Feedback Protocols for Increased Multiuser Diversity Gain in Cellular ALOHA Networks – A Comparative Study

Vegard Hassel, Hend Koubaa, and Geir E. Øien
Norwegian University of Science and Technology (NTNU)
Department of Electronics and Telecommunication
7491 Trondheim, Norway
Email: Vegard, Hend, Oien @iet.ntnu.no

NTNU
Innovation and Creativity

Abstract

Multiuser diversity (MUD) underlies much of the recent work on scheduling design in wireless networks. This form of diversity can for example be exploited by opportunistically scheduling the mobile user with the best channel quality [1]. In cellular networks exploiting MUD, the base station collects channel state information (CSI) from the mobile users. The process of obtaining CSI will be performed within a *guard time*, and the length of this guard time will depend on the feedback protocol implemented. In this context, it has already been shown that by applying multiple carrier-to-noise ratio thresholds, the number of mobile users giving feedback can be significantly decreased [2]. However, it has not been evaluated how the algorithm in [2] can be implemented in protocols for real-life networks. In this paper we analyze feedback protocols for reducing the guard time and resolving the feedback contention problem in a cellular, slotted ALOHA-based network. We propose three new feedback protocols based on the algorithm in [2] and we develop closed-form expressions for the guard time duration and the system spectral efficiency of these protocols. We also compare the three new protocols with the Splitting algorithm proposed by Qin and Berry [3] and a new and modified version of this algorithm. Plots show that the spectral efficiency in an IEEE 802.11 network can increase significantly for a high number of users when the Modified Splitting algorithm is used.

I. Introduction

In a wireless network, the signals transmitted from a base station to different mobile users often have different channel fluctuation characteristics. This diversity that exists between the mobile users is called *multiuser diversity* (MUD) and can be exploited to increase the throughput of wireless networks [1]. One way of exploiting MUD is by means of *opportunistic scheduling* of users, giving priority to users having favorable channel conditions [4], [5]. The Max Carrier-to-noise Scheduling (MCS) algorithm, where the user with the best channel quality is scheduled in each time-slot, maximizes the MUD in a time-slotted network. To be able to take advantage of the MUD, the base station needs feedback from the mobile users about their respective channel conditions. If the MCS algorithm is used, the base station only needs feedback from the user with the best channel conditions, but unfortunately each user does not know the carrier-to-noise ratio (CNR) of the other users. Therefore, in current cellular standards like Qualcomm's High Data Rate (HDR) system, the base station collects feedback from all the users [6]. In a time-slotted cellular network that exploits MUD, the base station can use the first part of the time-slot to collect feedback from the users and to decide which user to schedule [3]. We call this first part of the time-slot the *guard time*. Collecting feedback from all the users in a system can lead to a significant guard time and hence it is important to investigate alternative protocols for obtaining feedback.

One way of reducing the guard time is by implementing feedback algorithms that utilize *CNR thresholds* to reduce the number of users giving feedback and still be able to exploit MUD. At least two different types of such threshold-based feedback algorithms have already been proposed. The first type was initially proposed by Gesbert and Alouini and is based on a single CNR threshold value [7]. The users that have a CNR above this value give feedback to the scheduler. This algorithm does not always find the user with the highest CNR because there will always be a possibility that all users are below the threshold value, and in this case a random user is chosen. A generalized version of this algorithm has also been proposed [2]. By using several threshold values, the scheduler can request feedback in a successive fashion starting out with the highest of the threshold values. If the lowest threshold value is zero, the user with the highest CNR will always be found.

The second type of threshold-based feedback algorithm was proposed by Qin and Berry and is based on the ideas from binary search [3]. The proposed *Splitting algorithm* finds the user with the best channel quality by using an iterative procedure to update two CNR threshold values when the users are using a common ALOHA channel.

Contributions. For the Splitting algorithm, the guard time has already been analyzed for a slotted ALOHA channel. However, the multiple threshold algorithm in [2] has not yet been analyzed for a slotted ALOHA channel and it is therefore hard to decide which of the two threshold-based algorithms that perform best. In this paper we propose three new cellular ALOHA protocols for the algorithm in [2] and compare the performance of these algorithms with the Splitting algorithm as well as with a new and modified version of the Splitting algorithm [1].

Organization of the paper. The remainder of this paper is organized as follows. We outline the system model and the problem formulation in Section II, and present the five feedback protocols under study in Section III. In Section IV and Section V we develop analytical expressions for the guard time and the system spectral efficiency, respectively. Section VI discusses how the protocols should be optimized and presents plots comparing the guard time and the system spectral efficiency of the resulting five feedback protocols in an IEEE 802.11 network. Finally, our conclusions are listed in Section VII.

II. System Model and Problem Formulation

A. General System Model

We consider the downlink of a single-carrier cellular network where the base station wants to transmit data to N mobile users which have identically and independently distributed (i.i.d.) CNRs with an average of $\overline{\gamma}$. The channel is ALOHA-based, i.e., all the users can access the network at the same time. When more users transmit packets simultaneously, this will result in a collision and the information in the packets will be destroyed. The system uses time-slotted transmission and for each time-slot with duration T_{TS}, the base station schedules a user which will receive data. We assume slowly varying fading channels with a coherence time that is longer than one time-slot. This means that the same transmission rate is used for the whole time-slot. The system uses adaptive coding and modulation, i.e., the coding scheme and the modulation constellation used depend on the CNR of the selected user [10]. This has two advantages. On

[1] This paper is partially based on the work in [8] and [9]

one hand, the spectral efficiency for each user is increased. On the other hand, because the rate of the users are varied according to their channel conditions, it makes it possible to exploit MUD.

To be able to select the user which will receive data, the base station needs to receive channel state information (CSI) estimates from one or more users. Such CSI estimates can be obtained from pilot symbols that are transmitted in-between the data symbols. For the three feedback protocols that are based on [2], we use L feedback thresholds denoted by $\gamma_{\text{th},L} > \gamma_{\text{th},L-1} > \cdots > \gamma_{\text{th},0}$ to search for the users in a sequential manner. For convenience we define $\gamma_{\text{th},L} = \infty$ and $\gamma_{\text{th},0} = 0$, so that we can search for mobile users within the whole CNR range. Initially, we search for users that have a CNR above $\gamma_{\text{th},L-1}$. If no users are found, the feedback threshold is lowered to $\gamma_{\text{th},L-2}$, and we search for users that have a CNR above this threshold. The algorithm lowers the threshold value sequentially until one or more users are found. We denote the CNR interval where the first user is found as the *successful interval* and process of checking for users within one interval is referred to as a *trial*.

B. Further Specifications for an IEEE 802.11-Based Network

We want to investigate the gain from using multiple feedback thresholds in a cellular IEEE 802.11 network [11]. In such networks, the access mechanism is ALOHA-based, and one of the main problems that can arise in such networks is *collisions* between packets. To avoid collisions, a handshaking mechanism is often used between the transmitter and the receiver before starting any data transmission. The transmitter sends a *Request To Send* (RTS) packet to the receiver asking if he can transmit. The receiver replies with a *Clear to Send* (CTS) packet if he is ready for data reception. If we want to deploy the proposed feedback protocols in an IEEE 802.11 network, we can use packets similar to RTS and CTS to conduct the feedback collection process. Consequently, we define four different packets based on the general frame format defined in the IEEE 802.11 standard [11]:

- Query (QRY) packet
- Feedback (FB) packet
- Reservation (RES) packet
- Acknowledgment (ACK) packet

The QRY packet is used by the base station to initiate the feedback collection process. This packet contains the addresses of all the users that have data to receive and the number of thresholds L applied. As shown in [2], each of the users can calculate the feedback threshold values from the number of users N, the number of thresholds L, and the average CNR $\overline{\gamma}$ of the users. When all the users have calculated the threshold values, the feedback collection process can start. We denote the duration of this packet, including the packet processing time and the propagation delay, as T_{QRY} [seconds].

The FB packet is transmitted by the mobile users and contains the CSI estimate of a user's channel. This packet is also used for all the five protocols handled in this paper. Including packet processing time and propagation delay, this packet has the duration T_{FB} [seconds].

The RES packet is transmitted by a mobile user to inform the base station that he is not in the successful interval (Ranked Single-User Feedback protocol) or that he has a CNR between the two current threshold values (Splitting algorithm). Although the RES packet does not contain any information (See Section VI-A), it makes the base station able to detect if one or more users are between two threshold values. The total time to transmit and process this packet is denoted T_{RES} [seconds].

The ACK packet is transmitted by the base station to inform all the mobile users in the system about the status of a recent FB or RES packet transmission. If no packets were transmitted, this packet contains *0*, while for a successful packet transmission the ACK contains *1*. However, when two packets have collided, this packet contains *e*, denoting an erroneous transmission. It should be noted that not all FB and RES packets need no be followed by an ACK packet. The aggregated transmission and packet processing time of this packet is denoted T_{ACK} [seconds].

