# Relay Selection for Energy-Efficient Cooperative Media Access Control

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*Abstract*— **In this paper, we design an energy-efficient cooperative Medium Access Control (MAC) protocol combined with physical layer power / rate control in order to minimize the energy consumption. Based on the Channel State Information (CSI) and relay-to-destination distance, the potential candidate relays carry out autonomous decisions for minimizing the transmission power required for forwarding their data, when relying on their cooperation. Simulation results demonstrate that our scheme is capable of providing considerable energy savings, while maintaining the target Frame Error Ratio (FER), which is achieved at the cost of introducing a modest additional MAC overhead.**

## I. Introduction

The energy consumption of wireless networking may be beneficially reduced by exploiting a range of cooperative communications techniques, which have recently attracted substantial research attention [1], [2]. However, the original higher layer protocols such as for example those of the 802.11 system have not been designed for cooperative communications and hence they may erode the benefits of cooperative communications all together. Hence, it is very important to appropriately design the higher layer protocols, especially the Medium Access Control (MAC) protocol for cooperative systems.

The contributions found in the literature on designing cooperative MAC protocols may be classified into two categories according to the number of relay nodes involved in cooperation, namely into multiple relay aided and single relay assisted scenarios. Multiple relay selection is capable of offering considerable throughput improvements and outage probability reduction, albeit at the cost of eroding the energy efficiency [3]–[5], unless sophisticated cross-layer-operation aided physical layer processing, such as advanced beamforming, is employed [6]. On the other hand, single relay selection aided cooperation is capable of providing beneficial energy savings [7], [8], although they tend to complicate the protocol design. More explicitly, Liu *et al.* [7] proposed a single relay selection aided MAC protocol, where each low data rate node has to maintain a cooperative parameter table in order to record all the required information of the potential candidate relays. As a result, a large amount of extra control messages are required in order to collect the associated information. Hence, more energy is consumed by exchanging the control messages and updating the cooperative parameter table. By contrast, Zhou *et al.* [8] proposed an energy efficient single relay selection scheme, which exploited the prevalent Channel State Information (CSI) in order to minimize the total energy consumption and hence to maximize the network's lifetime. In their scheme, the best relay candidate broadcasts a beacon message in order to inform all other candidate relays about its cooperative transmission for the sake of preventing collisions. Nevertheless, hidden nodes may introduce potential collisions by adopting this selection scheme. To the best of the authors' knowledge, the hidden node problem has not been treated in the context of distributed cooperative MAC protocols, although the potential collisions were already noted in the literature [8].

Against the above background, this paper proposes an autonomous MAC layer protocol relying on single relay selection and incorporates a physical layer power / rate control technique for the sake of minimizing the network's energy consumption, where the main distinguishing aspects of our protocol are:

1) *We specifically design the cooperative MAC layer protocol by considering the hidden node problem and the resultant collision issues.*
2) *We exchange the order of data and control messages so that correct reception can be guaranteed at the relays.*
3) *We design a cooperative retransmission regime activated at the source for recovering the unsuccessful cooperative transmissions, which may also be invoked for direct non-cooperative transmissions.*

The rest of this paper is organized as follows. The details of our protocol design and the power / rate control approach are described in Section II. In Section III, the performance of our proposed scheme is evaluated and analysed. Finally, we conclude in Section IV.

## II. Protocol Description

### A. Configurations and Assumptions

Before introducing the cooperative MAC protocol advocated, the following assumptions are made:

1) Consider a cooperative network topology, which consists of a single source $\mathcal{S}$ as well as destination $\mathcal{D}$ and a total of $N$ relays $\mathcal{R} = \{\mathcal{R}_1, \ldots, \mathcal{R}_N\}$, as seen in Fig 1. We define a transmission burst as a single transmission attempt, excluding any subsequent retransmission attempts. All the channels involved are assumed to undergo quasi-static fading, hence the complex-valued fading envelope remains constant during a transmission burst, while it is faded

