Cooperative Multiple Access for Wireless Networks: Protocols Design and Stability Analysis

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***Abstract*— A new cooperative multiple-access protocol is proposed in which a relay utilizes the empty time slots available in a TDMA frame. In particular, the relay helps the users in the network forwarding their unsuccessfully transmitted packets during the empty time slots. This will better utilize the channel resources that are otherwise wasted, and will introduce on-demand spatial diversity into the network. The proposed cooperation protocol is also different from those proposed in the literature as it does not result in any bandwidth loss. Two different protocols are proposed to implement this new multiple-access scheme, and their stability regions are characterized. The stability regions of the proposed protocols are shown to contain that of TDMA without relaying, hence, relay deployment in wireless networks can increase the network throughput capacity. Moreover, the analysis and numerical results reveal that the proposed cooperative multiple access protocols can *simultaneously* achieve higher stable throughput and less energy expenditure compared to TDMA without relaying.**

I. Introduction

Over the past few decades, wireless communications and networking have witnessed an unprecedented growth. The growing demands require high data rate and considerably large coverage areas. Relay-based wireless networks have been discussed as a possible solution for these future demands in [1]. R. Pabst *et al.* [1] have envisioned that incorporating fixed (or moving) relays in the network might be a necessary modification in the wireless network architecture to meet the desirable high throughput and coverage requirements for future applications. This motivated us to study the implementation of new multiple-access protocols for relay-based wireless networks.The relay channel has been first addressed in the seminal work by Cover and El-Gamal [9]. Recently, the concept of cooperative diversity has gained a lot of interest [2]–[5]. In cooperative diversity, one or more relays cooperate with a source node to help in forwarding its data to a destination. This can achieve spatial diversity as the data is transmitted via spatially independent channels. In the previous works mentioned above, portion of the channel resources are assigned to the relay for cooperation, which results in some bandwidth efficiency loss.

In this paper, we investigate the possible impact of cooperation in the medium access layer. We propose a novel cooperative multiple-access protocol in which the relay utilizes the empty time slots in a TDMA frame to retransmit the failed transmitted packets of users in the network. More specifically, the relay stores the packets that were not received correctly by the AP in its queue. At the beginning of each time slot, the relay listens to the channel and if the time slot is empty the relay transmits the packet at the head of its queue. This new multiple-access (MA) approach thus jointly addresses the physical and MA layers in a cross-layer fashion. Furthermore, the proposed protocol does not require allocating part of the channel resources for cooperation as the relay utilizes the unused time slots for cooperation. We propose two protocols to implement this idea. To study the impact of the proposed protocols in the medium access layer, we investigate whether cooperation can increase the network stability region, and the stability criteria of the associated queueing systems are studied. To the best of our knowledge this is the first work that studies the impact of cooperation in increasing the stability region. The queues in one of the proposed protocols are interacting, therefore we develop a variant of the dominant system approach introduced in [8], [6] to analyze its stability. The stability regions of the proposed protocols are characterized and are shown to contain the stability region of TDMA without relaying. This means that the proposed cooperative protocols can achieve higher network throughput capacity compared to TDMA without relaying. Moreover, we study the effective energy required to successfully transmit a packet, which is an important measure for the energy efficiency a multiple access protocol. We show that our proposed cooperative multiple access protocol can *simultaneously* achieve higher stable throughput and smaller effective energy requirements, i.e., higher energy efficiency. This can also translate into coverage area extension.

II. Network and Channel Models

We consider the uplink of a TDMA system. Our network consists of a finite number of users $M < \infty$ numbered $1, 2, \cdots, M$, a relay node l[1], and a destination node d. Let $\mathcal{T} = \{\mathcal{M}, l\}$ denote the set of transmitting nodes, where $\mathcal{M} = \{1, 2, \cdots, M\}$ is the set of users, and $\mathcal{D} = \{l, d\}$ to denote the set of receiving nodes or possible destinations. In this paper, we only discuss the results for the $M = 2$ users scenario for lack of space (cf. Fig. 1).