In IEEE 802.11-based networks, all these packets are transmitted at the base rate of the system and we assume that the bit error probability of these packets are zero.

C. Problem Formulation

The main goal of this paper is to propose and analyze three protocols based on the feedback algorithm proposed in [2] and compare these protocols with the Splitting algorithm, both in its original and modified version, for an IEEE 802.11-based network. We want to evaluate the different feedback protocols according to their *Maximum Average System Spectral Efficiency* (MASSE) performance. The MASSE [bits/sec/Hz] is defined as the maximum average spectral efficiency that is possible within a cell, averaged over all the N mobile users. To be able to investigate the MASSE, the guard time, i.e., the duration of the feedback collection process, has to be quantified. This guard time analysis will be conducted in Section IV.

III. Proposed Feedback Protocols

In this section we will give an overview of the five different feedback protocols handled in this paper. The first three protocols are new and are based on the algorithm proposed in [2]. The fourth protocol is the Splitting algorithm introduced in [3] and the fifth protocol is a new and modified version of this algorithm.

A. Ranked Full Feedback

For this protocol, all the users that are above the current threshold value are allowed to transmit their CSI estimate simultaneously. For the first trial the users that have a CNR above $\gamma_{\text{th},L-1}$ are allowed to transmit feedback. If there are none, the threshold is successively lowered to $\gamma_{\text{th},L-2}, \gamma_{\text{th},L-3}, \cdots, \gamma_{\text{th},0}$. Consequently, the threshold is successively lowered until feedback is successfully transmitted or a collision occurs. Each trial is assigned the duration $T_{\text{FB}} + T_{\text{ACK}}$, so that an FB packet followed by an ACK packet can be transmitted. Thanks to the ACK, all the users in the system will be informed if other users transmitted feedback.

If a feedback transmission happens without a collision (ACK=*1*), the guard time is over. However, if a collision occurs (ACK=*e*), the contention problem is solved by letting all the users transmit their feedback sequentially depending on their *rank* in the system. The rank is simply an ordering pre-assigned by the base station. All the users will transmit their feedback to the base station during a time $N \cdot T_{\text{FB}}$; hence the user with the highest CNR is guaranteed to be found, which will maximize the MUD gain in the cell.

B. Ranked Single-User Feedback

As for the Ranked Full Feedback protocol, the Ranked Single-User Feedback protocol also lowers the threshold values in the same successive fashion, giving all the users the opportunity to transmit their feedback simultaneously for each trial. The duration $T_{\text{FB}} + T_{\text{ACK}}$ is assigned to each trial and the guard time is over if a successful FB packet transmission occurs. However, instead of letting all users transmit their feedback if a collision occurs, only the user with the highest rank within the successful interval transmits his feedback. When a collision occurs, the user with the highest rank is first given the opportunity to transmit his FB packet. If this user is within the successful interval, the FB packet is transmitted, a *1*-ACK packet is broadcasted, and the guard time is over. However, if a user is not within the successful interval, he transmits a RES packet and the base station will broadcast an ACK=*0* to inform the other users that this user's transmission is finished. Now, the user with the second highest rank will be given the opportunity to transmit an FB packet. This process continues until one of the users have transmitted an FB packet and the base station has broadcasted a *1*-ACK. For this protocol, the base station will not receive CSI feedback from all the users in the cell and, hence the user with the highest CNR is not always scheduled. Consequently, a certain MUD degradation will be experienced. However, the guard time will decrease, which will contribute to an increase in the overall MASSE. This protocol can also lead to an unfairness problem: If the rank of the users is fixed, the users with the highest rank will on average be selected more often than the users with lower rank. To have a more fair protocol, the rank of the users can be changed from time to time.

C. Exponential Backoff

For this protocol, as for the two protocols above, all the users are given the opportunity to transmit their FB packets simultaneously for each trial until a successful feedback transmission or a collision occurs. Each trial has the duration $T_{\text{FB}} + T_{\text{ACK}}$. For this protocol, the contention problem is solved by using a tailored version of the Exponential Backoff scheme [12]. If only one user is above a threshold, he will successfully feed back his CSI and the guard period will be over. However, if a collision takes place, the feedback transmission probability is lowered for the users within the successful interval and these users are again given the possibility to transmit their feedback within a time T_{FB}. After this time period the base station broadcasts an ACK packet to inform the users about the status of the feedback collection process. If more collisions are experienced (ACK=*e*), the transmission probability for the users within the successful interval is lowered one more time. The transmission probability is not changed if no users are transmitting feedback (ACK=*0*). This process will continue until one user has conducted a successful feedback transmission (ACK=*1*).

It can be shown that for n users contending, $1/n$ will be the transmission probability that maximizes the probability for a successful transmission. In [2] it has also been shown that the most probable number of users participating in a collision is two. Consequently, for the Exponential Backoff protocol the transmission probability is halved for each feedback collision. This protocol gives an increase in the fairness since a random user within the successful interval transmits feedback. However, the user with the highest CNR is not always feeding back his CSI and the MUD gain is not maximized.

D. Splitting Algorithm

The Splitting algorithm was proposed by Qin and Berry in [3] and uses principles from binary search to look for the user with the highest CNR. This protocol uses two threshold values and the users that have a CNR in the interval between these thresholds should transmit a RES packet simultaneously. The goal is that only the user with the best channel quality should be captured between the two thresholds. Initially, the highest threshold equals infinity and lowest threshold equals the value that maximizes the probability of having one user in the interval between the two thresholds. If more users have a CNR in the interval between the two thresholds, the base station broadcasts an *e*-ACK and the interval is split in two by increasing the lowest threshold value. However, if no users transmit a RES packet within the interval, a *0*-ACK is broadcasted and the highest threshold value is set to the lowest threshold value and the lowest threshold value is lowered. If only one user transmits his RES packet, the base station knows that this is the user with the highest CNR and a *1*-ACK is broadcasted. Finally, this user can transmit his CSI estimate by using an FB packet and the guard time is over. In [3] it is proven that maximally 2.5 iterations are needed on average to find the user with the best channel quality.

E. Modified Splitting Algorithm

As will be clear from Section VI-A, the RES packet is only slightly shorter than the FB packet in an IEEE 802.11-based network. We therefore propose a modification to the Splitting algorithm where an FB packet is used for the iteration process instead of a RES packet. For this protocol the iteration process will be slightly longer than for the original Splitting algorithm, however; the total guard time for an IEEE 802.11-based network will be shorter since it is not necessary to transmit an FB packet after the iteration process.

IV. Guard Time Analysis

The goal of this section is to develop analytical expressions for the guard time for the Ranked Full Feedback protocol, the Ranked Single-User Feedback protocol, and the Exponential Backoff protocol. These guard time expressions will be needed in the expressions for the MASSE (See Section V). To make the analysis simpler, we assume that the duration of the QRY packet is zero. Since the QRY broadcast time is the same for all the feedback protocols described above, this assumption will not affect the difference in guard time between the different protocols. Even if feedback is requested from all the users, a similar QRY packet needs to be broadcasted to inform the users about the order of their feedback transmission, since the users that have data to receive can change from time-slot to time-slot.

For the three proposed feedback protocols based on [2], the number of intervals checked before the successful interval is reached, is identical. The number of threshold values checked *before* the successful interval is found (number of trials), denoted M, will influence the guard time significantly. M can be modeled as a discrete random variable, and the probability that M has the value l can be expressed as follows:

$$\mathrm{Pr}(M = l) = P_\gamma^N(\gamma_{\mathrm{th},L-l}) - P_\gamma^N(\gamma_{\mathrm{th},L-l-1}),\ l = 0, 1, \cdots, L-1, \tag{1}$$

where $P_\gamma(\cdot)$ is the cumulative distribution function (CDF) of the CNR for one user. This equation expresses the probability of one or more users being in interval l while the rest of the users have lower CNR levels. The expected number of trials before the successful interval can now be expressed as:

$$\mathrm{E}[M] = \sum_{l=0}^{L-1} l\,[P_\gamma^N(\gamma_{\mathrm{th},L-l}) - P_\gamma^N(\gamma_{\mathrm{th},L-l-1})], \tag{2}$$

where $\mathrm{E}[\cdot]$ denotes the expectation operator.