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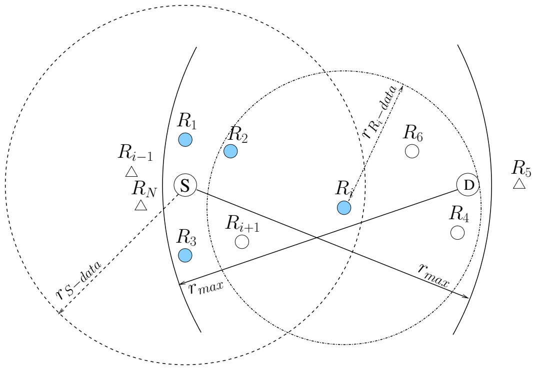


Fig. 1. The cooperative topology consists of one source $\mathcal{S}$, one destination $\mathcal{D}$ and a total of $N$ relays $\mathcal{R} = \{\mathcal{R}_1, \ldots, \mathcal{R}_N\}$.

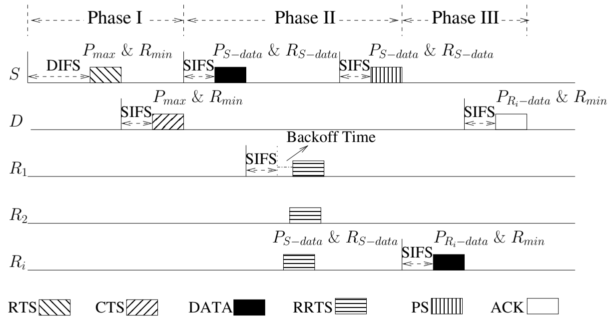


Fig. 2. The overall signalling procedure. RTS: Request-To-Send; CTS: Clear-To-Send; RRTS: Relay-Request-To-Send; PS: Please-Send; ACK: Acknowledgment; DIFS: Distributed Interframe Space; SIFS: Short Interframe Space.

independently between the consecutive transmission bursts.

2) Within a given transmission burst, the duplex bi-directional channels between a pair of actively communicating nodes are assumed to be identical, while the channels of any of the remaining links are independent. We assume perfect channel estimation for all nodes for their own channels, but no knowledge of the remaining links is assumed. Indeed, accurate channel estimation is feasible in low-velocity wireless environments, such as indoor Wireless Local Area Networks (WLAN). We consider the combined effects of flat Rayleigh fading as well as free-space pathloss that is modeled by $\rho = \lambda^2/16\pi^2 d^\eta$, where $\lambda$ represents the wave-length, $d$ is the transmitter-to-receiver distance and $\eta$ denotes the pathloss exponent which is set to $\eta = 2$ [9].
3) We define the transmission duration as $T$ and the transmission rate as $R = 1/T$. For simplicity, we assume a direct reciprocal relationship between $T$ and $R$. Hence, the maximum transmission energy becomes $E_{max} = P_{max}/R_{min}$, where we assume that all nodes are limited by the same maximum transmission power $P_{max}$ and only the transmissions involving the source have the flexibility of employing different transmission rates corresponding to adaptive-rate channel coding and adaptive modulation modes, such as QPSK, 16-QAM and 64-QAM.

Based on the Request-To-Send (RTS) / Clear-To-Send (CTS) signalling of the IEEE 802.11 protocol, we develop an autonomous cooperative MAC protocol that selects the best relay from a set of $N$ potential relays, as illustrated in Fig 1. The proposed signalling procedure is detailed in Fig 2, which includes three phases, as detailed below.

### B. Phase I: Initialization

Before the source node transmits any data frame, it issues a RTS message at the maximum transmission power $P_{max}$ and the minimum transmission rate $R_{min}$ for reserving the shared channel similar to the legacy IEEE 802.11 protocol, as shown in Fig 2. When the destination receives the RTS message correctly, it replies with a CTS message, again, employing the maximum transmission power $P_{max}$ and the minimum transmission rate $R_{min}$, as shown in Fig 2. Since a reciprocal channel is assumed, the correct reception of RTS at $\mathcal{D}$ implies the correct reception of CTS at $\mathcal{S}$. The instantaneous transmission ranges of the sources are illustrated in Fig 1.