First, we describe the multiple access channel model. Both of the two users and the relay l have an infinite buffer for storing fixed length packets. The channel is slotted, and a slot duration is equal to a packet duration. The arrival process at any user's queue is independent identically distributed

[1] We use l to denote the relay not to confuse with r that denotes distance

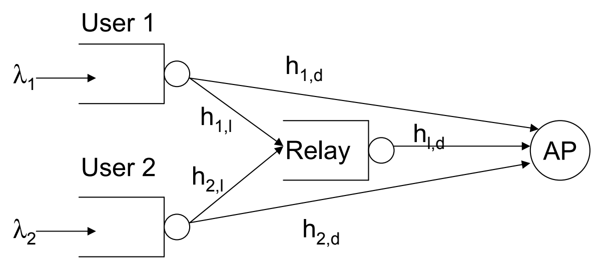

Fig. 1. $M = 2$-users Network model.

(i.i.d.) from one slot to another, and the arrival processes are independent from one user to another. The arrival process at the $i-th \in \{1,2\}$ queue is assumed stationary with mean λ_i. Hence, the vector $\Lambda = (\lambda_1, \lambda_2)$ denotes the average arrival rates. Users access the channel via dividing the channel resources, time in this case, among them, hence, each user is allocated a fraction of the time. Let $\Omega = (\omega_1, \omega_2)$ denotes a resource-sharing vector, where $\omega_i \geq 0$ is the fraction of the time allocated to user i. In another words, one can think of ω_i as the probability that user i is allocated the whole time slot. The set of all feasible resource-sharing vectors is

$$\mathcal{F} = \left\{ \Omega = (\omega_1, \omega_2) \in \Re^{+2} : \sum_{i \in \mathcal{M}} \omega_i \leq 1 \right\}. \tag{1}$$

For the symmetric case, where channel resources are allocated equally to all users, ω_i is simply equal to 0.5. The system is called stable for a given arrival rate vector and resource-sharing vector pair (Λ, Ω) if all the queues in $\mathcal{T}$ are stable, i.e., the users and the relay's queues are stable. If any queue in the set $\mathcal{T}$ is unstable, then the whole system is considered unstable. For an irreducible and aperiodic Markov chain with countable number of states chain, the chain is stable if and only if there is a positive probability for every queue of being empty, i.e.,

$$\lim_{t \to \infty} \mathcal{P}\{Q_i(t) = 0\} > 0. \tag{2}$$

(For a rigorous definition of stability under more general scenarios see [6], [8]). If the arrival and departure processes of a queueing system are strictly stationary, then one can apply Loynes's theorem to check for stability conditions [7]. This theorem states that, if the arrival process and the departure process of a queueing system are strictly stationary, and the average arrival rate is less than the average departure rate, then the queue is stable; if the average arrival rate is greater than the average departure rate then the queue is unstable.

Next, we describe the physical channel model. The wireless channel between any two nodes in the network is modeled as a Rayleigh flat fading channel with additive Gaussian noise. The signal received at a receiving node j from a transmitting node i at time t can be modeled as

$$y_{ij}^t = \sqrt{G r_{ij}^{-\gamma}} h_{ij}^t x_i^t + n_{ij}^t, \quad i \in \mathcal{T}, \, j \in \mathcal{D}, \, i \neq j, \tag{3}$$

where G is the transmitting power, assumed to be the same for all transmitting terminals, r_{ij} denotes the distance between the two nodes, γ is the path loss exponent, h_{ij}^t is the channel gain between nodes i and j at time t and is modeled as i.i.d. zero mean, circularly symmetric complex Gaussian random process with unit variance. The term x_i^t denotes the transmitted packet with average unit power at time t, and n_{ij}^t denotes i.i.d. additive white Gaussian noise with zero mean and variance N_o. Since the arrival, the channel gains, and the additive noise processes are assumed stationary, we can drop the index t without loss of generality. In this paper we characterize the success or failure of a packet reception by the outage event. Outage between two nodes i, j is defined as the event that the received SNR falls below a certain threshold β

$$O_{ij} \triangleq \{h_{ij} : \frac{| h_{ij} |^2 r_{ij}^{-\gamma} G}{N_o} \leq \beta\} \tag{4}$$

