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A Hybrid Feedback Mechanism to Exploit Multiuser Diversity in Wireless Networks

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Abstract
One of the most promising approaches to boost the communication efficiency in wireless systems is the use of multiuser diversity (MUDiv), where the fading of channels is exploited. The mechanism of scheduling the user with the best channel condition is called opportunistic scheduling (OS). In this paper we propose a joint polling and contention based feedback (JPCF) algorithm that exploits MUDiv while reducing the feedback load. The guard time, which is between bursts, is divided into minislots that alternate between polling-based feedback minislot (*p*-minislot) and contention-based feedback minislot (*c*-minislot). During the minislot, users feedback their channel qualities if above a predetermined threshold. We analyze the scheduling algorithm under slow Rayleigh fading assumption and derive the closed-form expressions of the feedback load as well as the system capacity. We also consider the delay resulting from the time needed to schedule a user and derive the system throughput. The scheduling algorithm is compared with other scheduling algorithms.

1. Introduction

With the emerging of new multimedia applications and the huge demand and growth for such applications, the need to provide high-speed high-rate transmission techniques is demanding. One technique that has the capability of supporting such applications is multiuser diversity (MUDiv), where the fading of channels is exploited (1). Assume that a reasonably large number of users are actively transmitting/receiving packets in a given cell, and they experience independent time-varying fading conditions. By transmitting data to only the instantaneous "on-peak" user, *opportunistic scheduling* (OS) can efficiently utilize the wireless resources and thus dramatically improve the overall system throughput (2), (3). In order to schedule the best user, in terms of channel quality, each user measures his instantaneous signal-to-noise ratio (SNR) and feeds it back to the network scheduler. Currently Qualcomm's high data rate (HDR) system require similar scheme (4). As the number of active users becomes high, resources are wasted in carrying this amount of feedback, which lead to inefficient use of the spectrum. This issue motivated researchers to propose new techniques to reduce the feedback load while exploiting MUDiv.
Many investigations have been conducted to exploit multiuser diversity while keeping the overhead as minimum as possible. For instance, the impact of the degree of quantization of the SNR measurements on the throughput of constant rate transmission was investigated in

(5). It was shown that reducing the feedback rate (few quantization levels) yields a good performance compared to the unquantized feedback. In single carrier systems, (6) proposed a discrete rate switch-based multiuser diversity (DSMUDiv) algorithm that reduced the feedback load and feedback rate while preserving the performance of OS. The scheduling algorithm relied on a probing mechanism. One drawback of this algorithm is that as the average SNR decreases the need for full probing increases, therefore, the algorithm suffers from high feedback load at low average SNR values. The work was extended to multi-carrier systems in (7), where further reduction in the feedback load was shown. Similarly, in (8) users compare their sum-rate on all sub-carriers to a predefined threshold value. In (9), the threshold value was optimized to meet a specified outage probability. Users with channel quality above the threshold are allowed to feedback their SNR measurements, while all others remain silent. In case no feedback, a random user is selected, which leads to loss in capacity. Also, the feedback values are unquantized (analog values), which increases the feedback rate. In (10), the work was extended, where the scheduler requests full feedback if none of the users' channel qualities are above the threshold. Although the loss in capacity was compensated by full feedback as opposed to (9), the feedback load was increased. In (11), multiple feedback thresholds are used in order to reduce the feedback load and exploit multiuser diversity. The feedback load was reduced at an expense of scheduling delay. In addition, a set of switched-based multiuser access schemes were proposed in (12) in order to reduce the feedback load. In (13), (14), the feedback rate was reduced to a one bit feedback per user. The scheduler uses these feedback bits to partition all users into two sets and assigns the channel to one user belonging to the set experiencing favorable channel conditions. Although this reduces the feedback load and feedback rate but some loss is expected due to the low resolution of the quantized feedback (one bit). Other work have considered multi-carrier systems, for instants, in (15) a clustering scheme was proposed to reduce the feedback load while slightly degrading the performance. Each user feeds back a figure-of-merit listing its strongest clusters of subcarriers. Similarly, in (16) a fixed number of subcarriers for each user is fed back instead of a full feedback. These subcarriers are either the best K out of M subcarriers or K predetermined subcarriers. All previously mentioned work considered a polling threshold-based scheduling schemes to reduce the feedback load.

Other work considered random access algorithms to exploit multiuser diversity while reducing the overhead. In (17) a distributed multiaccess scheme was proposed. Based on a channel quality threshold, users report the best m channels with quality above the threshold value. Optimization was performed to find the best threshold and m values to maximize the system capacity. In (18), a random access threshold-based feedback scheme was proposed to exploit diversity gain while reducing the feedback load. Parameter optimization is performed to allow only users with high channel gains to feedback, which maximizes the system capacity. In (19), a medium access control protocol was designed based on a splitting algorithms to resolve collisions over a sequence of minislots, and determine the user with the best channel. Contention resolution algorithms while exploiting the diversity gain were proposed in (20). Finally, reduced feedback overhead algorithms were studied in (21). Static splitting was considered for the best effort traffic scenario. Whereas, for the traffic mixture scenario combine contention and polling based feedback was considered to maintain quality of service.

While Polling-based algorithms, like the DSMUDiv, guarantee best user selection, it suffers from scheduling delay. On the other hand, although contention-based algorithms reduces the overhead more then centralized scheduling it suffers from loss in capacity. In this chapter we introduce an opportunistic scheduling algorithm that is not only a polling-based feedback

algorithm like in (6), but it is a joint polling and contention based feedback (JPCF) algorithm. During the guard time, which is divided into minislots, users feedback their channel qualities, based on a predetermined channel threshold, either in a polling-based feedback minislot (p-minislot) or/and a contention-based feedback minislot (c-minislot). When a the best user is found data transmission begins. The scheduling algorithm is analyzed under slow Rayleigh fading assumption and closed-form expressions of both the feedback load and the system capacity are derived. We also look at the effect of the delay on the throughput, where we derive the system throughput. The scheduling algorithm is compared with the DSMUDiv (6) and the optimal (full feedback) selective diversity scheduling algorithms.
This chapter is organized as follows. Section 2 introduces the system model. Section 3 and 4 present the scheduling algorithm and the mathematical analysis of the JPCF algorithm, respectively. In Section 5 we present some numerical examples. Finally, Section 6 ends the paper with some concluding remarks.

2. System Model

We consider a single free interference cell in a wireless network with K active users communicating with a base station (BS). We assume downlink scheduling, where only one user is allowed to receive data transmission in each time slot. The communication is based on time division duplex (TDD), where downlink and uplink channels are reciprocal.