A. Guard Time for Ranked Full Feedback

The time duration after the successful interval is found can be expressed as the sum of $T_{\mathrm{G,coll},l}$ and $T_{\mathrm{G,nocoll},l}$, where the former is the guard time contribution in the case a collision takes place in the successful interval l and the latter is the guard time contribution in the case only one user is found in the successful interval l. The expected values of these guard time contributions can be expressed as:

$$\mathrm{E}[T_{\text{G,coll},l}] = [(N+1)T_{\text{FB}} + T_{\text{ACK}}] \cdot \sum_{n=2}^{N} p(l,n), \tag{3}$$

and

$$\mathrm{E}[T_{\text{G,nocoll},l}] = (T_{\text{FB}} + T_{\text{ACK}}) \cdot p(l,1), \tag{4}$$

where $p(l,n)$ denotes the joint probability mass function (PMF) associated with the event of having n users in the successful interval l, i.e., $< \gamma_{\text{th},l}, \gamma_{\text{th},l+1}]$ [2]:

$$p(l,n) = \binom{N}{n} (P_\gamma(\gamma_{\text{th},l+1}) - P_\gamma(\gamma_{\text{th},l}))^n (P_\gamma(\gamma_{\text{th},l}))^{N-n}. \tag{5}$$

Now, the total expected guard time for the Ranked Full Feedback protocol can be expressed as:

$$\mathrm{E}[T_{\text{G}}] = (T_{\text{FB}} + T_{\text{ACK}}) \cdot \mathrm{E}[M] + \sum_{l=0}^{L-1} \mathrm{E}[T_{\text{G,coll},l}] + \sum_{l=0}^{L-1} \mathrm{E}[T_{\text{G,nocoll},l}], \tag{6}$$

for $L > 1$. For $L = 1$, all users will be within the successful interval. Therefore, collisions can be avoided, and the guard time equals the guard time for the Full Feedback protocol, $T_{\text{G}} = N \cdot T_{\text{FB}}$.

B. Guard Time for Ranked Single-User Feedback

As for the Ranked Full Feedback protocol, the time duration after the successful interval l is found can be expressed as the sum of the time contributions $T_{\text{G,coll},l}$ and $T_{\text{G,nocoll},l}$. The expected time contribution from the case where no collision takes place, $T_{\text{G,nocoll},l}$, is the same as for the Ranked Full Feedback protocol given in (4). The expression for the time contribution in the case of a collision yields:

$$\begin{aligned}
\mathrm{E}[T_{\text{G,coll},l}] &= 2(T_{\text{FB}} + T_{\text{ACK}}) \sum_{n=2}^{N} p(l,n) \\
&+ (T_{\text{RES}} + T_{\text{ACK}}) \sum_{n=2}^{N} \sum_{k=0}^{N-n} k \binom{N-k-1}{n-1} \\
&\times (P_\gamma(\gamma_{\text{th},l+1}) - P_\gamma(\gamma_{\text{th},l}))^n P_\gamma(\gamma_{\text{th},l})^{N-n},
\end{aligned} \tag{7}$$

where the first factor appears because one FB-collision arises when the successful interval is found and one FB packet is transmitted because the user with the highest rank within the successful interval feeds back his CSI, while the second factor is derived in Appendix I. The total expression for the expected guard time is the same as in (6). As for the Ranked Full

Feedback protocol, the guard time expression is only valid for $L > 1$. For $L = 1$, only the user with the highest rank feeds back his CSI, which gives $T_{\text{G}} = T_{\text{FB}}$. This CSI estimate is used to adapt the coding and modulation.

C. Guard Time for Exponential Backoff

The Exponential Backoff scheme can be described by the Markov chain shown in Fig. 1. Considering any successful interval l, we define the state $I = i$ as the number of collisions that have occurred. When the first collision occurs, the protocol goes to state $i = 1$ where the transmission probability is q^i. For each new collision, the state is incremented, and the time contribution from switching to a new state is T_{FB}+T_{ACK}. As mentioned in Section III-C, the value of q is one half, so the transmission probability is halved for each state. The probability for successful feedback transmission in state $I = i$ is $\text{P}_{\text{succ}} = nq^i(1-q^i)^{n-1}$, where n denotes the number of contending users. Correspondingly, the probability that none of the users are transmitting feedback in state $I = i$ is equal to $\text{P}_{\text{stay}} = (1-q^i)^n$. Because the sum of all transition probabilities from one state equals unity, the probability for going to the next state is $\text{P}_{\text{next}} = 1-(1-q^i)^n - nq^i(1-q^i)^{n-1}$. The joint probability of entering state $I = i$, and having n contending users in the successful interval l, can be written as a sum of the probabilities of the mutually exclusive events in the previous state that lead to the next:

$$\begin{aligned} \pi(i,l,n) &= \pi(i-1,l,n) \cdot \text{P}_{\text{next}} \sum_{k=0}^{\infty} (\text{P}_{\text{stay}})^k \\ &= \pi(i-1,l,n) \frac{1-(1-q^{i-1})^n - nq^{i-1}(1-q^{i-1})^{n-1}}{1-(1-q^{i-1})^n}, \end{aligned} \quad (8)$$

for $i \geq 1$. For $n \geq 2$ and $i = 1$, $\pi(i,l,n)$ equals the probability that there are multiple users in the successful interval, consequently $\pi(1,l,n) = p(l,n)$. For $n = 1$, there are no collisions ($i = 0$) and we have $\pi(0,l,n) = p(l,n)$.

By nesting the recursive relationship in (8) down to $i = 2$ and using the relations $\pi(1,l,n) = p(l,n)$ and $\pi(0,l,n) = p(l,n)$, we obtain:

$$\pi(i,l,n) = p(l,n) \prod_{m=1}^{i-1} \frac{1-(1-q^m)^n - nq^m(1-q^m)^{n-1}}{1-(1-q^m)^n}, \quad (9)$$

for $i \geq 0$ and $n \geq 1$. Note that the value $i = 0$ can only arise when $n = 1$, and that the product in this expression reduces to unity when $i = 0$ or $i = 1$. Now we can insert (5) into (9) and find

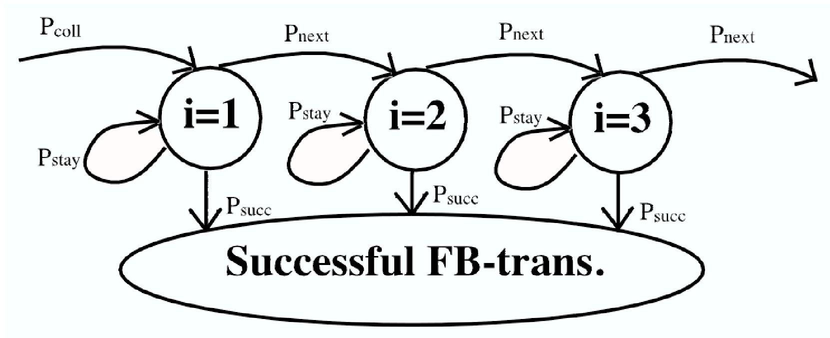

Fig. 1. Markov chain illustrating the exponential backoff scheme.

all the transition probabilities $\pi(i,l,n)$ for any number of contending users n in any successful interval l.

To find the number of T_{FB}+T_{ACK} used due to no feedback transmission, we calculate the probability of staying k transmission attempts in state $I=j$:

$$\text{Pr}(K_1=k)=(1-\text{P}_{\text{stay}})\cdot(\text{P}_{\text{stay}})^k=(1-(1-q^j)^n)\cdot((1-q^j)^n)^k. \quad (10)$$

This is a *geometric distribution*, and consequently, the expected number of T_{FB}+T_{ACK} used in state $I=j$, K_1, can be shown to be [13, (1.113)]:

$$\text{E}[K_1|j,n]=\frac{(1-q^j)^n}{1-(1-q^j)^n}. \quad (11)$$

Summing this expression over all the states *before and including* state $I=i$, for a successful feedback transmission in state $I=i$, and using the law of total expectation, the expected number of T_{FB}+T_{ACK} before experiencing a successful feedback transmission, K_2, can be found as:

$$\begin{aligned}\text{E}[K_2] &= \sum_{l=0}^{L-1}\sum_{n=2}^{N}\sum_{i=1}^{\infty}\sum_{j=1}^{i}\text{E}[K_1|j,n]\cdot\pi(i,l,n)\cdot\text{P}_{\text{succ}}\sum_{k=0}^{\infty}(\text{P}_{\text{stay}})^k\\ &= \sum_{l=0}^{L-1}\sum_{n=2}^{N}\sum_{i=1}^{\infty}\sum_{j=1}^{i}\frac{(1-q^j)^n}{1-(1-q^j)^n}\cdot\pi(i,l,n)\cdot\frac{nq^i(1-q^i)^{n-1}}{1-(1-q^i)^n}. \quad (12)\end{aligned}$$

Denoting the number of collisions by K_3, the expected number of collisions before successful feedback transmission can be found in a similar way:

$$\text{E}[K_3]=\sum_{l=0}^{L-1}\sum_{n=2}^{N}\sum_{i=1}^{\infty}i\cdot\pi(i,l,n)\cdot\frac{nq^i(1-q^i)^{n-1}}{1-(1-q^i)^n}. \quad (13)$$

The expected guard time can now be found as:

$$\mathrm{E}[T_{\mathrm{G}}] = (T_{\mathrm{FB}} + T_{\mathrm{ACK}})(1 + \mathrm{E}[M] + \mathrm{E}[K_2] + \mathrm{E}[K_3]), \tag{14}$$

where the single T_{FB}+T_{ACK} denotes the time it takes for the user to transmit his FB packet successfully. As for the two ranked protocols, the first collision will be avoided when $L = 1$ (all users are within the successful interval). Therefore, one T_{FB}+T_{ACK} has to be deducted from the expression of the expected guard time in (14) for $L = 1$.