To elaborate a little further, we include the transmitter's position information into the RTS and CTS signalling frame, thus any relay nodes in set $\mathcal{R}$ which can overhear both the RTS and CTS messages will be aware of the imminently forthcoming transmission, as well as of the position information of the source and destination. Hence, these relay nodes - which are denoted by filled or hollow circles in Fig 1 - form a potential cooperative relay set $\mathcal{R}_c \subset \mathcal{R}$, where the information of the source-to-relay distance $d_{\mathcal{S}\mathcal{R}_i}, \forall i \in \mathcal{R}_c$, the relay-to-destination distance $d_{\mathcal{R}_i\mathcal{D}}, \forall i \in \mathcal{R}_c$ and the source-to-destination distance $d_{\mathcal{S}\mathcal{D}}$ become available to each of the relay nodes belonging to the set $\mathcal{R}_c$.

### C. Phase II: Relay Selection

After the initialization phase, the relay selection procedure is constituted by a data transmission and two beacon message exchanges, as detailed below.

*1) Step I: Call for Cooperation:* As seen in Fig 2, after receiving the CTS message from the destination, the source node waits for a Short Interframe Space (SIFS) interval, before broadcasting the data frame at a *reduced* transmission power of $P_{\mathcal{S}-data}$ or an *increased* transmission rate of $R_{\mathcal{S}-data}$. It is important to note that the specifically selected transmission power of $P_{\mathcal{S}-data}$ or the transmission rate of $R_{\mathcal{S}-data}$ is included in the data frame so as to allow the relay node to reply to the source with a beacon message employing the same transmission power or rate [1]. As a result, the transmission energy consumed by the source is $E_{\mathcal{S}-data} = P_{\mathcal{S}-data}/R_{min}$ or $E_{\mathcal{S}-data} = P_{max}/R_{\mathcal{S}-data}$. More explicitly, when the reduced transmission power strategy is used, the source may either transmit at a power of

$$P_{\mathcal{S}-data} = \beta P_{max}, \qquad \beta \in (0, 1), \tag{1}$$

[1]In the IEEE 802.11 standard, SIFS is defined as the time from the end of the last symbol of the previous frame to the beginning of the first symbol of the subsequent frame at the air interface. A station should wait for a SIFS period, before sending an ACK frame, a CTS frame and the second or subsequent data frame of a fragment burst [10].

or may obey the transmit power defined as

$$P_{\mathcal{S}-data} = \frac{1}{2}\frac{\gamma_{R_{min}} P_N}{\rho |h_{\mathcal{S},\mathcal{D}}|^2}, \quad (2)$$

where $P_N$ and $|h_{\mathcal{S},\mathcal{D}}|$ represent the power of Additive White Gaussian Noise (AWGN) and the gain of the flat Rayleigh channel between the source $\mathcal{S}$ and the destination $\mathcal{D}$, respectively. Furthermore, $\gamma_{R_{min}}$ is the corresponding minimum required Signal to Interference plus Noise Ratio (SINR), when employing a rate of $R_{min}$ for achieving an acceptable physical layer integrity quantified for example in terms of the Frame Error Ratio (FER). Since the FER is a monotonically decreasing function of the SINR, we will use the FER as our physical layer performance metric. We refer to the power assignment regime based on Eq (2) as the source-adaptive power control.

*Remarks:* Both our power-and-rate adjustment strategies aim for reducing the transmission energy consumption. Transmission at an increased rate necessitates an increased SINR at the receiver for achieving an acceptable physical layer FER. Hence, when the transmission power remains constant, increasing the transmission rate typically leads to a reduced transmission range, since usually an increased SINR is required. This, in principle, may be deemed equivalent to the reduced-power transmission strategy. However, maintaining a constant transmission power while varying the transmission rate is always more desirable from a network stability perspective, rather than ramping up the power in the interest of maintaining the target FER.