2.1 Downlink Transmission Model

Let,

$$y_i(T) = h_i(T) \cdot x(T) + n_i(T);\ i = 1, 2, 3, ..., K \tag{1}$$

be the baseband channel model, where $x(T) \in C$ is the transmitted signal in time slot T and $y_i(T) \in C$ is the received signal of user i in time slot T. The noise processes $n_i(T)$ are independent and identical distributed ($i.i.d.$) sequences of zero mean complex Gaussian noise with variance σ_n^2. The fading channel gain from the BS to the ith user in time slot T is $h_i(T)$. We adopt a quasi-static fading channel model where $h_i(T)$ is $i.i.d.$ from burst to burst but remains constant over each burst. We consider a flat Rayleigh fading model, assuming the fading coefficients of all users are $i.i.d.$ Therefore, $h_i(T)$ is a zero-mean complex Gaussian random variable. The amplitude of $h_i(T)$, $\alpha_i(T) = |h_i(T)|$ is Rayleigh distributed with the probability density function (PDF) given by,

$$f_{\alpha_i}(\alpha_i) = \frac{2\alpha_i}{\Omega_i} \exp(-\frac{\alpha_i^2}{\Omega_i}) \tag{2}$$

where $\Omega_i = E[\alpha_i^2]$ is the average fading power of the ith user.

2.2 Quantized Feedback

In this work we assume that users adapt their modulation level based on the instantaneous channel condition. Using this transmission strategy, which is called adaptive modulation (AM), if the channel is strong at a given time, the transmission can occur with a higher constellation size. Otherwise, a lower constellation size has to be used. Note that the switching thresholds of the adaptive transmission modes are functions of the modulation scheme and target error performance. We consider adaptive multilevel quadrature amplitude modulation (M-QAM) scheme (22). Specifically, we consider a transmission scheme employing uncoded adaptive discrete rate M-QAM schemes with constellation sizes $\mathbb{M} = \{M_n : M_n < M_{n+1},\ 0 \leq$

$n \leq N\}$, where $M_0 = 1$ is the user outage (deep fade), and M_N is the highest modulation level. We assume perfect channel estimation and negligible time delay between channel estimation and signal set adaptation, and as such, the rate adaptation can happen instantaneously. We also assume error free feedback channels. If we denote the target average bit error probability (BEP) by BEP_o, thresholds or switching thresholds can be obtained according to (22, eq.(30)):

$$\begin{aligned} \gamma_{th}^{(1)} &= [\text{erfc}^{-1}(2 \cdot \text{BEP}_o)]^2, \\ \gamma_{th}^{(n)} &= -\frac{2}{3}(2^n - 1)\ln(5 \cdot \text{BEP}_o);\ n = 2, 3, ..., N, \\ \gamma_{th}^{(N+1)} &= +\infty, \end{aligned} \tag{3}$$

where $\text{erfc}^{-1}(\cdot)$ denotes the inverse complementary error function.
Similar to (6), with the assumption of discrete rates, a user estimates his SNR and instead of feeding back the analog value it is mapped to a quantized value that represent the modulation level, which can be supported, and then this quantized value is fed back.
Define the set of quantized values (binary bits) $\mathbb{Q} = \{q^{(n)} : q^{(n)} < q^{(n+1)},\ 0 \leq n \leq N\}$ that represents the modulation levels, $(q^{(n)} \rightarrow_{map} M_n)$. If we assume n modulation levels, then each quantized value $q^{(m)}$, $0 \leq m \leq n$, will be $\log_2 n$ bits in length. To illustrate the idea of the SNR mapping, assume γ_i is the estimated SNR of the ith user, then the quantized value is,

$$q_i = \begin{cases} q^{(0)} & \text{if } \gamma_i < \gamma_{th}^{(1)} \text{ (outage)}, \\ q^{(n)} & \text{if } \gamma_{th}^{(n)} \leq \gamma_i < \gamma_{th}^{(n+1)} \\ q^{(N)} & \text{if } \gamma_i \geq \gamma_{th}^{(N)}. \end{cases} \tag{4}$$

2.3 Uplink Feedback Structure

Fig. 1 shows the feedback channel structure, which consists of minislots. The number of minislots constructing the feedback channel can vary from 1 minislot, in the case the first user is granted the channel access, to $2K - 1$ minislots, where K is the total number of users, in the case all users feed back their channel qualities. This variation in length assumes that data transmission can begin at different time periods. Such assumption can be possible if dynamic spectrum access is implemented. The JPCF scheduling algorithm assumes that the feedback is polling-based or contention-based. The feedback channel is divided into polling-based feedback minislots (p-minislot) and contention-based feedback minislots (c-minislot), where each p-minislot is followed by a c-minislot, except the last p-minislot. The contention protocol is based on a modified slotted ALOHA protocol (23). As any random multiple access protocol one out of three possible outcomes will occur: no access, one access, and a collision. Multiple users feeding back the requested information will cause signals to interfere at the receiver which we consider as a collision. When a collision occurs no resolution is consider and the information is discarded.

3. Scheduling Algorithm

In this section, we will introduce our proposed algorithm, the JPCF scheduling algorithm. Similar to the optimal selective scheduling algorithm, the JPCF algorithm always guarantees that the best user is granted the channel access. The difference between the two is in the selection process. In the JPCF algorithm decisions on whom to schedule are based on threshold

test. In simple terms, the BS compares the channel quality of a user to a predetermined threshold value and selects the user if his channel quality exceeds the threshold. In case no user is found with channel quality exceeding the threshold, then the user with the highest channel quality among all is selected.
Let us define the following:

- $\mathbb{L} = \{(D(i), l) : 1 \leq l \leq K$ is the probing order , and $D(i)$ is the ID of user $i\}$. The set is generated randomly each time slot.
- The predetermined threshold value is set to $\gamma_{th}^{(N)}$. According to (3), $\gamma_{th}^{(N)}$ is the SNR threshold of the highest modulation level and $q^{(N)}$ is the quantized threshold value.
- The probability of contention in the c-minislot is ρ.

The feedback mechanism of the JPCF algorithm is based on both polling period and contention period. Each period is a minislot during. Fig. 1 shows the feedback channel structure, which consists of p-minislots and c-minislots. The following describes the scheduling algorithm (Fig. 2 shows the flowchart):

(i) Through the broadcast channel all users know their polling order ($\mathbb{L}$).

(ii) The feedback channel always begins with a p-minislot.

(iii) During the p-minislot the BS polls the channel state information of the user (his SNR) who is in order.