If the received SNR is higher than the threshold β, the receiver is assumed to be able to decode the received message with negligible probability of error. Given the channel model above, the outage probability can be calculated as follows

$$\mathcal{P}_{O,ij} = 1 - \exp(-\frac{\beta N_o r_{ij}^{\gamma}}{G}). \tag{5}$$

Since we will use frequently the above expression in our subsequent analysis, and for compactness of representation, we will use the following function to denote the success probability,

$$f_{ij} = \exp(-\frac{\beta N_o r_{ij}^{\gamma}}{G}). \tag{6}$$

III. Cooperative MA (CMA) Protocol S^1: Implementation and Analysis

The main characteristic of protocol S^1 is that when a user has a failed transmission in his time slot, and given that the relay was not able to deliver this packet during the rest of the TDMA frame and the turn comes again to this user, then this user retransmits this failed packet again even if it has new packets waiting transmission. We summarize the operation of the protocol in the following steps.

- Time is slotted and TDMA is utilized for multiple access.
- At the beginning of a time slot, if a user has a new packet to transmit and has no backlogged packets then the user transmits this packet to the AP. Due to the broadcast nature of the wireless channel, the relay can also receive the transmitted packet with some success probability.
- If the packet is not received correctly by the AP, then the AP is going to feedback a negative acknowledgement (NACK) declaring the packet's failure. In this case, if the relay was able to receive the packet correctly then it stores this packet in its queue waiting for a retransmission.
- At the beginning of each time slot during the rest of the TDMA frame, the relay senses the channel to check if there is a transmission. If the channel is free then the relay transmits the packet at the head of its queue. The assumption here is that there is enough guard time.
- At the beginning of a time slot, if the corresponding user has a failed transmitted packet, then the user is going to retransmit this packet even if he has new packets to

transmit.

According to the above description of protocol S^1, the relay's queue can at most have M backlogged packets, where M equals the number of users in the system. Therefore, the relay's queue never overflows and the stability of the system is mainly determined by the stability of the users' queues. Next we study the stability of protocol S^1. The system of queues in S^1 are interacting. The reason behind this is the fact that serving the failed packets of a certain queue depends on how often the other queues empty. Studying stability conditions for interacting queues has been addressed only for ALOHA systems, i.e., random access systems (for example cf. [6], [8]). Rao and Ephremides [8] introduced the concept of dominant systems to help finding bounds on the stability region of a system of interacting queues. The dominant system in [8] was defined by allowing a set of terminals that has no packets to transmit to continue transmitting dummy packets. In our system S^1, we define the dominant system in a different way that suits the TDMA framework and the employed relay in order to help decouple the interaction of the queues and hence analyze the system performance. We define the dominant system for S^1 as follows. For $1 \leq j \leq 2$, define S_j^1 as

- 1) Arrivals at queue i in S_j^1 is the same as S^1.
- 2) The channel realizations h_{kl}, where $k \in \mathcal{T}$ and $l \in \mathcal{D}$, for both S_j^1 and S^1 are identical.
- 3) The noise generated at receiving ends of both systems are identical.
- 4) The packets successfully transmitted by the relay for user j are not erased from user's j queue.

Conditions 1, 2, and 3 guarantee that the decisions made at the receiving ends of both systems are identical, i.e., the sequence of failed packets detected at both systems are identical. Condition 4 means that queue j in S_j^1 acts as in a TDMA system. The relay, however, can help the other user in the empty slots of the TDMA frame. Therefore, the queues in system S_j^1 are always not shorter than those in system S^1. This follows because a packet successfully transmitted for queue j in S_j^1 is always successfully transmitted from the corresponding queue in S^1. However, the relay can succeed in forwarding some packets from queue j in S^1, hence, queue j in S_j^1 is always not shorter than queue j in S^1. This means that queue j empties more frequently in S^1 and therefore the other user is better served in S^1 compared to S_j^1. S_j^1 is said to dominate S^1.