*2) Step II: Relay Ready to Cooperate:* If a relay node $\mathcal{R}_i \in \mathcal{R}_c$ received the data frame correctly, it calculates the minimum transmission power $P_{\mathcal{R}_i-data}$ that is required for successfully forwarding the data frame to the destination by employing the minimum possible transmission rate of $R_{min}$. This may be achieved by assuming the knowledge of the channel between relay $\mathcal{R}_i$ and the destination $\mathcal{D}$. This channel may be deemed to be identical to the channel estimated during the reception phase of $\mathcal{R}_i$, provided that the $\mathcal{R}_i$-$\mathcal{D}$ and $\mathcal{D}$-$\mathcal{R}_i$ links use the same carrier-frequency in a Time-Division-Duplex (TDD) fashion. More explicitly, the above-mentioned transmission power is given by:

$$P_{\mathcal{R}_i-data} = \frac{\gamma_{R_{min}} P_N}{\rho |h_{\mathcal{R}_i,\mathcal{D}}|^2}, \quad (3)$$

where $|h_{\mathcal{R}_i,\mathcal{D}}|$ represents the gain of the flat-fading Rayleigh channel between relay $\mathcal{R}_i$ and the destination $\mathcal{D}$.

Given the knowledge of the transmission power $P_{\mathcal{R}_i-data}$, if the sum of $E_{\mathcal{R}_i-data} = P_{\mathcal{R}_i-data}/R_{min}$ and $E_{\mathcal{S}-data}$ - where $E_{\mathcal{S}-data}$ was extracted from the data frame - is less than the maximum affordable transmission energy consumption of $E_{max}$, then the relay node $\mathcal{R}_i$ would be activated during the contention period after a SIFS interval has elapsed, as seen in Fig 2. Hence, the relay nodes which decide to contend for the shared channel form a smaller contending set of $\mathcal{R}_{cc} \subset \mathcal{R}_c$. These relay nodes are represented as filled circles in Fig 1.

Given the contending set $\mathcal{R}_{cc}$, the specific relay that has the shortest relay-to-destination distance $d_{rd}$ is granted the highest priority, hence it will return a Relay-Request-To-Send (RRTS) message to the source node earlier than the other relays in $\mathcal{R}_{cc}$ at the predefined transmission power of $P_{\mathcal{S}-data}$ or transmission rate of $R_{\mathcal{S}-data}$. The remaining nodes in the contending set $\mathcal{R}_{cc}$ will send RRTS messages to the source in the specific order of their priority, as seen in Fig 2. To elaborate a little further, the RRTS message is capable of informing the source about the relay's correct reception and its intention to cooperate. The format of the RRTS frame is the same as that of the RTS frame, which has both a transmitter address field and a receiver address field for the sake of enabling the source to uniquely recognize the different relay nodes. More explicitly, based on the position information of the source and the destination, relay $\mathcal{R}_i \in \mathcal{R}_{cc}$ simply generates its priority coefficient defined as the distance-ratio of:

$$\alpha_{\mathcal{R}_i} = \frac{d_{\mathcal{R}_i\mathcal{D}}}{d_{\mathcal{S}\mathcal{D}}}. \quad (4)$$

In the proposed relay selection scheme, the source prefers to recruit the specific relay node, which has the shortest relay-to-destination distance, since the relay suffers from the lowest pathloss. Before issuing the RRTS message, the relay $\mathcal{R}_i \in \mathcal{R}_{cc}$ has to wait for a SIFS interval and for a subsequent back-off time, as seen in Fig 2. Given the priority coefficient, i.e. the distance-ratio, the back-off time $T_{\mathcal{R}_i,bo}$ is written as:

$$T_{\mathcal{R}_i,bo} = \alpha_{\mathcal{R}_i} T_w, \quad (5)$$

where $T_w$ is the contention window length, which equals to the length of a SlotTime [2]. In the spirit of Eq (5), the best relay candidate will wait for the shortest time before reserving the channel.

*Remarks:* In contrast to the solution of [7], our proposed single relay selection acts in a *unilateral* fashion, where the relay or the source does not have to exchange detailed information with the other relay nodes, since each node executes the decision autonomously. Additionally, instead of incorporating the priority information into the data or control frame, which inevitably leads to a frame-length extension and to a potential transmission energy wastage, different back-off periods are used to reflect the specific priorities of relays.