(iv) The feedback channel is terminated and the data transmission begins if the polled user has $q_l = q^{(N)}$. By knowing (γ_l) and according to (4) q_l is determined.

(v) If $q_l \neq q^{(N)}$, then his information is stored and the feedback channel continues with a c-minislot following the previous p-minislot and step (vi) is performed.

(vi) During the c-minislot, which is a contention based minislot, users feedback their SNRs, with probability ρ, if it satisfy $q = q^{(N)}$. Otherwise, they keep silent.

(vii) If the contention is successful, then the feedback channel is terminated and the data transmission begins for that successful user. Otherwise, the feedback channel continues with a p-minislot following the previous c-minislot and step (iii) is performed.

(viii) In case all users are polled, the BS picks the user with the highest channel quality among them and the data transmission begins for that user.

(ix) In case a tie occurs, a random pick is performed.

4. Performance Analysis

The performance of the JPCF algorithm is evaluated in this section. Basically, we concentrate on the feedback load, the system capacity, and the scheduling delay. Closed form expressions for all three performance measures are also derived.

4.1 Feedback Load

We define the average feedback load (AFL) as the average number of responses until a user is scheduled. The feedback response includes the response on the p-minislot, and the response on the c-minislot. In the c-minislot, a contention resulting a success or a collision is counted as one response, and zero response is considered in case no contention occurs.

Consider two consecutive minislots (p-minislot and c-minislot) and denote the discrete random variable $\eta \in [1,2]$ by the total number of feedback during them. Let $\mathbf{U}$ be the set of events where a successful search occurs during the two minislots. Note that a *successful search* occurs when a user with $q = q^{(N)}$ is found. Therefore, the occurrence of a successful search is associated with one of the following events: (**i**) The polled user during the p-minislot has $q = q^{(N)}$, or (**ii**) The polled user during the p-minislot has $q < q^{(N)}$ and a successful contention occurs in the following c-minislot.
The probability of $\mathbf{U}$ given l probes is:

$$\Gamma^{\mathbf{U}}(l,\rho) = \left[1 - F_\gamma(\gamma_{th}^{(N)})\right] + \left[F_\gamma(\gamma_{th}^{(N)})\left\{\sum_{i=1}^{K-l}\binom{K-l}{i}\left(1 - F_\gamma(\gamma_{th}^{(N)})\right)^i\left(F_\gamma(\gamma_{th}^{(N)})\right)^{K-l-i} \times \left(i\rho(1-\rho)^{i-1}\right)\right\}\right], \tag{5}$$

where

$$F_\gamma(\zeta) = P[\gamma < \zeta] = (1 - e^{\frac{-\zeta}{\bar{\gamma}}}), \tag{6}$$

is the cumulative distribution function (CDF) of the SNR (γ). The first part of the right hand side of (5) refers to the success in the p-minislot and the second part refers in the success in the c-minislot.
let $\mathbf{X}$ represent the set of events where no feedback occurs on the c-minislot and $\mathbf{Y}$ to be the set of events where a feedback occurs on the c-minislot. Conditioning on l, the probability of $\mathbf{X}$ and the probability of $\mathbf{Y}$, respectively, are:

$$\Gamma^{\mathbf{X}}(l,\rho) = \left[1 - F_\gamma(\gamma_{th}^{(N)})\right] + \left[F_\gamma(\gamma_{th}^{(N)})\left\{\sum_{i=0}^{K-l}\binom{K-l}{i}\left(1 - F_\gamma(\gamma_{th}^{(N)})\right)^i\left(F_\gamma(\gamma_{th}^{(N)})\right)^{K-l-i} \times \left((1-\rho)^i\right)\right\}\right], \tag{7}$$

and

$$\Gamma^{\mathbf{Y}}(l,\rho) = F_\gamma(\gamma_{th}^{(N)})\left\{\sum_{i=0}^{K-l}\binom{K-l}{i}\left(1 - F_\gamma(\gamma_{th}^{(N)})\right)^i\left(F_\gamma(\gamma_{th}^{(N)})\right)^{K-l-i}\left(1 - (1-\rho)^i\right)\right\}. \tag{8}$$

The conditioned expected value of η is:

$$\overline{\eta}(l,\rho) = 1 \cdot \Gamma^{\mathbf{X}}(l,\rho) + 2 \cdot \Gamma^{\mathbf{Y}}(l,\rho). \tag{9}$$

Therefore, the AFL is:

$$\begin{aligned}\mathrm{AFL}(\rho) = &\sum_{l=1}^{K-1}\left(\sum_{i=1}^{l}\overline{\eta}(i,\rho)\right)\prod_{i=1}^{l-1}\left(1 - \Gamma^{\mathbf{U}}(i,\rho)\right)\Gamma^{\mathbf{U}}(l,\rho) \\ &+ \left[\left(\sum_{l=1}^{K-1}\overline{\eta}(l,\rho)\right) + 1\right]\prod_{l=1}^{K-1}\left(1 - \Gamma^{\mathbf{U}}(l,\rho)\right).\end{aligned} \tag{10}$$

4.2 System Capacity

The average spectral efficiency (ASE) is defined as the average transmitted data rate per unit bandwidth in bits/sec/Hz for specified power and target error performance. In this work we are considering discrete rates and using quantized SNR values (q). For example: if two users with $\gamma_1 \in [\gamma_{th}^{(i)}, \gamma_{th}^{(i+1)})$, $\gamma_2 \in [\gamma_{th}^{(i)}, \gamma_{th}^{(i+1)})$, and $\gamma_1 \neq \gamma_2$, then according to (4) both users feedback $q^{(i)}$. Therefore, scheduling either one will result a transmission rate of $\log_2 M_i$ bps/Hz.

Based on the algorithm's description in Section 3, it is clearly seen that both the DSMUDiv scheduling algorithm proposed in (6) and the JPCF scheduling algorithm will always select the best user. Therefore, resulting a similar performance in terms of spectral efficiency.

It has been shown in (6) that with i users in the system, scheduling the best user yields the following average spectral efficiency:

$$\begin{aligned} \mathrm{R}(i) = b_o &\left([F_\gamma(\gamma_{th}^{(1)})]^i \right) \\ &+ \sum_{n=1}^{N-1} b_n \left([F_\gamma(\gamma_{th}^{(n+1)})]^i - [F_\gamma(\gamma_{th}^{(n)})]^i \right) \\ &+ b_N \left(1 - [F_\gamma(\gamma_{th}^{(N)})]^i \right) \end{aligned} \tag{11}$$

where $b_n = \log_2 M_n$ is the number of bits per constellation.