Consider system S_1^1 in which the relay only helps user 2 and user 1 acts exactly as in a TDMA system. In order to apply Loynes' theorem, we require the arrival and service processes for each queue to be stationary. Denote the queue size for user $i \in \{1, 2\}$ in system S_1^1 at time t by $Q_i^t(S_1^1)$, and it evolves as

$$Q_i^{t+1}(S_1^1) = (Q_i^t(S_1^1) - Y_i^t(S_1^1))^+ + X_i^t(S_1^1), \qquad (7)$$

where $X_i^t(S_1^1)$ represents the number of arrivals in slot t and is a stationary process by assumption with finite mean $E\left(X_i^t(S_1^1)\right) = \lambda_i$. Function $()^+$ is defined as $(x)^+ = \max(x, 0)$. The definition of the service process $Y_i^t(S_1^1)$ differs according to the user i. For user $i = 1$, it is given by

$$Y_1^t(S_1^1) = \mathbf{1}\{A_1^t \cap O_{1,d}^{c,t}\}, \qquad (8)$$

where $\mathbf{1}\{\}$ is the indicator function, A_1^t denotes the event that slot t is available for user 1; this happens with probability ω_1. $O_{1,d}^{c,t}$ denotes the complement of the event that the channel between user 1 and the destination d is in outage at time t. Due to the stationarity assumption of the channel gain process $\{h_{i,d}^t\}$, and using the outage expression in (5), the probability of this event is given by $\mathcal{P}(O_{1,d}^{c,t}) = f_{1d}$. From the above discussion, it is clear that the service process $Y_1^t(S_1^1)$ is stationary and has a finite mean given by

$$E\left(Y_1^t(S_1^1)\right) = \omega_1 f_{1d}. \qquad (9)$$

According to Loynes, stability of queue 1 is achieved if

$$\lambda_1 < \omega_1 f_{1d}. \qquad (10)$$

Consider now queue 2 in system S_1^1. The difference between the evolution of this queue and queue 1 is in the definition of the service process $Y_2^t(S_1^1)$. A packet from queue 2 can be served in a time slot in either one of the two following events:

$$Y_2^t(S_1^1) = \mathbf{1}\{A_2^t \cap O_{2,d}^{c,t}\} + \mathbf{1}\{A_1^t \cap \{Q_1^t(S_1^1) = 0\} \cap A_2^{t-1} \cap O_{2,l}^{c,t-1} \cap O_{2,d}^{t-1} \cap O_{l,d}^{c,t}\}, \qquad (11)$$

where A_2^t denotes the availability of time slot t for user 2, $\{Q_1^t(S_1^1) = 0\}$ denotes the event that user's 1 queue is empty in time slot t. The average rate of the service process can be found from

$$E\left(Y_2^t(S_1^1)\right) = \omega_2 f_{2d} + \omega_1 \mathcal{P}(\{Q_1^t(S_1^1) = 0\}) \omega_2 \left(1 - \mathcal{P}_{O,2l}\right) \times \mathcal{P}_{O,2d}(1 - \mathcal{P}_{O,ld}). \qquad (12)$$

Using Little's theorem [10], the probability of queue 1 becomes empty is given by

$$\mathcal{P}(Q_1^t(S_1^1) = 0) = 1 - \frac{\lambda_1}{\omega_1 f_{1d}}. \qquad (13)$$

Since the service process of queue 2 is a function of stationary processes only, it is stationary. Using the expression of the outage probability in (5) and Loynes conditions for stability [7], the stability condition for queue 2 in the dominant system S_1^1 is given by

$$\lambda_2 < \omega_2 f_{2d} + \omega_1 \omega_2 \left(1 - \frac{\lambda_1}{\omega_1 f_{1d}}\right) \left(1 - f_{2d}\right) f_{2l} f_{ld}. \qquad (14)$$