*3) Step III: Source Accepts Relay for Cooperation:* The source appoints the relay associated with the first correctly received RRTS message as the best relay. Following the elapse of a SIFS interval, the source transmits the Please-Send (PS) message to the best relay at the transmission power of $P_{\mathcal{S}-data}$ or at the transmission rate of $R_{\mathcal{S}-data}$, as seen in Fig 2. In order to guarantee that only the best relay node forwards its data message to the destination, we introduce the above-mentioned PS message into the legacy IEEE 802.11 MAC protocol, where the format of the PS frame is the same as that of the ACK frame, which includes the receiver's address. Since the source sends its

[2]In the IEEE 802.11 standard, a SlotTime consists of the time required to physically sense the medium and to declare the channel as "clear", plus the MAC processing delay, the propagation delay, and the "receiver/transmitter turn-around time" which is the time required for the physical layer to change from receiving to transmitting at the start of the first bit. It may be used to measure the time required by a station to detect the transmission of a frame from another station [11].

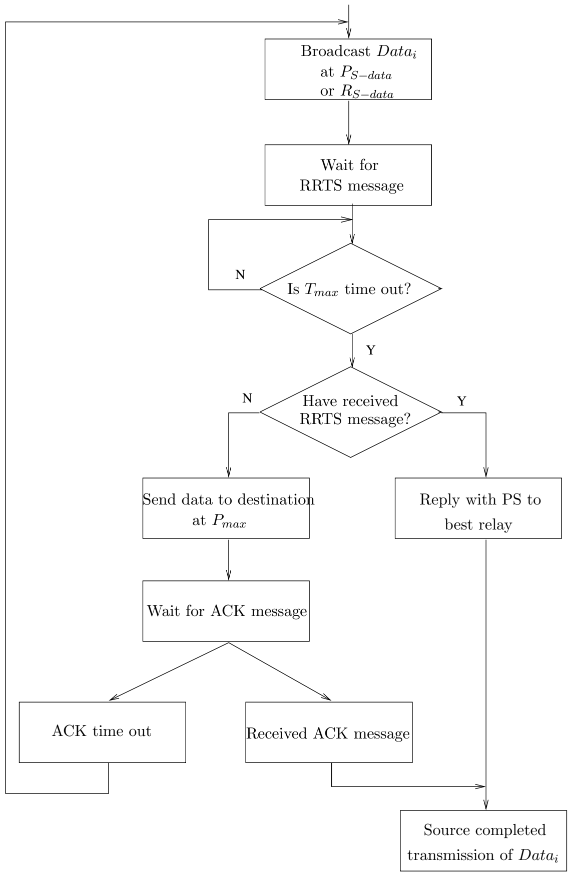


Fig. 3. The flow chart of source retransmission.

data frame and PS message at the same transmission power or rate, all the relay nodes $\mathcal{R}_i \in \mathcal{R}_{cc}$, which correctly received the data frame from the source previously, will overhear the PS message. This guarantees that only the best relay forwards its data frame to the destination. If we opt for dispensing with the PS message required for the best relay's transmission, an alternative solution would be to allow the relay node having the highest priority to broadcast a RRTS message to all other nodes. Hence the rest of the relay nodes would not broadcast their own RRTS messages to indicate their intention to cooperate, when they overhear the best relay's RRTS message during their back-off time. However, if some of the relay nodes roam outside the adequate reception range of this RRTS message, these more distant relay nodes remain oblivious of the best relay's RRTS message and hence will also forward their data to the destination, thus collisions occur.

*Remarks:* One of the distinguishing design aspects of our solution w.r.t. the existing literature [8], is that we allow the source to broadcast its data frame before exchanging control messages, which would be typically required for the best relay selection. If the source only sent a data frame to the best relay after exchanging control messages, the best relay may receive the data frame contaminated by decision errors that leads to a potential loss of the data frame. However, this potential problem is resolved by our proposed scheme, since only the specific nodes, which receive the data frame correctly will be employed as relay nodes.

