuser usage to different contexts.

Data Availability

The data used to support the findings of this study are included within the article.

Disclosure

Their research did not receive specific funding but was performed as part of the employment of the authors: IRT b-com.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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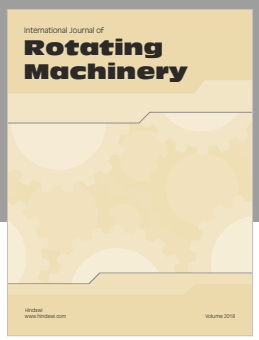

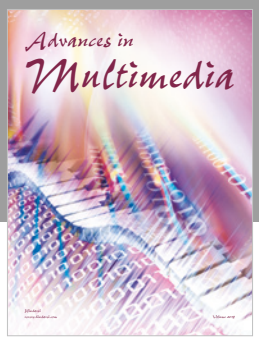

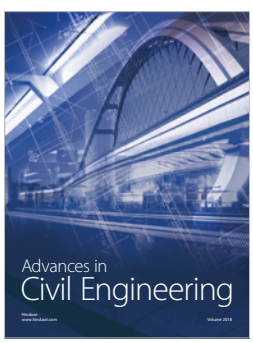

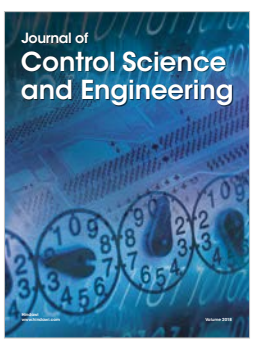

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