D. Guard Time for the Splitting Algorithm

To calculate the expected guard time for the Splitting algorithm and the Modified Splitting algorithm for different number of users, we have used [3, Eq. (13)] in combination with [3, Eq. (6)].

V. Analysis of the Maximum Average System Spectral Efficiency

In this section we derive expressions for the MASSE for all the feedback protocols, taking the degradation due to the guard time into account in each case. The expressions are first presented in a general form which holds for any channel fading distribution, and then closed-form expressions are presented for i.i.d. Rayleigh fading channels.

A. Spectral Efficiency When the User With Highest CNR is Selected

The MASSE of the Full Feedback protocol can be expressed as follows:

$$\begin{aligned} \mathrm{MASSE}_{\mathrm{FF}} &= \frac{T_{\mathrm{TS}} - N \cdot T_{\mathrm{FB}}}{T_{\mathrm{TS}}} \int_0^{\infty} \log_2(1+\gamma) p_{\gamma^*}(\gamma) d\gamma \\ &= \frac{T_{\mathrm{TS}} - N \cdot T_{\mathrm{FB}}}{T_{\mathrm{TS}}} \frac{N}{\ln 2} \sum_{n=0}^{N-1} \binom{N-1}{n} \frac{(-1)^n}{1+n} e^{(1+n)/\overline{\gamma}} E_1\left(\frac{1+n}{\overline{\gamma}}\right), \end{aligned} \tag{15}$$

where $p_{\gamma^*}(\gamma) = N \cdot P_{\gamma}^{N-1}(\gamma) \cdot p_{\gamma}(\gamma)$ is the probability density function (PDF) of the CNR of the user with the highest CNR, $p_{\gamma}(\gamma)$ being the PDF of the CNR of a single user. T_{TS} is the total time assigned for a transmission, with the guard time included.

Both the Ranked Full Feedback protocol and the Splitting algorithm will lead to a selection of the user with the highest CNR. When the user with the highest CNR is always chosen to receive or transmit, the following expression for the MASSE is employed [4]:

$$\text{MASSE}_{\text{best}} = \sum_{l=0}^{L-1} \frac{T_{\text{TS}} - \text{E}_l[T_{\text{G}}]}{T_{\text{TS}}} \int_{\gamma_{\text{th},l}}^{\gamma_{\text{th},l+1}} \log_2(1+\gamma) p_{\gamma^*}(\gamma) d\gamma, \tag{16}$$

where $\text{E}_l[T_{\text{G}}]$ is the expected guard time given that interval l is the successful interval. The relation between $\text{E}_l[T_{\text{G}}]$ and $\text{E}[T_{\text{G}}]$ found in the previous section can be expressed as follows:

$$\text{E}[T_{\text{G}}] = \sum_{l=0}^{L-1} \text{E}_l[T_{\text{G}}] p_N(l), \tag{17}$$

where $p_N(l)$ is the PMF of l being the successful interval with N users in the system:

$$p_N(l) = P_\gamma^N(\gamma_{\text{th},l+1}) - P_\gamma^N(\gamma_{\text{th},l}). \tag{18}$$

The corresponding expression for $\text{E}_l[T_{\text{G}}]$ for the Ranked Full Feedback protocol is given by:

$$\text{E}_l[T_{\text{G}}] = (L-l-1) \cdot (T_{\text{FB}} + T_{\text{ACK}}) + \frac{T_{\text{G,coll},l} + T_{\text{G,nocoll},l}}{p_N(l)}, \tag{19}$$

where the expressions for $T_{\text{G,coll},l}$ and $T_{\text{G,nocoll},l}$ are given by (3) and (4), respectively. For $L = 1$ all the users will be in the successful interval and consequently we will have full feedback load, $\text{E}_l[T_{\text{G}}] = N \cdot T_{\text{FB}}$.

By using the derivation shown in Appendix II, we obtain the MASSE for a Rayleigh fading channel given in (20), where $E_1(x) = \int_1^\infty e^{-xt}/t \, dt$ is the first order exponential integral function.

B. Spectral Efficiency When One Random User Within the Successful Interval is Selected

The Ranked Single-User Feedback protocol and the Exponential Backoff protocol will both choose a random user within the successful interval. Observing that picking a random user within the successful interval is similar to having quantized feedback, we can utilize the results from previous publications to develop an expression for the system spectral efficiency. Modifying [14, Eq. (17)] it can be shown that the spectral efficiency can be written as:

$$\text{MASSE}_{\text{single}} = \sum_{l=0}^{L-1} \frac{T_{\text{TS}} - \text{E}_l[T_{\text{G}}]}{T_{\text{TS}}} \frac{p_N(l)}{p_1(l)} \int_{\gamma_{\text{th},l}}^{\gamma_{\text{th},l+1}} \log_2(1+\gamma) p_\gamma(\gamma) d\gamma, \tag{21}$$

$$\begin{aligned}\mathrm{MASSE}_{\text{best}} &= \sum_{l=0}^{L-1}\frac{T_{\text{TS}}-\mathrm{E}_l[T_{\text{G}}]}{T_{\text{TS}}}\frac{N}{\ln 2}\sum_{n=0}^{N-1}\binom{N-1}{n}\frac{(-1)^n}{1+n}\\ &\times \left[\ln(1+\gamma_{\text{th},l})\cdot e^{-\frac{(1+n)\gamma_{\text{th},l}}{\overline{\gamma}}}-\ln(1+\gamma_{\text{th},l+1})\cdot e^{-\frac{(1+n)\gamma_{\text{th},l+1}}{\overline{\gamma}}}\right]\\ &+ \sum_{l=0}^{L-1}\frac{T_{\text{TS}}-\mathrm{E}_l[T_{\text{G}}]}{T_{\text{TS}}}\frac{N}{\ln 2}\sum_{n=0}^{N-1}\binom{N-1}{n}\frac{(-1)^n}{1+n}\\ &\times e^{\frac{(1+n)}{\overline{\gamma}}}\left(E_1\left(\frac{(1+n)(\gamma_{\text{th},l}+1)}{\overline{\gamma}}\right)-E_1\left(\frac{(1+n)(\gamma_{\text{th},l+1}+1)}{\overline{\gamma}}\right)\right)\end{aligned} \tag{20}$$

$$\begin{aligned}\mathrm{MASSE}_{\text{single}} &= \frac{1}{\ln 2}\sum_{l=0}^{L-1}\frac{T_{\text{TS}}-\mathrm{E}_l[T_{\text{G}}]}{T_{\text{TS}}}\frac{p_N(l)}{p_1(l)}\\ &\times \left[\ln(1+\gamma_{\text{th},l})\cdot e^{-\frac{\gamma_{\text{th},l}}{\overline{\gamma}}}-\ln(1+\gamma_{\text{th},l+1})\cdot e^{-\frac{\gamma_{\text{th},l+1}}{\overline{\gamma}}}\right]\\ &+ \frac{1}{\ln 2}\sum_{l=0}^{L-1}\frac{T_{\text{TS}}-\mathrm{E}_l[T_{\text{G}}]}{T_{\text{TS}}}\frac{p_N(l)}{p_1(l)}\\ &\times \left[e^{\frac{1}{\overline{\gamma}}}\left(E_1\left(\frac{(\gamma_{\text{th},l}+1)}{\overline{\gamma}}\right)-E_1\left(\frac{(\gamma_{\text{th},l+1}+1)}{\overline{\gamma}}\right)\right)\right]\end{aligned} \tag{22}$$

---

where $\mathrm{E}_l[T_{\text{G}}]$ is the guard time contribution from a trial with threshold $\gamma_{\text{th},l}$ and $p_1(l)$ is the probability that a random user is in the successful interval l. By using a similar derivation as in Appendix II, we obtain the MASSE for a Rayleigh fading channel given in (22).

The two random single user feedback protocols have different values of $\mathrm{E}_l[T_{\text{G}}]$ which make their MASSE different. For the Ranked Single-User Feedback protocol, $\mathrm{E}_l[T_{\text{G}}]$ in (22) is the same as in (19), where the expressions for $T_{\text{G,coll},l}$ and $T_{\text{G,nocoll},l}$ are given by (7) and (4), respectively.