TABLE I

MAIN PARAMETERS OF THE SIMULATION.

| | |
|---|---|
| $P_{max}$ | $2\ mW$ |
| $R_{min}$ | $1\ bit/symbol$ |
| Data Length | $1024\ Bytes$ |
| SlotTime | $20\ \mu s$ |
| SIFS | $10\ \mu s$ |
| Modulation | QPSK, 16-QAM, 64-QAM |
| Channel Coding | 1/2 Convolutional Code |
| FER Threshold | 0.1 |
| $\gamma_{th-cc-QPSK}$ | $5.96\ dB$ |
| $\gamma_{th-cc-16QAM}$ | $12.26\ dB$ |
| $\gamma_{th-cc-64QAM}$ | $17.66\ dB$ |

### D. Phase III: Data Forwarding

If the relay node $\mathcal{R}_i \in \mathcal{R}_{cc}$ received the PS message from the source, it will forward the data frame to the destination at its pre-calculated transmission power of $P_{\mathcal{R}_i-data}$ after a SIFS period, acting as the best relay, as seen in Fig 2. On the other hand, if none of the relay nodes received the data frame correctly or multiple RRTS messages collided at the source, or alternatively, the RRTS messages are corrupted due to the fading, the source will directly transmit its data frame to the destination at the maximum transmission power of $P_{max}$ and the minimum transmission rate of $R_{min}$, as shown in Fig 3. Finally, at the destination, the classic Automatic Repeat reQuest (ARQ) will be initiated, when receiving the forwarded data and then the ACK message is issued in order to reply to the source or the relay. Consider the source's retransmissions for example in the scenario, when the source does not receive any response from the destination before the timer set for waiting for an ACK message is expired. Then the source will broadcast its data again at $P_{S-data}$ in order to seek cooperation and the procedure described above for relay selection is repeated. The procedure of source retransmission is also characterized in Fig 3, which includes both the relay selection procedure and the source's direct transmission.

## III. SIMULATION RESULTS

Let us now opt for presenting our simulation results generated using Omnet++ for evaluating the achievable performance of the proposed protocol. In our Omnet++ simulations, all the relay nodes are randomly distributed across the entire network area, while the source and destination have fixed positions. In order to evaluate the performance effectively, we adopt the common assumption that the control messages are received without errors and compare the attainable performance to that of the bench-marker constituted by the non-cooperative direct source-to-destination transmission using $P_{max}$ based on the classic RTS/CTS signalling. Furthermore, we employ QPSK and a half-rate convolutional code, yielding a throughput of 1 bit/symbol as our standard minimum transmission rate of unity. We define the maximum tolerable physical layer FER as 0.1 and find the corresponding SINR threshold by Monte Carlo simulations. Then we modelled the associated FER curve by polynomial curve-fitting. The number of nodes

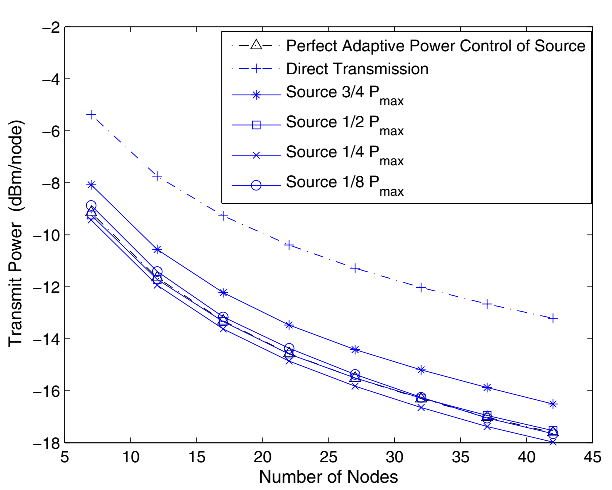


Fig. 4. Transmit power as a function of network size when using different power control strategies.