Therefore, the ASE of the JPCF algorithm is:

$$\mathrm{ASE} = \mathrm{R}(K). \tag{12}$$

In the above expression (12) it is assumed that the guard time duration is negligible, meaning that the feedback rate will not degrade the total system spectral efficiency. Practically, this is not valid. Therefore, the amount of bits transmitted as feedback has to be counted and at the end it will influence the performance of the system. To look into this issue, which is spectral efficiency degradation caused by the feedback traffic, we define a the system capacity as [bits/channel use]. Assuming N modulation levels, then we need $\log_2 N$ bits to represent them. Therefore, the system capacity is:

$$\mathrm{C}_{sys} = \mathrm{R}(K) - \frac{\mathrm{AFL} \cdot \log_2 N}{S}, \tag{13}$$

where S is the number of symbols transmitted in the data transmission time slot.

In (13), the last term takes into account the amount of bits transmitted as feedback. Also, in the same expression the time delay is not taken into account, which is the guard time duration. The only consideration is the feedback rate, or the amount of bits transmitted as feedback. In the next section we investigate the effect of delay on the system performance.

4.3 Scheduling Delay

In this section we investigate the scheduling delay and its effect on the system performance. This time delay is part of the system resources and it is important to identify the amount of resources consumed when performing the JPCF algorithm.

4.3.1 Guard time

The scheduling process will take place during the gaud time (τ_g), which is between bursts. The delay resulted from this scheduling process is measured as the time needed to schedule a user, which is simply the time duration of the minislots used (idle minislots are counted) until data transmission is allowed. By looking at Fig. 1, we can see that $\tau_f \leq \tau_g \leq (2K-1)\tau_f$. For simplicity, we assume that both p-minislot and c-minislot have the same time length (τ_f).
Assuming a successful search at the lth p-minislot, then the guard time is:

$$\tau_g(l) = \tau_f(2l-1), \tag{14}$$

with probability:

$$P^{(p)}(l) = \left[\prod_{i=1}^{l-1}\left(1-\Gamma^{\mathbf{U}}(i,\rho)\right)\right]\cdot\left[1-F_\gamma(\gamma_{th}^{(N)})\right]. \tag{15}$$

On the other hand, if the successful search occurs at the lth c-minislot, then the guard time is:

$$\tau_g(l) = 2l\tau_f, \tag{16}$$

with probability:

$$P^{(c)}(l) = \left[\prod_{i=1}^{l-1}\left(1-\Gamma^{\mathbf{U}}(i,\rho)\right)\right]\cdot\left[\Gamma^{\mathbf{U}}(l,\rho)-\left(1-F_\gamma(\gamma_{th}^{(N)})\right)\right]. \tag{17}$$

Therefore, the average guard time is:

$$\begin{aligned}\overline{\tau} = &\sum_{l=1}^{K-1}\left[\tau_f(2l-1)P^{(p)}(l)+2l\tau_f P^{(c)}(l)\right]\\ &+\left((2K-1)\tau_f\right)\cdot\left[\prod_{i=1}^{K-1}\left(1-\Gamma^{\mathbf{U}}(i,\rho)\right)\right].\end{aligned} \tag{18}$$

4.3.2 System throughput

The system throughput (STH) is the amount of data bits transmitted per time, where this time includes the data transmission time (T_d) and the guard time (τ_g). In (12), we looked at the amount of bits per data transmission time, where the effect of the scheduling delay was not included. To have a better insight, we derive the average system throughput (ASTH) by taking into account the effect of the guard time duration.
The average system throughput is:

$$\begin{aligned}\text{ASTH} = &\sum_{l=1}^{K-1}\left[\left(\frac{T_d-\tau_f(2l-1)}{T_d}\right)P^{(p)}(l)+\left(\frac{T_d-2l\tau_f}{T_d}\right)P^{(c)}(l)\right]\cdot\text{R}(K)\\ &+\left(\frac{T_d-(2K-1)\tau_f}{T_d}\right)\cdot\text{R}(K)\cdot\left[\prod_{i=1}^{K-1}\left(1-\Gamma^{\mathbf{U}}(i,\rho)\right)\right].\end{aligned} \tag{19}$$

4.4 Parameters Optimizations

The algorithm's objective is to strictly schedule the best user, therefore the search process will last until a user with $q = q^{(N)}$ is found, which depends on $\gamma_{th}^{(N)}$ and ρ. In this section we investigate the optimization of ρ with the objective to minimize the feedback load:

$$\begin{aligned} \{\rho\} =& \arg\min_{\{\rho\}} \mathrm{AFL}(\gamma_{th}^{(N)}, \rho, K), \\ & \text{subject to } 0 \leq \rho \leq 1. \end{aligned} \tag{20}$$

Similarly, the optimization solution is well defined by the equation:

$$\begin{cases} \frac{\partial \mathrm{AFL}(\rho,K)}{\partial \rho} = 0, \\ 0 \leq \rho \leq 1. \end{cases} \tag{21}$$

Note that the optimization may not be convex. The derivation of (10) is involved so we apply an exhaustive search method to find an optimal value. Table 3 shows the optimal values with different K given the parameters in Section 5. It is clearly seen from Table 3 that for a given K, ρ has two optimal values at the two average SNR regions. This is due to the collision. At low average SNR values, the value of ρ is increased to encourage good users to compete, whereas, at higher average SNR values the value of ρ is decreased to lower the possibility of collision.

5. Numerical Results

In this section we elaborate on the the performance of the JPCF algorithm by presenting some numerical examples. We compare its performance with both the DSMUDiv and the optimal selective diversity scheduling schemes. Parameters values are found in Tables 1 and 2. Fig. 3 shows the normalized average feedback load (*i.e.*, the average feedback load divided by the number of users K) of the JPCF algorithm for different values of ρ, which is the probability of contention. As the value of the average SNR changes from low to high, the optimal value of ρ, at which the feedback is minimized, changes from $\rho = 1$ to $\rho = 0.13$, for a given value of K. Table 3 shows the optimal values of ρ for different values of K. The reason for the change of the optimal value is the threshold value. For a given threshold value, the percent of users with channel quality exceeding it increases as the average SNR increases, which leads to higher probability of collision. As more users contend the feedback load increases, which forces the value of ρ to change to maintain the minimization in (20). The point at which this change happens depend on the value of $\gamma_{th}^{(N)}$ and the BEP_o.
The comparison of the JPCF algorithm with both the DSMUDiv and the optimal selective diversity scheduling algorithms is presented in Fig. 4. In the figure, although the DSMUDiv algorithm has decreased the feedback load compared to the optimal algorithm, the JPCF algorithm has decreased the feedback load even more. This extra reduction comes from the introduction of the contention-based feedback (c-minislot), where not all users need to be polled as opposed to the DSMUDiv algorithm, which is a pure polling-based feedback algorithm. In terms of spectral efficiency, as shown in Section 4.2, both the JPCF algorithm and the DSMUDiv algorithm have the same spectral efficiency (here the feedback rate is not included). In (6), it has been proven that the DSMUDiv algorithm maintain the performance of the full feedback algorithm in terms of spectral efficiency, which means that the JPCF algorithm also maintain the same performance. The difference will come when you include the feedback rate ($\log_2 N$), which is defined as [bits/channel use]. From (13), we can see that as the feedback