Both conditions (10) and (14) represent the stability region for system S_1^1 for a specific resource-sharing vector (ω_1, ω_2) pair. Call this region $\mathcal{R}(S_1^1)$. Using similar arguments for the dominant system S_2^1, we can characterize the stability region $\mathcal{R}(S_2^1)$ for this system by the following pair of inequalities

$$\begin{aligned} &\lambda_2 < \omega_2 f_{2d} \\ &\lambda_1 < \omega_1 f_{1d} + \omega_2 \omega_1 \left(1 - \frac{\lambda_2}{\omega_2 f_{2d}}\right) \left(1 - f_{1d}\right) f_{1l} f_{ld}. \end{aligned} \qquad (15)$$

Note that the regions $\mathcal{R}(S_1^1)$ and $\mathcal{R}(S_2^1)$ determined above are for a fixed resource-sharing vector (ω_1, ω_2). The whole stability region for system S^1 can be determined from the following lemma.

Lemma 3.1: The stability region of system S^1 is given by the union over all possible resource-sharing vectors as follows

$$\mathcal{R}(S^1) = \bigcup_{\Omega \in F} \mathcal{R}(S_1^1) \cup \mathcal{R}(S_2^1). \tag{16}$$

Proof: The proof depends on showing the indistinguishability of the original and dominant systems at saturation, and follows arguments similar to that in [8]. Proof Omitted for lack of space. ■

The boundary of the stability region $\mathcal{R}(S^1)$ can be determined from solving a constrained maximization problem. We omit this result here, however, for space limitations. Nevertheless, we state some of the observations we made from solving this maximization problem. The stability region of TDMA is contained in that of system S^1

$$\mathcal{R}_{TDMA} \subseteq \mathcal{R}(S^1), \tag{17}$$

where the stability region of TDMA is determined according to the following parametric equations inequalities

$$\lambda_1 \leq \omega_1 f_{1d}, \qquad \lambda_2 \leq \omega_2 f_{2d} \tag{18}$$

The equality in (17) is achieved if the following two conditions occur simultaneously

$$(1 - f_{2d}) f_{2l} f_{ld} < f_{2d}, \qquad (1 - f_{1d}) f_{1l} f_{ld} < f_{1d}. \tag{19}$$

IV. CMA Protocol S^2: Implementation and Analysis

In this section, we describe the implementation of protocol S^2 and an enhanced version of it $S^{2,e}$.

A. Protocol S^2

The main difference between protocols S^1 and S^2 is in the role of the relay and the behavior of the users' regarding their backlogged packets. Consider a test user who has a new packet to transmit and who does not have any backlogged packets

- At the beginning of this test user's time slot, the user transmits the new packet, and both the relay and the AP try to decode the packet. If the packet is received correctly by the AP then it sends back an ACK and the packet is released from both the relay's and the user's queues, otherwise the AP sends back a NACK. In case of the later event, if the relay was able to receive the packet correctly then it stores the packet in its queue and sends back an ACK.
- If an ACK is received back from either the AP or the relay, then the test user releases this packet completely from his queue.
- At the beginning of each time slot, the relay senses the channel to decide whether or not a new transmission is taking place. If not, then the relay transmits the packet at the head of his queue.
- In the next test user's time slot, if the test user has a new packet to transmit then he transmits this packet whether or not he has any backlogged packets stored at the relay.

One can now figure out the differences between the queues in system S^1 and S^2: i) The relay's queue can grow without limit in S^2, however, it can not exceed size M in S^1. ii) The user's queues in S^2 are not interacting as the case in S^1. This is because servicing the queue of any user depends only on the channel conditions from that user to the AP and relay. In S^2, a packet is released from a user's queue if either the AP or the relay receives this packet correctly. The success probability of the user $i \in \{1, 2\}$ in S^2 can be calculated as

$$P_i = \mathcal{P}(O_{i,l}^c \cup O_{i,d}^c) = f_{i,d} + f_{i,l} - f_{i,d} f_{i,l}. \tag{20}$$

First, consider the stability region for the system determined just by the users' queues. Since for each queue $i \in \mathcal{M}$, the queue behaves exactly as in a TDMA system with the success probability determined by (20), the stability region $\mathcal{R}_{\mathcal{M}}(S^2)$ for the set of queues in $\mathcal{M}$ in system S^2 is given by

$$\mathcal{R}_{\mathcal{M}}(S^2) = \big\{(\lambda_1, \lambda_2) \in R^{+2} : \lambda_i < \omega_i P_i, \forall i \in \mathcal{M}, \text{ and } (\omega_1, \omega_2) \in F\big\}. \tag{21}$$