The expected guard time for the Exponential Backoff protocol, given success in interval l, can be found by modifying (14) as follows:

$$\begin{aligned}\mathrm{E}_l[T_{\mathrm{G}}] &= (T_{\mathrm{FB}}+T_{\mathrm{ACK}})\cdot(L-l)\\ &+ (T_{\mathrm{FB}}+T_{\mathrm{ACK}})\cdot\sum_{n=2}^{N}\sum_{i=1}^{\infty}\sum_{j=1}^{i}\frac{(1-q^j)^n}{1-(1-q^j)^n}\cdot\frac{\pi(i,l,n)}{p_N(l)}\cdot\frac{\mathrm{P_{succ}}}{1-(1-q^i)^n}\\ &+ (T_{\mathrm{FB}}+T_{\mathrm{ACK}})\cdot\sum_{n=2}^{N}\sum_{i=1}^{\infty} i\cdot\frac{\pi(i,l,n)}{p_N(l)}\cdot\frac{\mathrm{P_{succ}}}{1-(1-q^i)^n}.\end{aligned} \tag{23}$$

When $L=1$ all the users are within the successful interval, and the user with the highest rank among the N users will be chosen for the Ranked Single-User Feedback protocol. In this case (22) reduces to:

$$\mathrm{MASSE_{RR}} = \frac{T_{\mathrm{TS}}-T_{\mathrm{FB}}}{T_{\mathrm{TS}}}\frac{1}{\ln 2}e^{1/\overline{\gamma}}E_1\left(\frac{1}{\overline{\gamma}}\right), \tag{24}$$

where the subscript RR denotes *Round Robin*. The ratio $\frac{T_{\mathrm{TS}}-T_{\mathrm{FB}}}{T_{\mathrm{TS}}}$ arises because the selected user feeds back his CSI estimate so that adaptive modulation and coding can be employed. For $L=1$ the Exponential Backoff protocol avoids the first collision and resolves the contention problem as usual.

VI. Performance Evaluation of the Proposed Feedback Protocols: Discussion and Numerical Results

The main emphasis of this section is to evaluate the performance of the five described feedback protocols together with the the Full Feedback protocol and the Round Robin protocol based on the analysis in Section IV and Section V. The performance of the protocols will be evaluated by plotting the guard time and the MASSE for different number of thresholds (L) and users (N). Before presenting the numerical results we describe the IEEE 802.11 parameter values chosen for our numerical analysis.

A. IEEE 802.11 Parameter Values

To implement our protocols in an IEEE 802.11 network, we describe the following four packet types based on the general frame format defined in the standard [11].

Query (QRY) packet:

- 2 bytes FC (frame control)
- N times 6 bytes RA (receiver address)

- 1 byte Number of thresholds, L
- 4 bytes FCS (frame check sequence)

Feedback (FB) packet:

- 2 bytes FC
- 6 bytes TA (transmitter address)
- 1 byte CNR estimate
- 4 bytes FCS

Reservation (RES) packet:

- 2 bytes FC
- 4 bytes FCS

Acknowledgment (ACK) packet:

- 2 bytes FC
- 1 byte (0,1,e) ACK
- 4 bytes FCS

The FC field identifies the function and the fields of the packet, while the FCS field makes it possible for the receiver to separate packets from noise. In addition to these MAC-layer protocol fields, we also have to take the physical layer protocol fields into account. In IEEE 802.11 the physical layer protocol is called Physical Layer Convergence Protocol (PLCP) [15]. The packet headers of this protocol consists of a preamble and a header. If we assume that Direct Sequence Spread Spectrum (DSSS) is implemented at the physical layer the PLCP preamble consists of 18 bytes and the PLCP header consists of 5 bytes [15]. It should be observed that this implementation of DSSS does only combat interference and does not facilitate that multiple users can access the channel simultaneously.

To be able to calculate the duration of the packets listed above we have assumed that they are transmitted at the base rate 2 Mbps and that the propagation delay and packet processing time has the duration of a Short Interframe Space (SIFS). If we assume that a SIFS equals 10 μs (IEEE 802.11b) then T_{FB} equals 154 μs, T_{RES} equals 128 μs, and T_{ACK} equals 130 μs. For the Full Feedback protocol and the Round Robin protocol, no ACK packets are necessary, so the feedback from each user has the duration T_{FB}. As already mentioned in Section IV, we have also assumed that T_{QRY} has zero duration for all the algorithms.

B. Numerical Results for the Guard Time

In Figs. 2 and 3 we show plots of how the guard time varies with the number of thresholds for 4 and 12 users, respectively. For 4 users we see that the Ranked Single-User Feedback protocol gives the shortest guard time, while the Modified Splitting algorithm gives the shortest guard time for 12 users. It should also be noted that the Full Feedback protocol gives a relatively short guard time for 4 users. However, since the guard time is proportional to the number of users for Full Feedback protocol, this protocol will perform the worst for a high number of users.

C. Numerical Results for the MASSE

Figs. 4 and 5 show how the MASSE varies with the number of thresholds for short time-slots ($T_{\rm TS}$=5 ms), for 4 and 12 users, respectively. The corresponding plots for long time-slots ($T_{\rm TS}$=50 ms) are shown in Figs. 6 and 7.

For comparison purposes we have included graphs of the MASSE for *No Guard Time* and *Round Robin*. The former case corresponds to a theoretical system with no guard time and full MUD exploitation. The latter case corresponds to a system where adaptive coding and modulation are used, while opportunistic scheduling is not implemented. For this latter system, the users are scheduled in a Round Robin fashion. Feedback is still needed from the selected user in order to perform adaptive coding and modulation.

Although the Ranked Single-User Feedback protocol had the shortest guard time for 4 users, the Full Feedback protocol ensures that the MUD gain is maximized, and therefore the Full Feedback protocol yields the best MASSE performance for 4 users. For a higher number of users, the Modified Splitting algorithm shows the best MASSE performance since this protocol ensures full MUD exploitation and has a relatively short guard time.

For long time-slots, we see that the gain from the feedback reducing protocols diminishes. However, for many users the Modified Splitting protocol still gives a small gain over the other feedback protocols.

VII. Conclusions

In this paper we studied feedback protocols for possible use in slotted cellular ALOHA-based networks exploiting MUD. We considered downlink transmission where the base station transmits data to the mobile users. To be able to exploit MUD, the base station wants to schedule the user with the best channel quality for each time-slot. Therefore, the base station needs to collect feedback from the mobile users. In conventional networks that exploit MUD, feedback is collected from all users, which can be a time-consuming process. Consequently, we analyzed feedback protocols aimed at reducing the number of users transmitting feedback, and hence the guard time used to collect feedback.

We proposed three new feedback protocols for ALOHA-based cellular networks, namely, (i) Ranked Full Feedback, (ii) Ranked Single-User Feedback, and (iii) Exponential Backoff. Closed-form expressions were also found for the guard time duration and the MASSE for these three protocols. We also investigated the guard time and MASSE performance in an IEEE 802.11-based cellular network for the three new protocols and compared their performance with the Splitting algorithm proposed in [3] and a new and modified version of this algorithm. Our plots showed that the five different feedback protocols all give a feedback reduction for a system with many mobile users, and that the Modified Splitting algorithm showed the best MASSE performance. However, for a low (4) number of users the Full Feedback algorithm surprisingly showed the best MASSE performance.

APPENDIX I
DERIVATION OF THE LAST TERM IN (7)

For the Ranked Single-User Feedback protocol, we sequentially investigate if the users are within the successful interval based on their rank. We denote X as the number of users investigated *before* a user within the successful interval is found. The probability of finding one of the n users within the successful interval for the first user investigated is :

$$\Pr(X=0)=\frac{n}{N}. \tag{25}$$

If the search is not successful for the first user, the user with the second highest rank will have to be investigated. Now, we have already investigated one user. Consequently, the probability of finding a user within the successful interval is given as:

$$\Pr(X=1)=\left(1-\frac{n}{N}\right)\frac{n}{N-1}=\frac{N-n}{N}\frac{n}{N-1}. \tag{26}$$

Correspondingly, the probability of finding a successful user for the third user yields:

$$\Pr(X=2)=\left(1-\frac{n}{N}\right)\left(1-\frac{n}{N-1}\right)\frac{n}{N-2}=\frac{N-n}{N}\frac{N-n-1}{N-1}\frac{n}{N-2}. \tag{27}$$

Generalizing (25), (26) and (27), we obtain the expression for success for the $(k+1)$th user:

$$\Pr(X=k)=\frac{N-n}{N}\frac{N-n-1}{N-1}\cdots\frac{N-n-k+1}{N-k+1}\frac{n}{N-k}=\frac{n(N-n)!(N-k-1)!}{N!(N-n-k)!}. \tag{28}$$

The expected number of users investigated before success is now given as:

$$\mathrm{E}[X]=\sum_{k=0}^{N-n}k\frac{n(N-n)!(N-k-1)!}{N!(N-n-k)!}. \tag{29}$$

We know from Section IV that the probability of having n users in interval l is given by:

$$p(l,n)=\binom{N}{n}(P_\gamma(\gamma_{\text{th},l+1})-P_\gamma(\gamma_{\text{th},l}))^n(P_\gamma(\gamma_{\text{th},l}))^{N-n}. \tag{30}$$

To obtain the time contribution from interval l, the expected number of users that are investigated before a user within the successful interval is found, are weighted by the probability of being in this interval:

$$\begin{aligned}&\sum_{k=0}^{N-n}k\frac{n(N-n)!(N-k-1)!}{N!(N-n-k)!}\binom{N}{n}(P_\gamma(\gamma_{\text{th},l+1})-P_\gamma(\gamma_{\text{th},l}))^n(P_\gamma(\gamma_{\text{th},l}))^{N-n}\\ =&\sum_{k=0}^{N-n}k\binom{N-k-1}{n-1}(P_\gamma(\gamma_{\text{th},l+1})-P_\gamma(\gamma_{\text{th},l}))^n(P_\gamma(\gamma_{\text{th},l}))^{N-n}.\end{aligned} \tag{31}$$

Summing this expression over all values of n gives the same expression as the last term in (7).