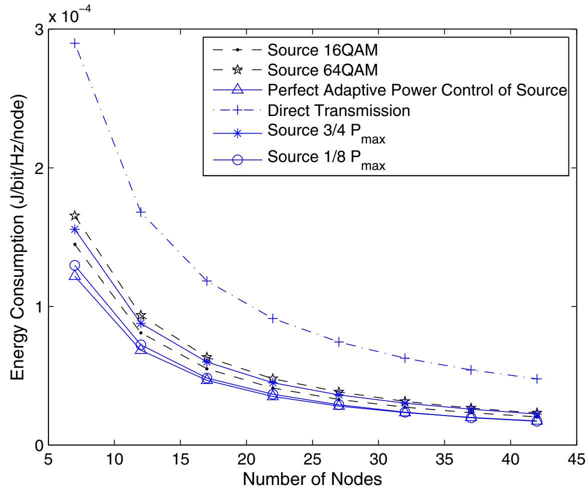


Fig. 6. Energy consumption as a function of network size when using both power and rate control strategies.

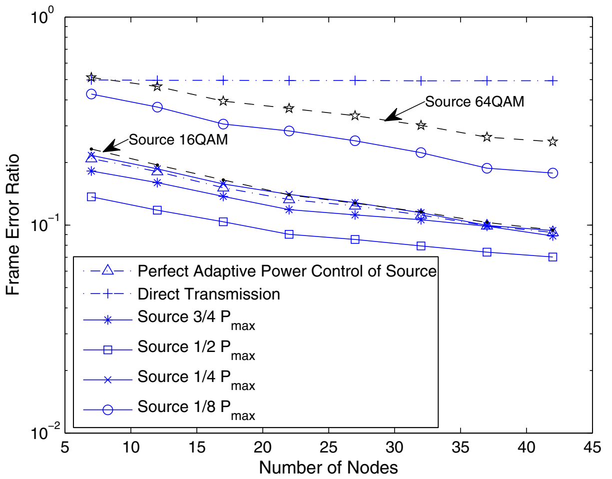


Fig. 5. Frame error ratio as a function of network size when using different power control strategies.

was ranging from 7 to 42 in order to investigate the effects of node density on the achievable network performance. The main system parameters employed are listed in Table I.

### A. *Effect of Different Transmission Powers*

Based on the fixed transmission rate of unity, we investigate different transmission power control strategies invoked by the source in order to broadcast its data frames in Step I of Phase II. The power consumption and the FER performance are characterized in Fig 4 and Fig 5, respectively. Since a fixed transmission rate is employed, the power consumption metric is equivalent to the energy consumption metric. Observe in Fig 4, that the proposed cooperative MAC protocol associated with different power control configurations is capable of achieving a significant power saving compared to direct non-cooperative transmission. Quantitatively, in excess of $3dBm/node$ transmit power reduction is achieved w.r.t. classic direct transmissions, when the source uses a fraction of $\beta = 3/4$ of $P_{max}$ for its data in a network hosting 32 nodes. However, a slightly better performance is achieved by all the other source power allocations. As a further benefit, it can be seen in Fig 5 that our proposed cooperative MAC relying on different power control configurations is also capable of reducing the FER, albeit our main design objective is that of reducing the energy consumption, whilst satisfying the target FER [3]. To elaborate a little further, the best FER is 0.08, when the configuration of $\beta = 1/2$ is used to assign half of $P_{max}$ to the source and the number of nodes is 32. Furthermore, both the power consumption as well as the FER of the proposed cooperative MAC protocol decreases gradually, as the network becomes larger, since the number of potential candidate relays increases.

When comparing different power control configurations, it can be seen in Fig 4 that the faction of $\beta = 3/4$ configuration reduces the power by $3.2dBm/node$, while the $\beta = 1/4$ configuration saves about $4.6dBm/node$, when the number of nodes is 32. On the other hand, it can be seen in Fig 5 that the $\beta = 1/2$ configuration provides the best FER, which is under 0.1 when the network supports more than 17 nodes. By contrast, the $\beta = 1/8$ configuration has the highest FER, which remains high even when the number of nodes is 42. The rest of the configurations have similar FER performances. These investigations imply that there is no single configuration which achieves the best performance in terms of both the power consumption and the FER, albeit the $\beta = 1/2$ configuration strikes a good compromise, since it can provide significant power savings while guaranteeing the lowest FER [4].