Next we study the stability of the relay's queue l. The evolution of the relay's queue can be modeled as

$$Q_l^t(S^2) = \left(Q_l^t(S^2) - Y_l^t(S^2)\right)^+ + X_l^t(S^2), \tag{22}$$

Now we establish the stationarity of the arrival and service processes of the relay. If the users' queues are stable, then by definition the departure processes from both users are stationary. A packet departing from a user queue is stored in the relay's queue (i.e., counted as an arrival) if simultaneously the following two events happen: the user-destination channel is in outage and the user-relay channel is not in outage. Hence, the arrival process to the queue can be modeled as follows

$$X_l^t(S^2) = \sum_{i \in \mathcal{M}} \mathbf{1}\left\{A_i^t \cap \{Q_i^t \neq 0\} \cap O_{id}^t \cap O_{il}^{c,t}\right\}, \tag{23}$$

where all of the evens in the summation are disjoint. In (23), $\{Q_i^t \neq 0\}$ denotes the event that user's i queue is not empty, i.e., the user has a packet to transmit, and according to Little's theorem it has probability $\lambda_i/(\omega_i P_i)$, where P_i is user's i success probability and is defined in (20). The random processes involved in the above expressions are all stationary, hence, the arrival process to the relay is stationary. The expected value of the arrival process can be computed as follows

$$\lambda_l = \lambda_1 \frac{(1 - f_{1d}) f_{1l}}{P_1} + \lambda_2 \frac{(1 - f_{2d}) f_{2l}}{P_2}. \tag{24}$$

The service process of the relay's queue can be modeled as

$$Y_l^t(S^2) = \sum_{i \in \mathcal{M}} \mathbf{1}\left\{A_i^t \cap \{Q_i^t = 0\} \cap O_{ld}^{c,t}\right\}, \tag{25}$$

The average service rate of the relay can be determined from the following equation

$$E(Y_l^t(S^2)) = \left(\omega_1(1 - \frac{\lambda_1}{\omega_1 P_1}) + \omega_2(1 - \frac{\lambda_2}{\omega_2 P_2})\right) f_{ld}. \quad (26)$$

Using Loynes and equations (24) and (26), the stability region for the relay $\mathcal{R}_l(S^2)$ is determined by the condition

$$E(X_l^t(S^2)) < E(Y_l^t(S^2)). \quad (27)$$

The total stability region for system S^2 is given by the intersection of two regions $\mathcal{R}_{\mathcal{M}}(S^2) \cap \mathcal{R}_l(S^2)$ which is easily shown to be equal to $\mathcal{R}_l(S^2)$. We summarize these results in the following theorem

Theorem 1: The stability region for system S^2 with $M = 2$ users is determined by

$$\mathcal{R}(S^2) = \Big\{(\lambda_1, \lambda_2) \in R^{+2} : \frac{\lambda_1}{P_1}\left((1 - f_{1d})f_{1l} + f_{ld}\right) + \frac{\lambda_2}{P_2}\left((1 - f_{2d})f_{2l} + f_{ld}\right) < f_{ld}\Big\} \quad (28)$$

Theorem 1 reveals that the stability region of protocol S^2 is bounded by a straight line. Since the stability region for TDMA is also determined by a straight line, it is enough when comparing both stability regions to compare the intersection of these lines with the axes. These intersections for system S^2 can be easily shown to be equal to

$$\lambda_1^*(S^2) = \frac{f_{ld} P_1}{f_{ld} + (1 - f_{1d})f_{1l}}, \quad \lambda_2^*(S^2) = \frac{f_{ld} P_2}{f_{ld} + (1 - f_{2d})f_{2l}}. \quad (29)$$