APPENDIX II
DERIVATION OF (20)

The CDF of the CNR of the user with the highest CNR can be found from *order statistics* [16]:

$$P_{\gamma^*}(\gamma) = P_\gamma^N(\gamma), \tag{32}$$

where $P_\gamma(\gamma)$ is the of the CNR for a single user. To find the MASSE for such a scenario, the PDF of the highest CNR between all the users has to be found. This PDF can be obtained by differentiating (32) with respect to γ [16, (5.85)]:

$$p_{\gamma^*}(\gamma) = N \cdot P_\gamma^{N-1}(\gamma) \cdot p_\gamma(\gamma), \tag{33}$$

where $p_\gamma(\gamma)$ is the PDF for a single user. Inserting the CDF and PDF for Rayleigh fading channels ($p_\gamma(\gamma) = (1/\overline{\gamma})e^{-\gamma/\overline{\gamma}}$) and using binomial expansion [13, (1.111)], we obtain:

$$p_{\gamma^*}(\gamma) = \frac{N}{\overline{\gamma}} \sum_{n=0}^{N-1} \binom{N-1}{n} (-1)^n e^{-(1+n)\gamma/\overline{\gamma}}. \tag{34}$$

Inserting (34) into the expression for the spectral efficiency ([Bit/Sec/Hz]) for optimal rate adaptation [17]:

$$\text{MASSE} = \int_0^\infty \log_2(1+\gamma) p_{\gamma^*}(\gamma)\, d\gamma, \tag{35}$$

we get the following expression for the MASSE:

$$\text{MASSE}_{\text{best}} = \frac{N}{\overline{\gamma}\ln 2} \sum_{n=0}^{N-1} \binom{N-1}{n} (-1)^n \int_0^\infty \ln(1+\gamma) e^{-(1+n)\gamma/\overline{\gamma}}\, d\gamma. \tag{36}$$

The expression for MASSE has to be weighted by the factor $(T_{\text{TS}} - \text{E}_l[T_{\text{G}}])/T_{\text{TS}}$. This factor is dependent on l, and consequently the integral in the expression above has to be split into L parts before the weighting operation can take place. This leads to the following expression:

$$\text{MASSE}_{\text{best}} = \frac{N}{\ln 2} \sum_{l=0}^{L-1} \frac{T_{\text{TS}} - \text{E}_l[T_{\text{G}}]}{T_{\text{TS}}} \sum_{n=0}^{N-1} \binom{N-1}{n} (-1)^n \int_{\gamma_{\text{th},l}}^{\gamma_{\text{th},l+1}} \ln(1+\gamma) e^{-(1+n)\gamma/\overline{\gamma}}\, d\gamma, \tag{37}$$

To solve this integral we can use *integration by parts*:

$$\int_{\gamma=a}^{\gamma=b} u dv = \lim_{\gamma\to b} uv - \lim_{\gamma \to a} uv - \int_{\gamma=a}^{\gamma=b} v du, \tag{38}$$

where both u and v are functions of γ. Setting $u = \ln(1+\gamma)$ and $v = \frac{-\overline{\gamma}}{1+n}e^{-(1+n)\gamma/\overline{\gamma}}$, we can write the integral in (37) as:

$$\int_{\gamma_{\text{th},l}}^{\gamma_{\text{th},l+1}} \ln(1+\gamma)e^{-(1+n)\gamma/\overline{\gamma}}\, d\gamma$$
$$= \frac{\overline{\gamma}}{1+n}\left[\ln(1+\gamma_{\text{th},l}) \cdot e^{-\frac{(1+n)\gamma_{\text{th},l}}{\overline{\gamma}}} - \ln(1+\gamma_{\text{th},l+1}) \cdot e^{-\frac{(1+n)\gamma_{\text{th},l+1}}{\overline{\gamma}}}\right]$$
$$+\frac{\overline{\gamma}}{1+n}\int_{\gamma_{\text{th},l}}^{\gamma_{\text{th},l+1}} \frac{e^{-(1+n)\gamma/\overline{\gamma}}}{\gamma}\, d\gamma, \tag{39}$$

using [13, (3.352.2)], to solve the integral in (39) and inserting the result in (37), gives the expression in (20).

REFERENCES

[1] P. Viswanath, D. N. C. Tse, and R. Laroia, "Opportunistic beamforming using dumb antennas," *IEEE Trans. Inform. Theory*, vol. 48, pp. 1277–1294, June 2002.

[2] V. Hassel, M.-S. Alouini, D. Gesbert, and G. E. Øien, "Exploiting multiuser diversity using multiple feedback thresholds." In *Proc. IEEE Vehicular Technology Conference (VTC'05-spring)*, Stockholm, Sweden, May 2005.

[3] X. Qin. and R. Berry, "Opportunistic splitting algorithms for wireless networks," in *Proc. IEEE International Conference on Computer Communications (INFOCOM'04)*, (Hong Kong, PR China), pp. 1662 – 1672, Mar. 2004.

[4] R. Knopp and P. A. Humblet, "Information capacity and power control in single cell multiuser communications," in *Proc. IEEE Int. Conference on Communications (ICC'95)*, (Seattle, WA, USA), pp. 331–335, June 1995.

[5] M. Andrews, K. Kumaran, K. Ramanan, A. Stolyar, P. Whiting, and R. Vijayakumar, "Providing quality of service over a shared wireless link," *IEEE Communications Mag.*, vol. 39, pp. 150–154, Feb. 2001.

[6] P. Bender, P. Black, M. Grob, R. Padovani, N. Sindhushyana, and S. Viterbi, "CDMA/HDR: A bandwidth-efficient high-speed wireless data service for nomadic users," *IEEE Communications Mag.*, vol. 38, pp. 70–77, July 2000.

[7] D. Gesbert and M.-S. Alouini, "How much feedback is multi-user diversity really worth?," in *Proc. IEEE Int. Conference on Communications (ICC'04)*, (Paris, France), pp. 234–238, June 2004.

[8] H. Koubaa, V. Hassel, and G. E. Øien, "Multiuser diversity gain enhancement by guard time reduction." In *Proc. IEEE Workshop on Signal Processing Advances in Wireless Communications (SPAWC'05)*, New York, NY, USA, June 2005.

[9] H. Koubaa, V. Hassel, and G. E. Øien, "Contention-less feedback for multiuser diversity scheduling." In *Proc. IEEE Vehicular Technology Conference (VTC'05-fall)*, Dallas, TX, USA, Sept. 2005.

[10] K. J. Hole and G. E. Øien, "Spectral efficiency of adaptive coded modulation in urban microcellular networks," *IEEE Trans. on Veh. Technol.*, vol. 50, pp. 205–222, Jan. 2001.

[11] IEEE Standards Department, "IEEE Std 802.11. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications," tech. rep., IEEE, September 1999.

[12] D. G. Jeong and W. S. Jeon, "Performance of an exponential backoff scheme for slotted-ALOHA protocol in local wireless environment," *IEEE Trans. on Veh. Technol.*, vol. 44, pp. 470–479, Aug. 1995.

[13] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*. San Diego, CA, USA: Academic Press, 6th ed., 2000.

[14] F. Florén, O. Edfors, and B.-A. Molin, "The effect of feedback quantization on the throughput of a multiuser diversity scheme," in *Proc. IEEE Global Communications Conference (GLOBECOM'03)*, vol. 1, (San Francisco, CA, USA), pp. 497–501, Dec. 2003.

[15] M. Ergen, "IEEE 802.11 tutorial." University of California Berkeley, `http://www.eecs.berkeley.edu/~ergen/docs/ieee.pdf`, June 2002.

[16] G. L. Stüber, *Principles of Mobile Communications*. Norwell, MA, USA: Kluwer, 1996.

[17] A. J. Goldsmith and P. P. Varaiya, "Capacity of fading channels with channel side information," *IEEE Trans. Inform. Theory*, vol. IT-43, pp. 1896–1992, Nov. 1997.

