Cooperative MAC protocol with distributed relay selection and physical rate adaptation

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***Abstract*— In this paper, a new cooperative MAC protocol with distributed relay selection and rate adaptation is proposed in the context of multi-rate ad hoc networks. When the wireless link between a source and a destination nodes experiences poor channel conditions, a relay station is selected in the vicinity of both nodes so that the low data rate direct link is replaced by a two-hop path with a higher data rate. The relay station is selected through a distributed contention process. The procedure requires no topology knowledge and no communication among potential relays. A data rate adaptation is also performed without any additional signaling. The best-relay selection and the rate adaptation are based on instantaneous channel measurements to adapt to dynamic channel conditions. Results show that cooperative transmissions significantly outperform conventional non-cooperative transmissions in terms of throughput, delay and energy consumption.**

I. Introduction

The throughput of IEEE 802.11-based wireless networks is highly affected by wireless channel impairments, such as interference and fading. It also depends on the presence of low data rate nodes. In multi-rate wireless networks, nodes with lower data rates occupy the channel for a longer time in order to transmit the same amount of data. This rate anomaly problem causes a decrease in the overall network throughput [1]. This problem can be tackled using cooperative communications. In a cooperative transmission scheme, the direct link with a low data rate between a source node *S* and a destination node *D* is replaced by two relayed links with higher data rates: one link from *S* to a relay node *R*, and a link from *R* to *D*. The purpose of our work is to improve the efficiency of cooperative protocols in terms of throughput by taking into account rate adaptation mechanisms (RAAMs) in the design of the protocols. The motivation for this is that RAAMs are already implemented in IEEE 802.11 cards and their functioning may modify the rate selection that is performed at the cooperative protocol level. Note that RAAMs are not part of the IEEE 802.11 standard. The most widely deployed RAAMs involve sender-based approaches, such as the Auto Rate Fallback (ARF) protocol [2], that rely on channel statistics, and receiver-based approaches, such as the Receiver-Based AutoRate (RBAR) protocol [3], that rely on instantaneous channel state information (CSI). Channel statistics are based on the history of previous transmissions whereas the CSI is based on instantaneous channel measurements such as the Signal to Noise Ratio (SNR). CSI-based protocols are considered as being more reactive than statistics-based protocols.

Several cooperative protocols have been already proposed in order to replace a low data rate direct transmission link by a relayed transmission link supporting higher data rates [4][5][6]. The multi-rate capability of the IEEE 802.11 protocol has also been considered in [7][8]. A common feature is that the relay node is chosen in a reactive way. In contrast, in CoopMAC [9] and in rDCF [10], a relay is selected in a proactive way from a relay-nodes table. This table is updated based on either passive listening to ongoing traffic or on exchanging a willing list proposed by the potential relays. The point here is that the RAAMs are independent from the cooperative protocols; hence the data rate selected by the latter may be different from the data rate provided by the former.

A cooperative protocol implementing the RBAR rate adaptation mechanism (CRBAR) has been proposed in [11]-[12]. This protocol uses two relaying modes. The first mode, uses a simple relaying without combining data packet at the destination *D*. In the second mode, a Maximum Ratio Combiner (MRC) is used at *D* to combine two copies of data received from both the source *S* and the relay *R*. The data rates have to be the same on the two hops: *S* to *R*, and *R* to *D*. In the first hop, the data rate is computed based on the *S* to *R* link quality. This may prevent the destination terminal from successfully decoding the source message as it is adapted to the single hop source-relay. Furthermore, relay selection choices are restricted to the use of the same data rate on the two links.

Our proposal combines a cooperative protocol with a data rate adaptation mechanism. The improvement over typical reactive and proactive cooperative protocols is the addition of the data rate adaptation feature. The improvements over the approaches in [11]-[12] are as follows. Since no MRC is required, different data rates are now possible over the two wireless links: *S* to *R*, and *R* to *D*. Having just a simple relaying mode could provide more opportunities in maximizing the overall throughput on the *S-R-D* link. Moreover, we found that not all the data rate combinations in the relayed link are beneficial. This is because we take into account the signaling overhead in evaluating the rate combinations. In CRBAR, the cooperation is triggered by the relays when the relayed-link is faster than the direct-link. Even when there is no need for cooperation, the source has to wait for potential relays, for each data transmission, before choosing the direct transmission. In contrast, in our protocol the cooperation decision is made by the destination when it realizes that the direct link quality is bad. This approach allows to the source *S*, delay saving. In addition, in CRBAR, the channel information used for rate adaptation is collected at the receiver and transmitted back to the sender. In our scheme, the rate selection is performed at the sender. This allows more accurate selection as the channel state information is more up-to-date.