load increases the system capacity decreases, therefore, we deduce that the JPCF algorithm has the highest system capacity compared to the other two algorithms, which can be seen in Fig. 5 and 6. As a benchmark we include the average spectral efficiency (ASE) that does not include the feedback rate. The gap between the system capacity and the ASE shrinks with the increase of number of symbols transmitted in the data transmission time slot.
Although the number of minislots of the JPCF algorithm varies from 1 to $2K-1$, which is much greater than the DSMUDiv algorithm, where the minislots varies from 1 to K, the average guard time of the JPCF algorithm is much smaller than the guard time of the DSMUDiv algorithm as depicted in Fig. 7. Such advantage occurs at medium to high average SNR. As the average SNR decreases this advantage diminishes as seen in Fig. 8. The reason is that the JPCF algorithm has contention minislots which creates an additional delay on top of the delay created by the polling minislots. This delay increase as the probability of finding a user with channel gain exceeding the threshold value decreases, which is the case for low average SNR values. Fig. 9 shows the effect of different data transmission time durations on the system throughput. Obviously, higher values give better performance.

6. Conclusions

In this chapter we proposed a scheduling algorithm that maximizes the spectral efficiency while reducing the feedback load. The algorithm, called joint polling and contention based feedback (JPCF) algorithm, collects channel quality information of the users either in a polling form or in a contention form. Compared to the optimal (full feedback) algorithm, the JPCF algorithm has a similar spectral efficiency and a higher system capacity, which takes into account the effect of the feedback rate. Also, the JPCF algorithm shows more reduction in feedback load compared to the DSMUDiv algorithm. One drawback of the JPCF algorithm is the high delay compared to the DSMUDiv algorithm as the average SNR decreases, which affects the performance. As the average SNR increases, the delay encountered when using the JPCF algorithm drops below the delay created by using the DSMUDiv algorithm, which improves the system performance. The work presented in this paper includes analysis of the JPCF algorithm under slow Rayleigh fading assumption. Closed-form expressions of the feedback load, system capacity and scheduling delay are also presented in this paper.

Modulation Level	Switching Threshold (dB)
BPSK	$\gamma_{th}^{(1)} = 4.8$
4-QAM	$\gamma_{th}^{(2)} = 7.8$
16-QAM	$\gamma_{th}^{(3)} = 15$
64-QAM	$\gamma_{th}^{(4)} = 20$

Table 1. A List of Selected Modulation Levels ($\text{BEP}_o = 10^{-2}$)

Parameter	Value
N	4 modulations
K	30 users
τ_f	154 μsec (based on reference (24))
T_d	5 msec (based on reference (24))

Table 2. A List of Parameters

K=5	K=30	K=50	K=100
$\rho = 0.2,\ \overline{\gamma} > 19$ dB	$\rho = 0.13,\ \overline{\gamma} > 15$ dB	$\rho = 0.12,\ \overline{\gamma} > 15$ dB	$\rho = 0.1,\ \overline{\gamma} > 14$ dB
$\rho = 1,\ \overline{\gamma} \leq 19$ dB	$\rho = 1,\ \overline{\gamma} \leq 15$ dB	$\rho = 1,\ \overline{\gamma} \leq 15$ dB	$\rho = 1,\ \overline{\gamma} \leq 14$ dB

Table 3. The Parameters Optimizations

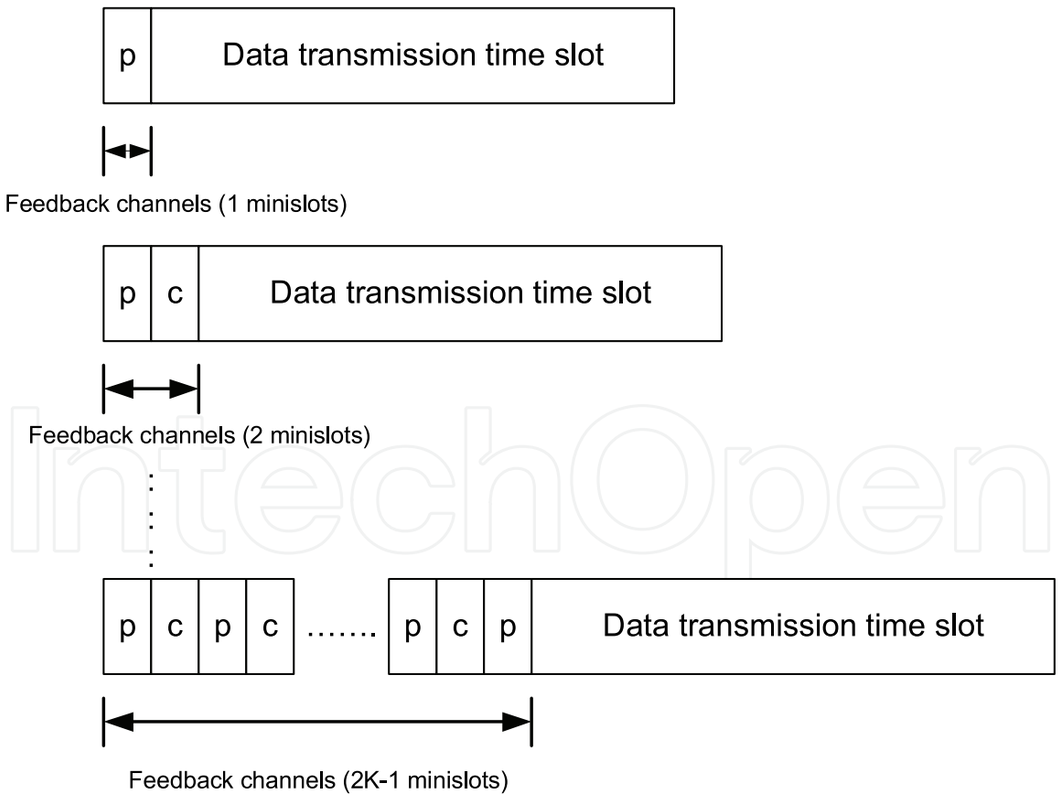


Fig. 1. The framing structure of a TDD system. Each polling-based feedback minislot (p-minislot) is followed by a contention-based feedback minislot (c-minislot), where they carry the feedback information.