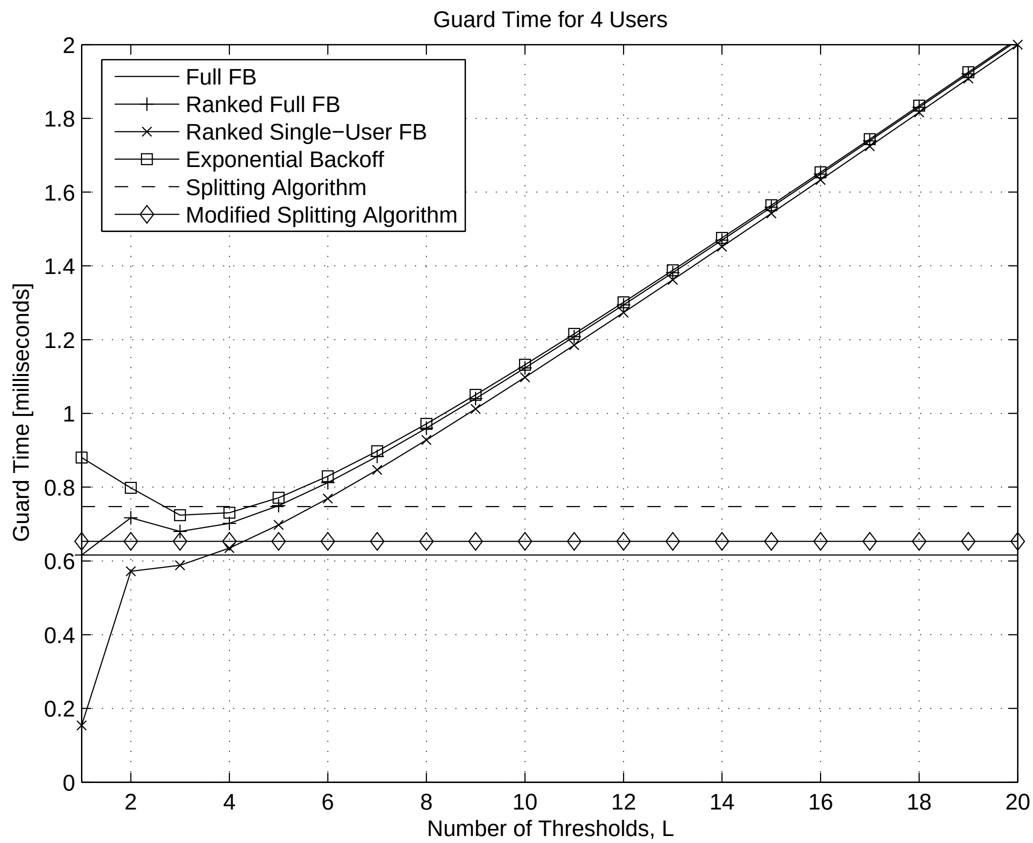

Fig. 2. Guard time for Rayleigh fading with $\overline{\gamma} = 15$ dB and 4 users.

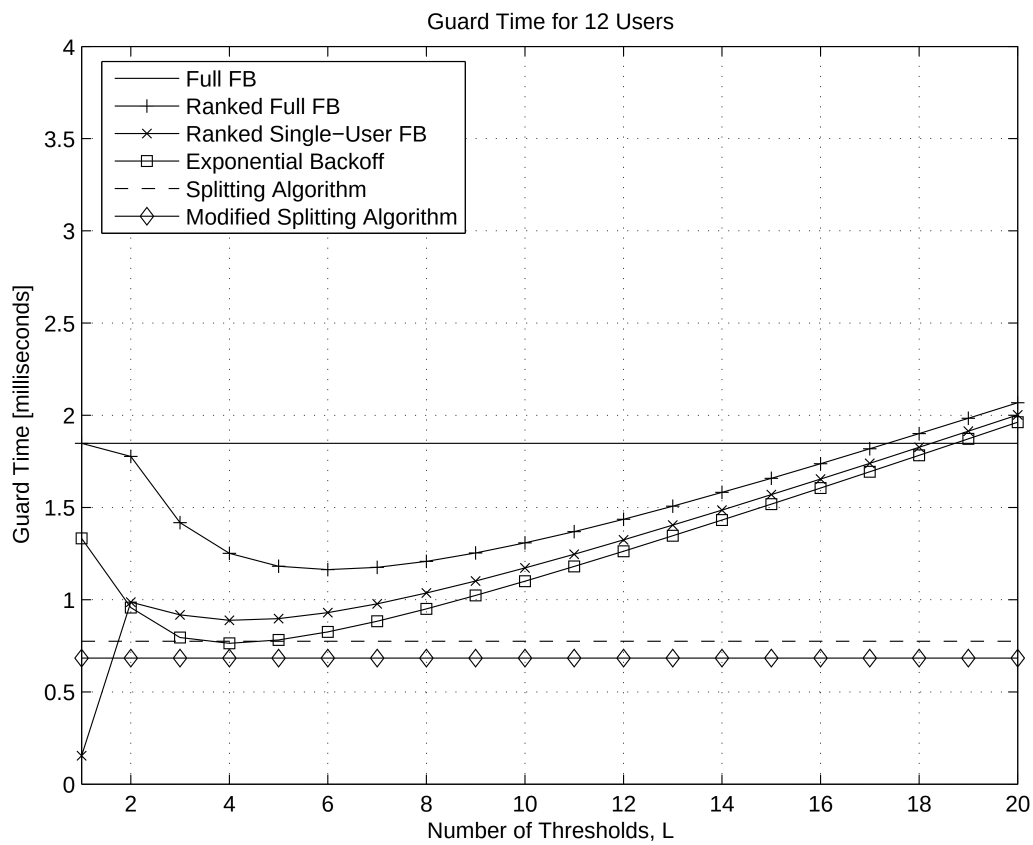

Fig. 3. Guard time for Rayleigh fading with $\overline{\gamma} = 15$ dB and 12 users.

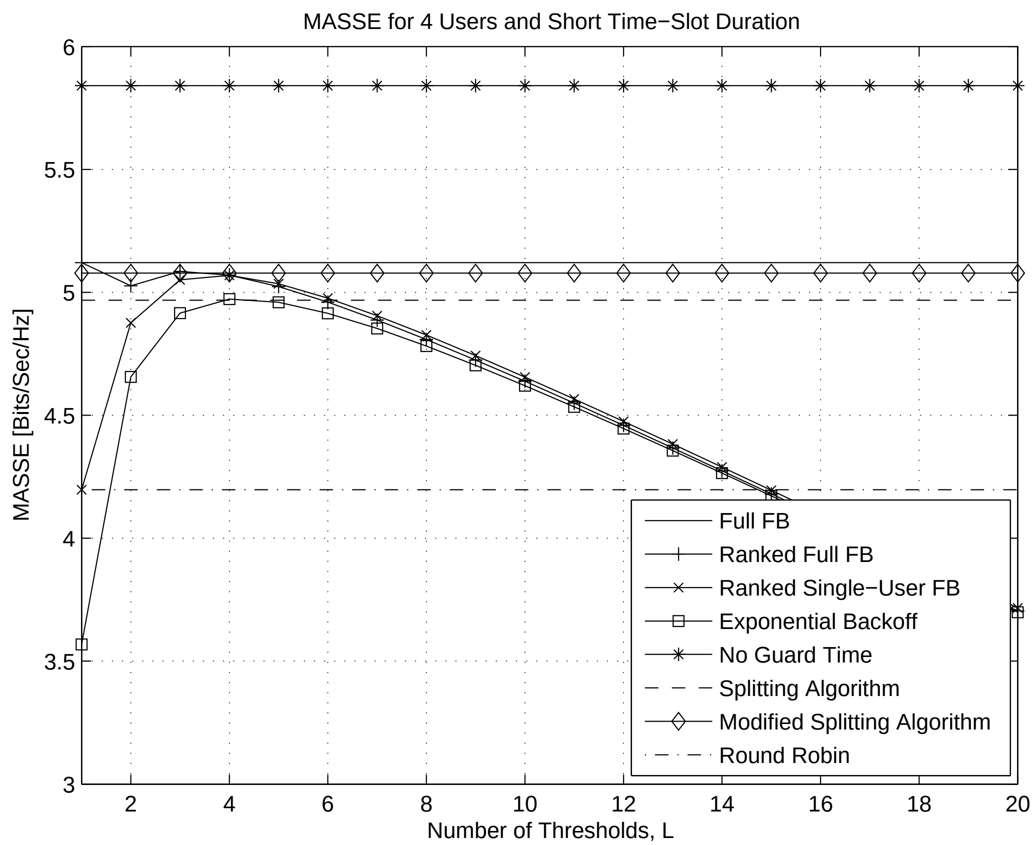

Fig. 4. MASSE for Rayleigh fading with $\overline{\gamma} = 15$ dB and 4 users. T_{TS} =5 ms.