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Also, since there is no need to transmit information to the sender, no extra resources are used. Furthermore, our protocol does not change the packet format and requires no information exchange.

The rest of the paper is organized as follows. The proposed protocol is described in Section II. Results are provided in Section III. The conclusions are drawn in Section IV.

II. PROPOSED PROTOCOL

A. The protocol description

The proposed protocol is based on the Distributed Coordination Function (DCF) of IEEE 802.11 standard and is backward compatible with it. The basic idea is to allow nodes to choose a transmission scheme (direct or relayed) and a data rate based upon real-time link measurements. A distributed scheme to select the best relay candidate is implemented. Each potential relay selects itself as the best relay for the cooperation based only on instantaneous local channel information. This way, the selection is reactive to channel and network topology variations. A second mechanism is used to select the most suitable data rate. To make the rate selection more reactive to real-time link variations, the rate is chosen for each data transmission by sensing the signal strength of the control frames. This scheme does not change the format of the control frames. To perform both relay selection and rate adaptation no signaling exchange is required.

Once a source node *S* has a data packet to transmit, it sends an RTS (Ready-To-Send) frame to the destination node *D*. When *D* receives the RTS frame it chooses the transmission scheme (direct, relayed) based on the SINR (Signal to Interference and Noise Ratio) value measured from the RTS frame signal; *D* compares this SINR value with a predefined SINR threshold, denoted by $SINR_{coop}$. Note that the $SINR_{coop}$ threshold is set so that a relayed transmission is selected on the *S-R-D* link only when the direct link data rate is lower than 12 Mbps. So, when the SINR value is greater than $SINR_{coop}$, a direct transmission is implemented and our protocol just reduces to a RAAM (described in subsection *B*). Otherwise, cooperation is triggered and node *D* sends a CCTS (Cooperative Clear-To-Send) frame toward node *S*. The CCTS indicates to *S* that the level of the SINR is very low at *D* and the direct transmission does not allow a high rate. Each node located around *S* and *D* listens to the ongoing control traffic. Upon successful decoding of the RTS frame from *S*, node measures the SINR of the frame and calculates the achievable data rate between itself and node *S* using the RAAM. Also, when node successfully receives the CCTS frame from *D*, it calculates the achievable data rate between nodes *D* and . All the nodes that have successfully passed the two steps mentioned above are considered as being potential relays for the *S-D* pair. These nodes then enter a relay selection phase.

In the relay selection phase, the potential relays use a contention resolution mechanism in order to allow the best relay to access the medium first. The contention resolution mechanism classifies the potential relays into six classes based on their rates and . The classes are presented in the Table I ordered by increasing transmission duration of the relayed link *S-* *-D* (source-relay-destination). Each class corresponds to a relayed transmission mode. The classification order is obtained based on the computed transmission time for different relayed modes. Note that we take into account the overhead introduced by the relays. The potential relays that belong to the A_6 class, do not improve the transmission delay of the direct link. Hence, they are never used in a relayed transmission.

TABLE I: THE DIFFERENT CLASSES OF POTENTIAL RELAYS(MODES)

Class A_j	A1	A2	A3	A4	A5	A6
Rate R_{SRi}-R_{RiD} Mbps	54-54	54-24	24-24	54-12	24-12	12-12

For each relay , the quality of the relayed path *S-* *-D* is described by the SINR measurement. The use of a function that involves the link quality of the two jumps is essential because it expresses the end-to-end performance. We have implemented a function similar to [13].

After classification, each relay triggers a timer T_i that is inversely proportional to the value of *hi* according to:

(*k* is a constant with the unit of time) (2)

The relay with the best end-to-end link quality has the timer with the shortest duration. Hence, according to (2) and (3), the best relay R_b will finish its timer T_b first.

Where is the value of for the best relay and *M* is the number of nodes in the network. It is possible that two relay nodes of two different classes have a very close Timer value T_i, while they belong to two different classes. That is why we favored nodes of each class A_i over the nodes of the class A_{i+1} by adding in each time a duration *t* to the timer T_i of nodes in the class A_{i+1}. The value of *t* represents the maximal propagation time between two nodes distanced by the maximal range. The best relay sends a Clear For Cooperation frame (CFC) to indicate its willingness to participate in data transmission from *S* to *D*. The rest of the relays stop the relay selection phase once they realize that the channel state becomes busy. Then they update their Networks Allocation Vector (NAV) upon receiving the CFC frame from . Canceling the relay selection phase as soon as the channel state changes from idle to the busy state instead of waiting until the end of the CFC reception can reduce the probability of collision between the relays. When *S* successfully decodes the CFC frame, a relayed transmission is initiated after a SIFS (Short Inter Frame Space) duration; *S* sends data to the best relay at the rate and the relay will forward this packet immediately to *D* at the rate . After successfully decoding the data frame by *D*, An ACK frame will be sent directly to the source *S*. In case of a collision between relays of the same class or absence of potential relays, *S* sends the data directly to *D* after a SIFS duration at the rate .