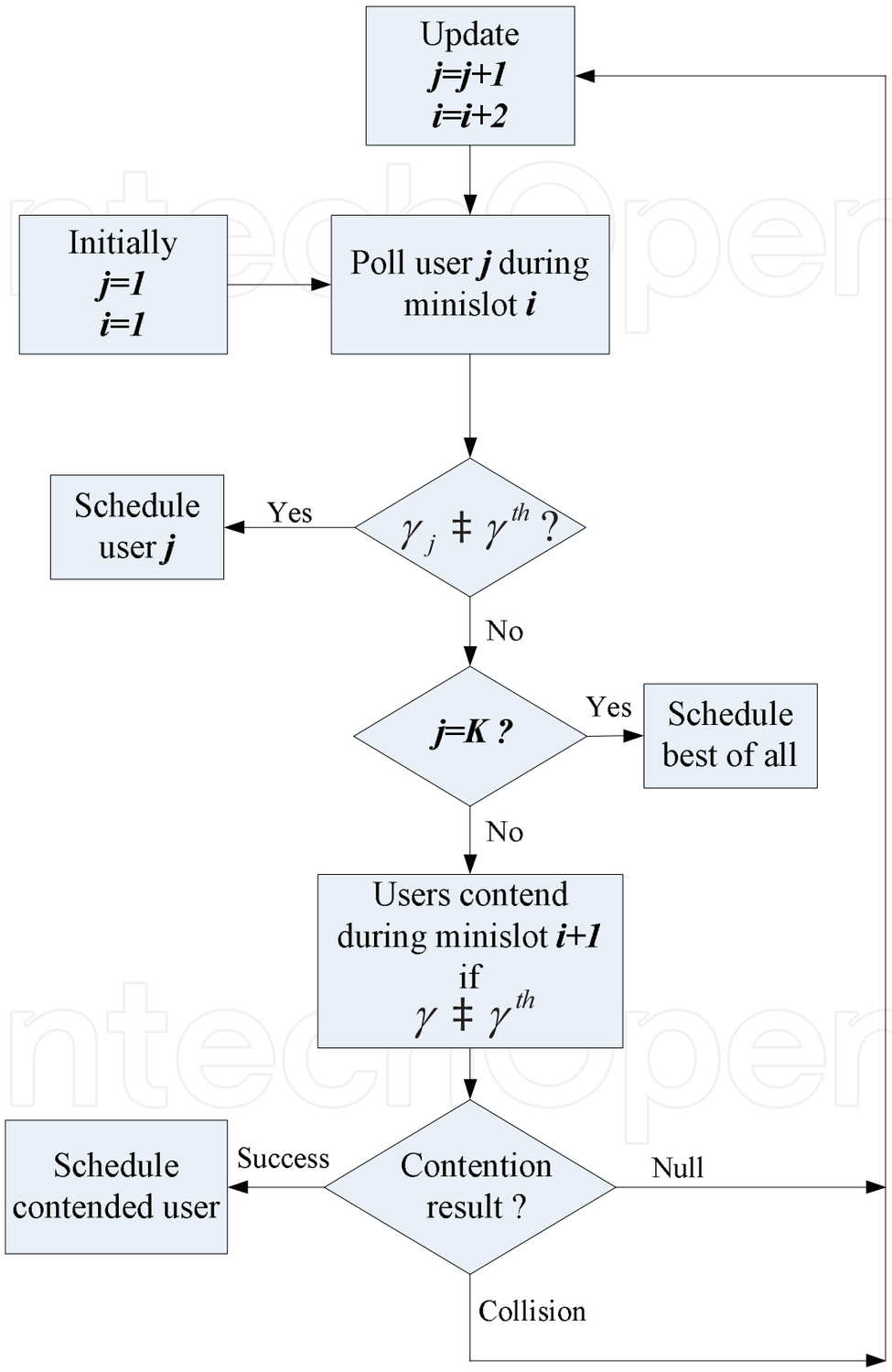


Fig. 2. A flowchart of the JPCF algorithm.

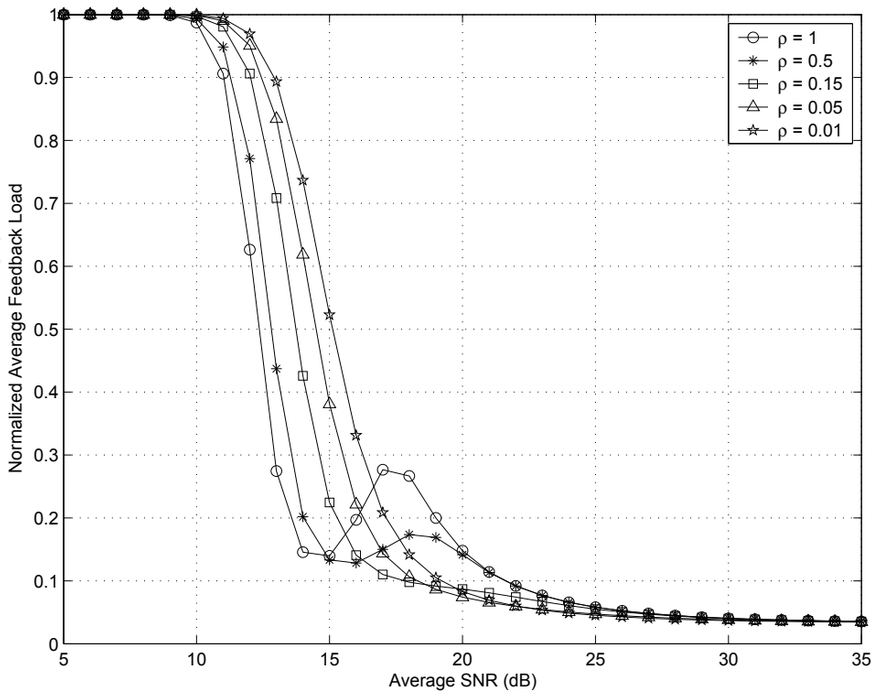


Fig. 3. Normalized average feedback load of the JPCF scheduling algorithm with different values of ρ.