### B. *Effect of Different Transmission Rates*

The energy consumption may also be reduced by increasing the transmission rate, while maintaining the max-

[3]In this context we note that reducing the transmit power of the source does not imply increasing the relay's power, since our goal is again to 'just' satisfy the target FER at the lowest possible energy consumption. This is in contrast to the conventional relaying assumption of having a total power of unity.

[4]Again, we emphasize that our design objective is the minimization of the energy consumption, whilst satisfying the $FER = 0.1$ constraint.

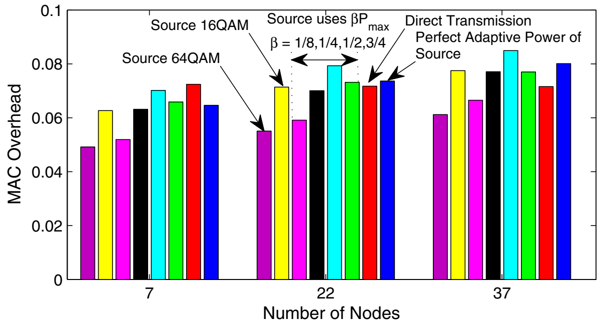


Fig. 7. MAC overhead of different transmission strategies.

imum transmission power $P_{max}$, as shown in Fig 6. Compared to the direct non-cooperative transmission, the energy consumption was also noticeably reduced, when the source employs 16QAM or 64QAM. Since the FER of 16QAM is lower than that of 64QAM, as seen in Fig 5, the transmission range of 16QAM becomes higher at a given transmission power and prevalent channel conditions. As a result, employing 16QAM results in a potentially higher number of candidate relays and hence it also outperforms 64QAM in terms of its energy consumption, as shown in Fig 6. When compared to the different transmission power adaptation configurations characterized in both Fig 5 and Fig 6, the 64QAM transmission strategy performs the worst. By contrast, it can also be observed that the 16QAM transmission strategy outperforms the $\beta = 1/8$ power control configuration in terms of its FER and the $\beta = 3/4$ power control configuration in terms of its energy consumption.

### C. Effect of MAC Overhead

Finally, Fig 7 compares the MAC overhead of the different transmission strategies, which is defined as the ratio of the number of bits of all MAC control messages plus the sum of the header and tailing bits of the MAC data frame related to the number of bits in the payload data packet. It can be seen in Fig 7 that the overhead of our cooperative MAC protocol increases as the network becomes larger, because more RRTS messages are generated, when the number of potential relays increases. Furthermore, for direct non-cooperative transmission, a RTS message is issued whenever the source intends to retransmit the data to the destination. By contrast, in our scheme the source will retransmit the data without any extra control message exchange with the destination. Hence, the proposed cooperative retransmission scheme is capable of reducing the overhead, when retransmissions are required. More specifically, Fig 5 and Fig 7 reflect the classic tradeoff between the achievable FER and the MAC overhead imposed, i.e. the lower the FER, the higher the overhead imposed.

Overall, observe in Fig 4, Fig 5 and Fig 7 that although the configuration of $\beta = 1/2$ exhibits the lowest FER, its overhead is only marginally higher than that of the $\beta = 1/8$ configuration. Therefore, the configuration of $\beta = 1/2$ still tends to be the best compromise, when considering the achievable energy efficiency, FER as well as MAC overhead.

## IV. Conclusions

In this paper, a novel energy-efficient cooperative MAC scheme was proposed, which relies on an autonomous relay selection regime combined with physical layer power / rate control. When compared to the non-cooperative direct transmission regime, the proposed scheme is capable of achieving considerable transmission energy savings and beneficial FER reductions at the cost of introducing a modest MAC overhead, which is at most 8 %, when a 1024-byte data frame is assumed. In terms of the transmission power control strategy, the $\beta = 1/2$ arrangement appears to be the best cooperative option. If the source prefers to minimize its transmission energy by adjusting the transmission rate, 16QAM provides a satisfactory performance.

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