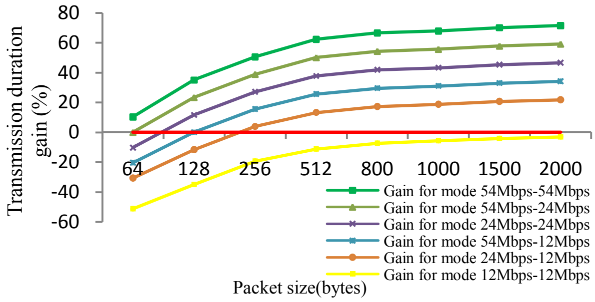

Fig. 1: Transmission duration gain vs. packet size

B. Physical rate adaptation mechanism

The rate adaptation mechanism aims to select the most appropriate rate for data packet, between any two nodes. The selection is based upon SINR measurements made on the received control frame signals. As known, each data rate corresponds to a target SINR threshold value that guarantees a certain bit error rate (BER). When the cooperation is not needed, the destination sends a CTS frame to the source station. When the source receives the CTS frame, it measures the SINR and then selects the corresponding data rate between itself and the destination. Since the channel is assumed to be symmetric, the attenuation between the two nodes is the same in both directions; hence is equal to . In the same way, when the cooperation is needed, each potential relay that receives a CCTS frame measures the SINR and selects the rate to be potentially used to transmit data to the destination. When the source receives the CFC frame it selects the rate between itself and the relay .

The advantages of our approach are threefold. First, the rate selection is performed using real time channel measurements. This approach is more accurate than the ones that use the history of previous transmissions such as the ARF protocol. Second, performing the rate adaptation at the sender allows a more accurate tracking of channel variations compared to the adaptation schemes implemented at the receiver side, such as the RBAR protocol. Third, acquiring this information at the receiver requires transmitting it to the sender. This can be costly; both in terms of resources consumed in transmitting this information as well as the extra transmission delays that potentially affect the timeliness of the information.

C. Network Allocation Vector (NAV) mechanism

The IEEE 802.11 standard defines in the RTS/CTS frames a *duration field* that contains the time value, in microseconds, required to reserve the wireless medium for the current communication. The *duration field* value of the RTS frame is:

where , denote the times required to transmit the DATA, CTS and ACK frames, respectively. The *duration field* of the CTS frame (contains the corresponding time value:

We modify the values of and as follows: the time T_{DATA} is computed considering the basic rate of 6 Mbps. This maximizes the duration over which the channel is referred to as being in a busy state. This has no impact on the protocol performance since this value is updated in either the CTS or the CFC frame. Upon receiving the RTS frame, node *D* measures the received SINR and selects the corresponding data rate . Two cases are possible. When cooperation is not needed, *D* updates the value of T_{DATA} in based on and sends a CTS frame accordingly. Otherwise, when cooperation is needed, *D* sends a CCTS frame with the time value calculated in (5). Upon receiving the CCTS frame, potential relays enter the selection process. When a best relay node is selected, it sends a CFC frame with an updated *duration field* (

where is the sum of two terms: the transmission time from node *S* to the best relay node, and the transmission time from the best relay node to node *D*. Each node updates its NAV each time it receives a control frame. Thus, no NAV problem arises. The problem of hidden terminals can be avoided, since (i) control frames are transmitted at the basic rate and with the highest transmission power; hence have a long transmission range, (ii) current wireless cards have higher power sensibility which leads to a carrier sensing range that is much larger than the transmission range.

III. PERFORMANCE EVALUATION

The performance of our protocol is evaluated and compared to the IEEE 802.11 standard using the extended model IEEE 802.11Ext of the NS2 simulator. We evaluate the throughput, the end-to-end delay, the total energy consumption and the transmission duration gain of cooperative transmissions, in several relayed modes, relative to direct transmission.