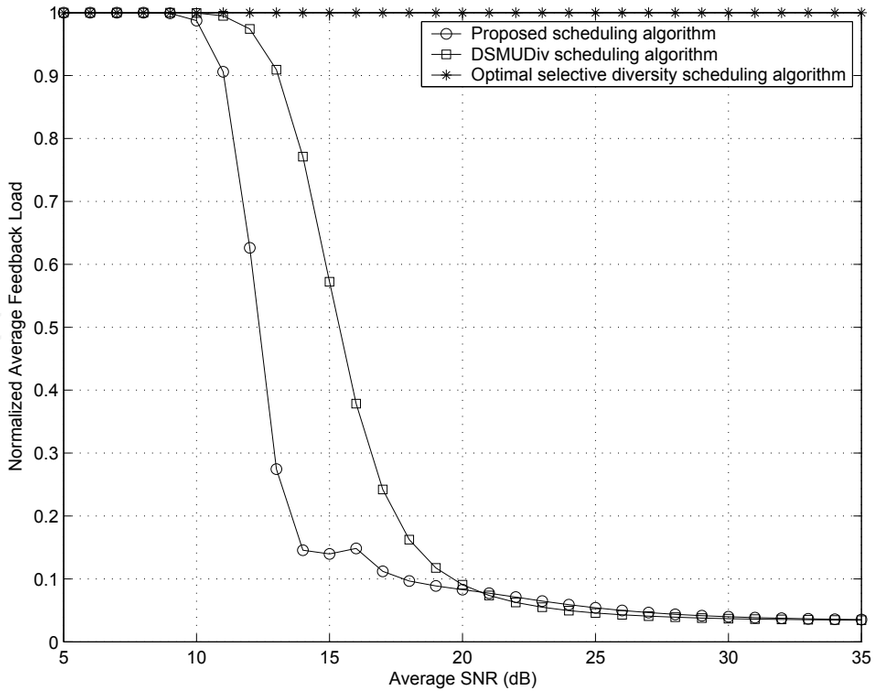


Fig. 4. Comparison of the normalized average feedback load of: (**i**) the proposed (JPCF) scheduling algorithm, (**ii**) the DSMUDiv scheduling algorithm, and (**iii**) the optimal (full feedback) scheduling algorithm.

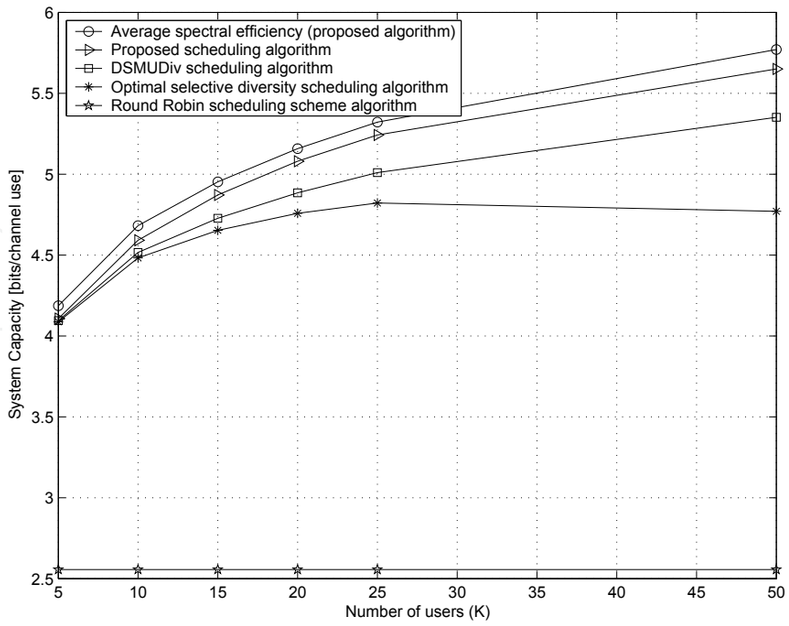


Fig. 5. System capacity of: (**i**) the proposed (JPCF) scheduling algorithm, (**ii**) the DSMUDiv scheduling algorithm, and (**iii**) the optimal (full feedback) scheduling algorithm. Setting $\rho = 1$, 100 symbols are transmitted, and $\overline{\gamma} = 15$dB.

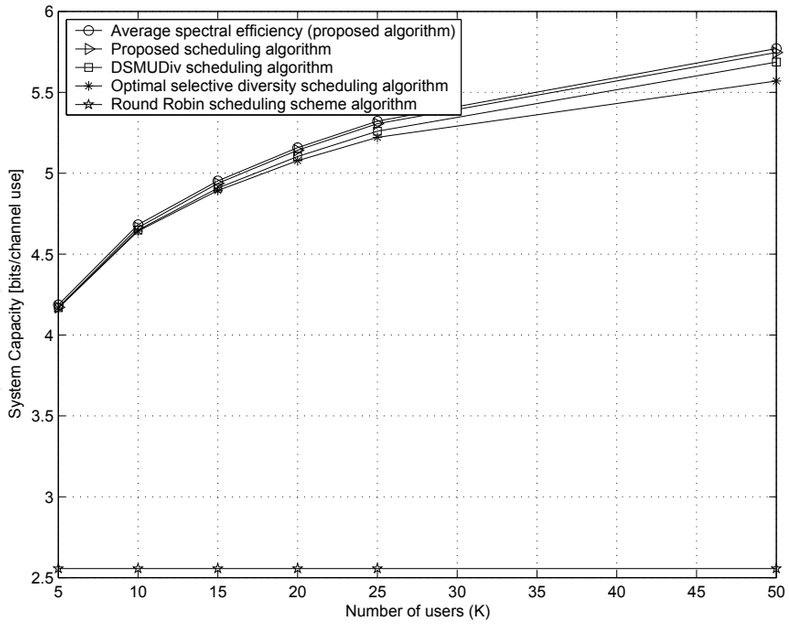


Fig. 6. System capacity of: (**i**) the proposed (JPCF) scheduling algorithm, (**ii**) the DSMUDiv scheduling algorithm, and (**iii**) the optimal (full feedback) scheduling algorithm. Setting $\rho = 1$, 500 symbols are transmitted, and $\overline{\gamma} = 15$dB.