While the corresponding values for TDMA are given by

$$\lambda_1^*(TDMA) = f_{1d}, \qquad \lambda_2^*(TDMA) = f_{2d}. \quad (30)$$

The stability region for TDMA is completely contained inside the stability region of S^2 if $\lambda_1^*(S^2) > \lambda_1^*(TDMA)$ and $\lambda_2^*(S^2) > \lambda_2^*(TDMA)$. Using (29) and (30), these two conditions are equivalent to

$$f_{ld} > f_{1d}, \qquad f_{ld} > f_{2d}. \quad (31)$$

These conditions have the following intuitive explanation, if the relay-destination channel is worse than the user-destination channel then it is better to have the user transmit his packets. It is clear from the above that TDMA can offer better performance for the user whose condition in (31) is violated. This calls for the development of an enhanced version of protocol S^2 that takes this into account.

B. Enhanced Protocol $S^{2,e}$

The previous discussion leads to the design of an enhanced version of system S^2, which we refer to as $S^{2,e}$. In this enhanced system, the relay only helps the users which are in worst channel condition than the relay himself. In other words, the relay helps the user whose outage probability to the destination satisfy the following inequality $f_{ld} > f_{id}$ for $i \in \mathcal{M}$. For other users who do not satisfy this inequality, they just operate as in conventional TDMA, i.e., the relay never helps them.

Next we calculate the stability region for the enhanced system. Assume that the relay only helps user 1. Similar to our calculations for the arrival and service processes for the relay in system S^2, we can show that the average arrival rate to the relay in system $S^{2,e}$ is given by

$$E(X_l^t(S^{2,e})) = \frac{\lambda_1}{P_1}(1 - f_{1d})f_{1l}, \quad (32)$$

and the average service rate to the relay is given by

$$E(Y_l^t(S^{2,e})) = \left(\omega_1(1 - \frac{\lambda_1}{\omega_1 P_1}) + \omega_2(1 - \frac{\lambda_2}{\omega_2 f_{2d}})\right). \quad (33)$$

Using Loynes and equations (32) and (33), the stability region $\mathcal{R}(S^{2,e})$ is given by

Corollary 4.1: The stability region for an M-users $S^{2,e}$ protocol is given by

$$\mathcal{R}(S^{2,e}) = \Big\{(\lambda_1, \lambda_2, \cdots, \lambda_M) \in R^{+M} : \sum_{i \in \mathcal{M}_1} \frac{\lambda_i}{P_i}\left((1 - f_{id})f_{il} + f_{ld})\right) + \sum_{j \in \mathcal{M}_1^c} \lambda_j \frac{f_{ld}}{f_{jd}} < f_{ld}\Big\}. \quad (34)$$

where $\mathcal{M}_1 = \{i \in \mathcal{M} : f_{ld} > f_{id}\}$, or the set of users that the relay helps.

The stability region for the enhanced protocol $S^{2,e}$ is no less than the stability region of TDMA.

$$\mathcal{R}(TDMA) \subseteq \mathcal{R}^{2,e} \quad (35)$$

The proof simply follows from the construction of the enhanced protocol $S^{2,e}$.

V. Numerical Results

We consider the two users scenario depicted in Fig. 1. The propagation path loss is taken equal to $\gamma = 3.7$ and the SNR threshold $\beta = 15dB$. The transmitted signal power is $P =$ 10mW, and the noise power is $N_o = 10^{-11}$. In Fig. 2 the values of the distances among the 2-users, relay, and access point are indicated on the top of the figure. Note that the distance from user 1 to the access point is equal to that from the relay to the access point, and hence all the stability regions intersect at the λ_1 axis. In Fig. 3, the relay it taken to be closer to the access point than the two users. In both scenarios, it is obvious that the stability region of S^1 is contained inside that of $S^{2,e}$. Note that the boundary for the stability region of S^1 is in general not differentiable.

Next we study the energy efficiency of protocol $S^{2,e}$ and compare it to conventional TDMA. By energy efficiency we mean the average energy required per successfully transmitted packet and can be defined for user $i \in \mathcal{M}$ as follows

$$E_{eff,i} = P\overline{N}_i, \quad (36)$$

where P is the energy per transmitted packet (assuming unit length packets), and $\overline{N}_i$ denotes the average number of retransmissions until the successful reception of the packet.