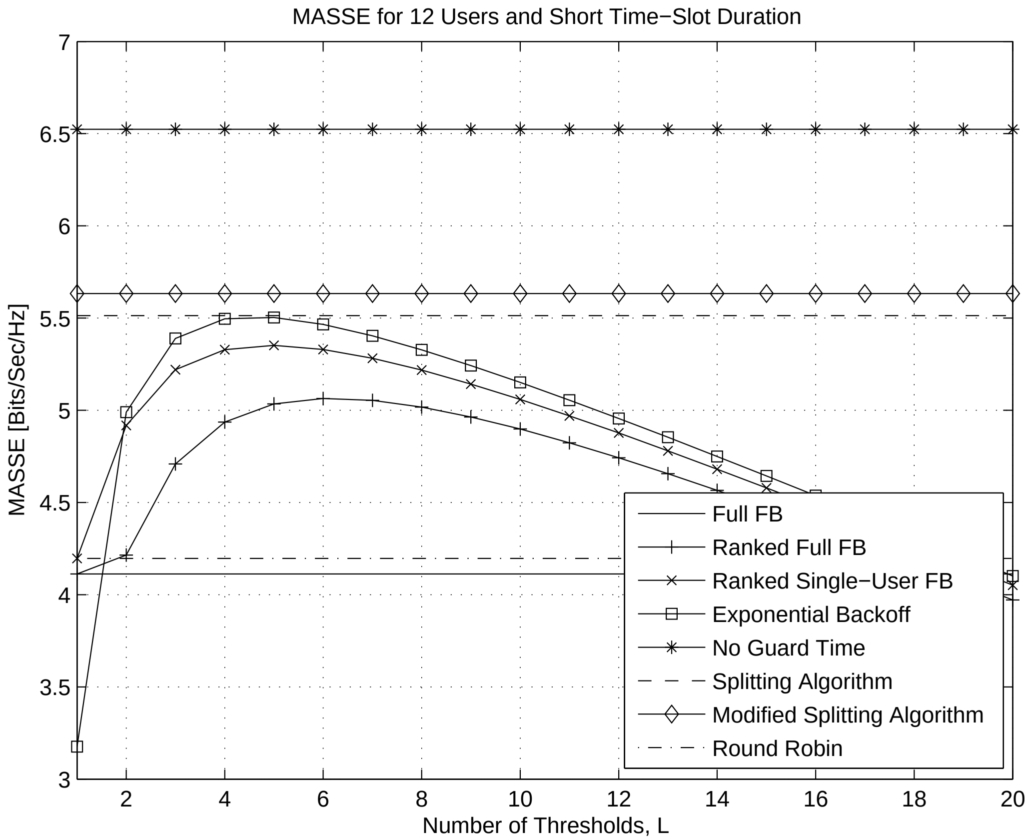

Fig. 5. MASSE for Rayleigh fading with $\overline{\gamma} = 15$ dB and 12 users. $T_{\rm TS}$ =5 ms.

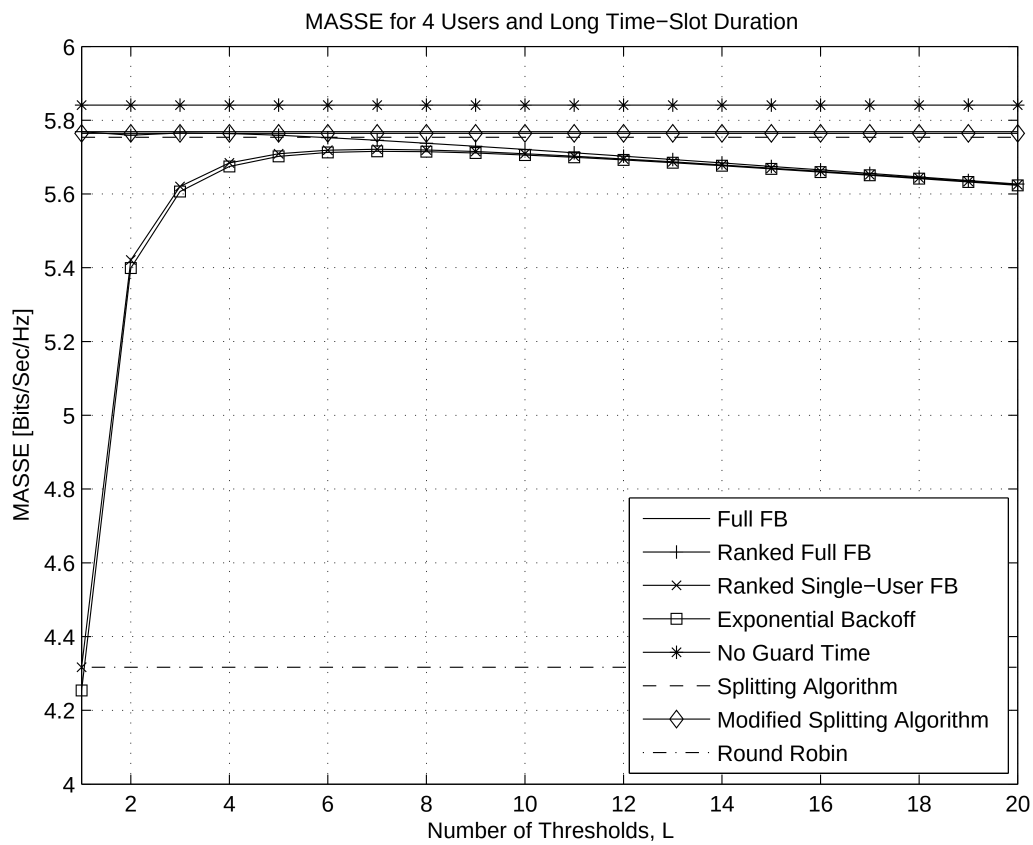

Fig. 6. MASSE for Rayleigh fading with $\overline{\gamma} = 15$ dB and 4 users. T_{TS} =50 ms.

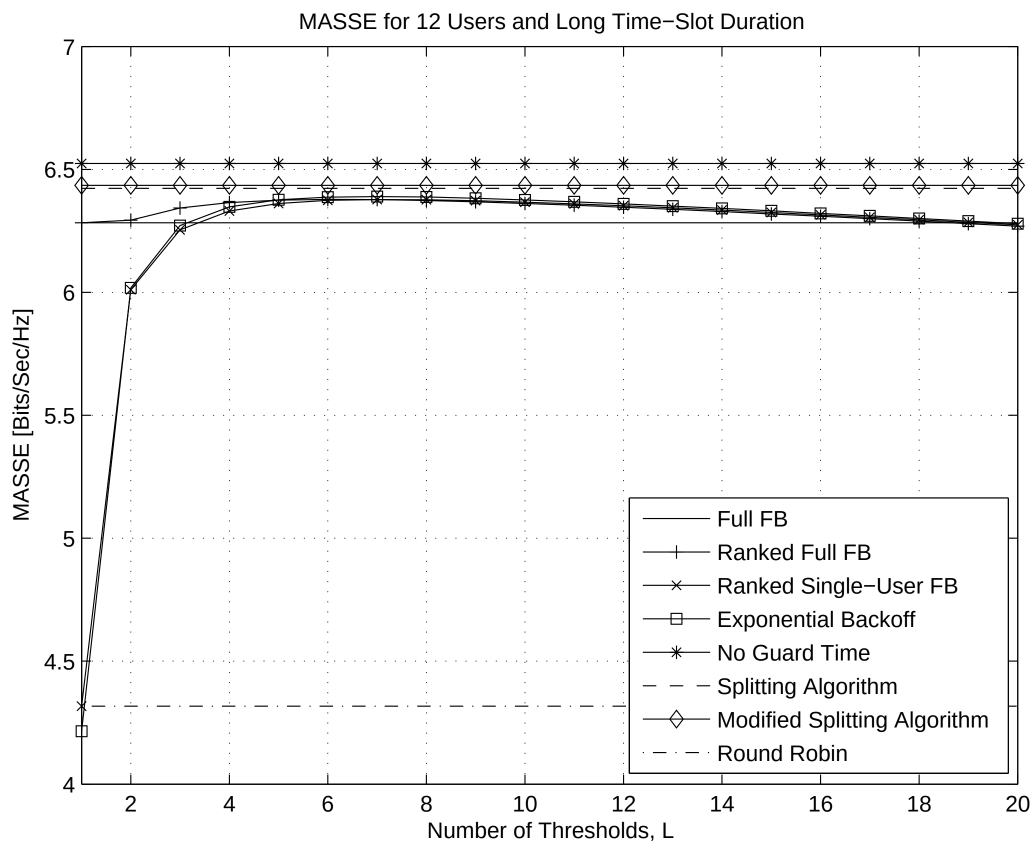

Fig. 7. MASSE for Rayleigh fading with $\overline{\gamma} = 15$ dB and 12 users. T_{TS} =50 ms.