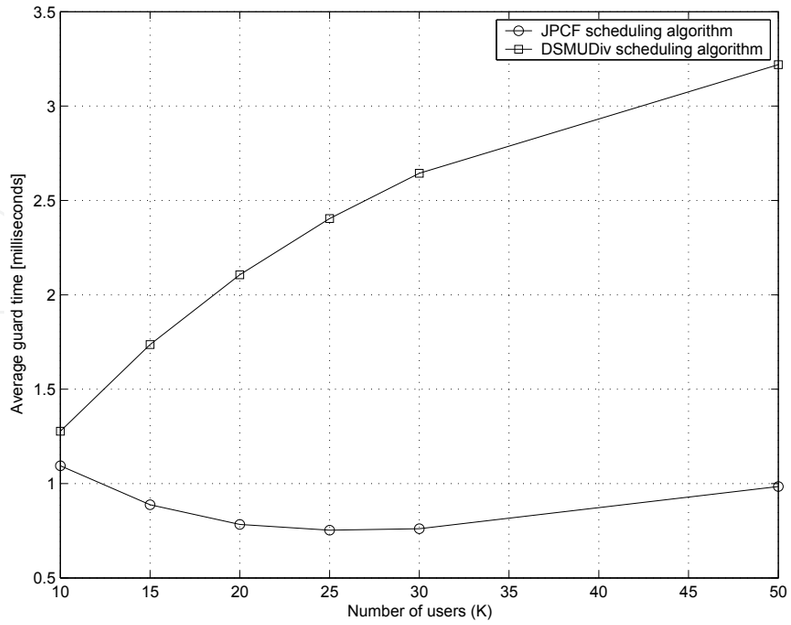


Fig. 7. Average guard time of: (**i**) the JPCF scheduling algorithm, and (**ii**) the DSMUDiv scheduling algorithm. Setting $\overline{\gamma} = 15$dB.

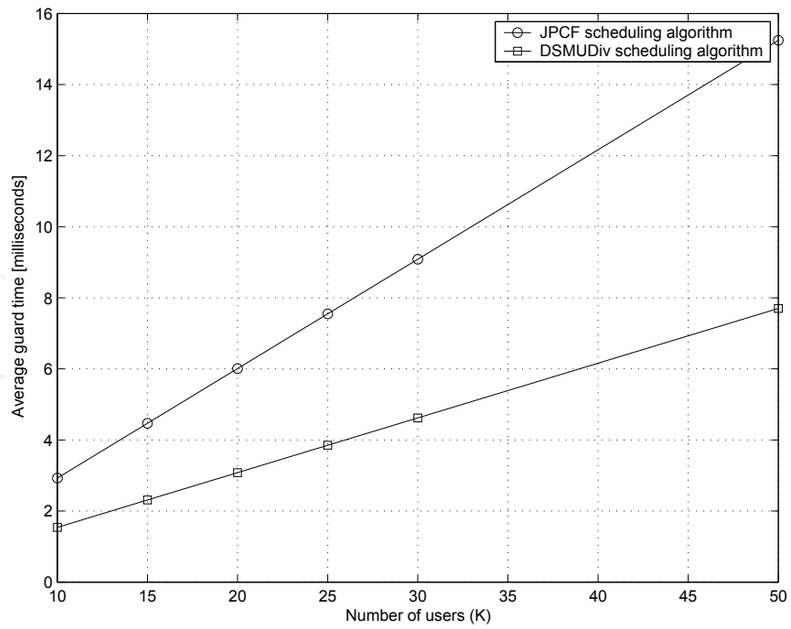


Fig. 8. Average guard time of: (**i**) the JPCF scheduling algorithm, and (**ii**) the DSMUDiv scheduling algorithm. Setting $\overline{\gamma} = 5$dB.

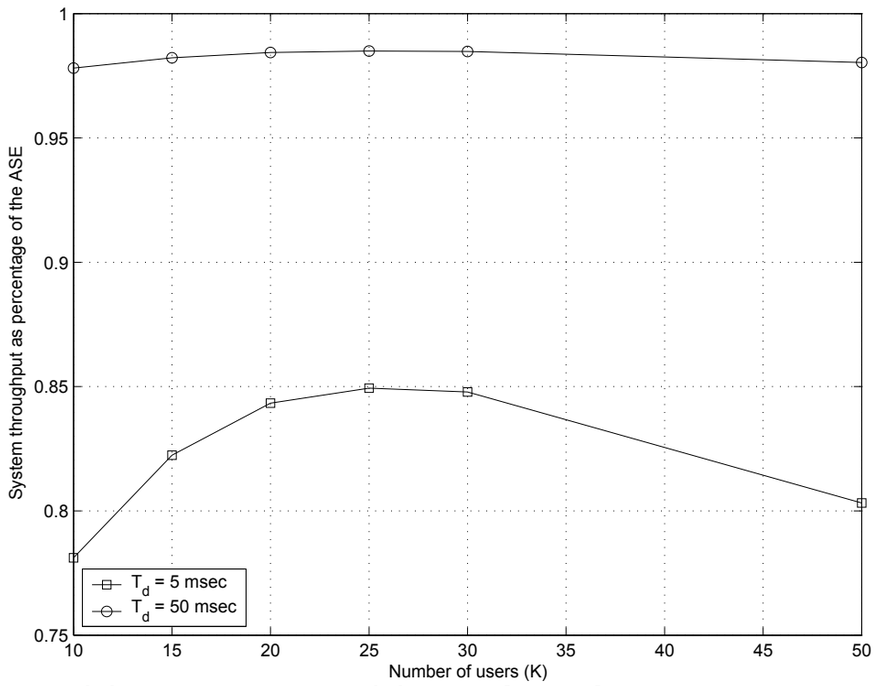


Fig. 9. System throughput as percentage of the average spectral efficiency of the JPCF scheduling algorithm. Setting $\overline{\gamma} = 15$dB, and 1 symbol is transmitted.

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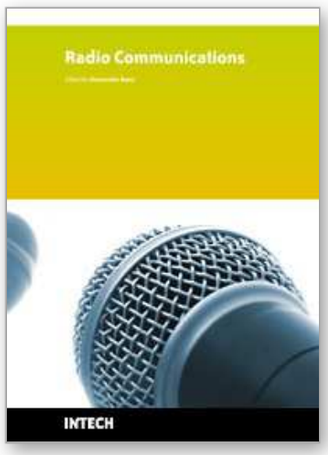
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In the last decades the restless evolution of information and communication technologies (ICT) brought to a deep transformation of our habits. The growth of the Internet and the advances in hardware and software implementations modified our way to communicate and to share information. In this book, an overview of the major issues faced today by researchers in the field of radio communications is given through 35 high quality chapters written by specialists working in universities and research centers all over the world. Various aspects will be deeply discussed: channel modeling, beamforming, multiple antennas, cooperative networks, opportunistic scheduling, advanced admission control, handover management, systems performance assessment, routing issues in mobility conditions, localization, web security. Advanced techniques for the radio resource management will be discussed both in single and multiple radio technologies; either in infrastructure, mesh or ad hoc networks.

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