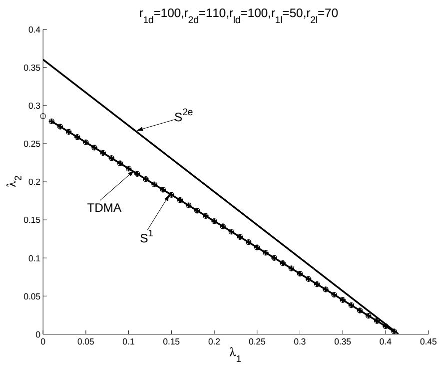

Fig. 2. Stability regions of the proposed protocols. User 1 and the relay are at equal distances from the AP.

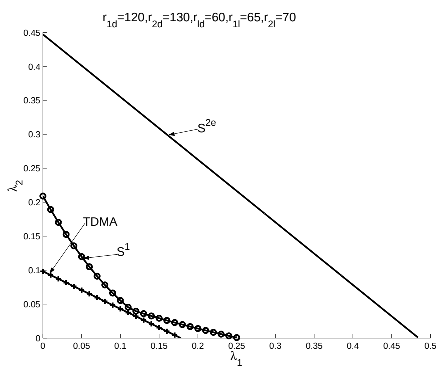

Fig. 3. Stability regions of the proposed protocols. The relay is closer to the AP.

For TDMA, the random variable N_i is a geometric random variable with parameter f_{id}. Therefore the effective energy for user i in TDMA is given by

$$E_{eff,i}(TDMA) = \frac{P}{f_{id}}. \tag{37}$$

For protocol $S^{2,e}$, we need to calculate the quantity $\overline{N}_i$ taking into account both the possible transmissions from the user and the relay. Using the law of total probability, the probability that the random variable N_i equals $n \geq 1$ is given by

$$\mathcal{P}(N_i = n) = \sum_{m=1}^{n} \mathcal{P}(N_{ui} = m, N_l = n - m), \tag{38}$$

where N_{ui} denotes the number of transmissions from user i, and N_l denotes the number of transmissions from the relay.After some calculations that are omitted here for lack of space, the effective energy for protocol $S^{2,e}$ is given by

$$E_{eff,i}(S^{2,e}) = \frac{P(f_{ld} + (1 - f_{id})f_{il})}{P_1 f_{ld}}. \tag{39}$$

We compare the performance of TDMA and protocol $S^{2,e}$ under varying the average transmitted power P. For the simplicity of presenting the results we consider a symmetric users case. Fig. 4 depicts the average number of transmitted packets per successfully received packet for both protocols. It

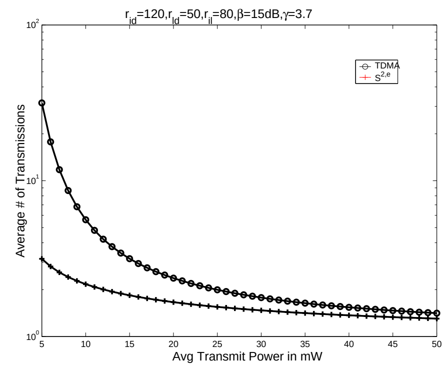

Fig. 4. Average number of transmissions per successfully transmitted packet as a measure for the energy efficiency of the multiple access protocol.

is clear that protocol $S^{2,e}$ can achieve higher energy savings.

VI. Conclusions and Future Work

In this paper, we proposed a new cooperative multiple access approach for relay-based wireless networks under a TDMA framework. The proposed protocol does not incur the system any bandwidth loss as cooperation is only done during empty time slots. Our stability analysis of the proposed protocols reveal an increase in the stability region compared to TDMA without relaying, hence, higher throughput can be achieved. Our analysis and numerical results illustrate that our proposed cooperative multiple access protocol can *simultaneously* achieve higher network throughput capacity and lower average energy requirements compared to TDMA. Future work includes looking into the multi-relay scenario, and characterizing the delay performance of the proposed protocols.

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