Fig. 1 reveals the relationship between the transmission duration gain (%) of cooperative transmissions for several modes and the packet sizes. We observe that the higher the packet sizes, the higher the gain. This is due to the fact that long size packet requires more time to be transmitted in non-cooperative transmission at 6Mbps than cooperative transmissions at different rates. Moreover, the fastest modes give a higher gain than the slowest ones, since the higher rate gives shorter transmission duration than the lower rate. We notice that only the 12-12Mbps mode has a gain below zero. This is because the transmission duration of $DATA_{SR}$ and $DATA_{RD}$ plus the overhead time introduced is larger than the direct transmission duration under the basic rate. Another important observation that we can conclude from this figure is that not all the data rate combinations are beneficial in cooperative transmission. The gain obtained can reach 71% with the 54-54Mbps mode, in 802.11g, and can achieve 75% in IEEE 802.11b with the rate 11-11Mbps. Results in Fig. 1 are obtained analytically and confirmed by simulations.

Fig. 2 gives the throughput comparison as the packet size increases. We can notice that for large packet sizes cooperative protocol outperforms the standard IEEE 802.11 protocol. Nevertheless, for small packet sizes the proposed protocol performs exactly the same as IEEE 802.11. The explanation to these statements comes from the fact that our protocol adds an extra control frame (CFC) to announce the participation of the helper relay in cooperation and a SIFS interval. Thus, it increases the overhead. For small frames, this overhead affects the overall transmission time, cancelling the benefits of cooperation. When the packet size exceeds a certain threshold, the benefits from transmitting the data frame

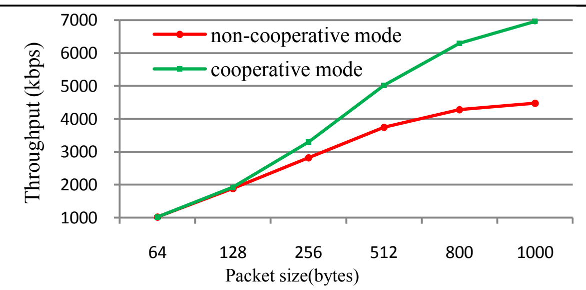

Fig. 2: Throughput in cooperative and non-cooperative mode vs. packet size

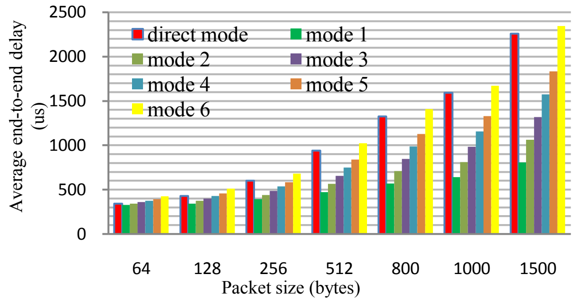

Fig. 3: The average end-to-end delay vs. packet size

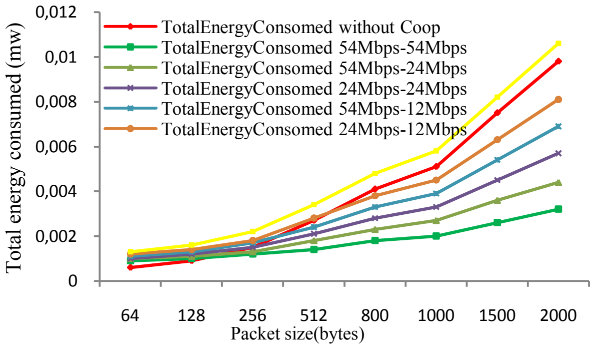

Fig. 4: Total energy consumption for 10 stations in different modes vs. packet size

with cooperation cancel the overhead, and we can see an improvement in the throughput. This improvement is higher as the packet size increases, and it depends also on which mode has been chosen in the cooperative transmission.

Fig. 3 compares the average end-to-end delay for relayed modes with the direct mode for different packet sizes. The end-to-end delay refers here to the average time taken for a packet to be transmitted across a network from the source to the destination. We notice that when the size of the data increases almost all modes have better delay than the non-cooperative mode except mode 6. This mode has a negative gain; this is why the delay is larger than the direct mode.

Fig. 4 gives the total energy consumption for different modes with different packet sizes. We observe that after a certain threshold all modes consume less energy than the non-cooperative mode except for the 12-12Mbps mode. Indeed the transmission duration gain obtained for small packet sizes is not significant. Also, since the direct mode uses a basic rate, the time to transmit and receive data packet is larger than in relayed modes, hence the direct mode consumes more energy than the relayed modes (except the mode 6).

In addition to the improvements that were quoted previously (throughput, energy consumption, delay), other improvements could be found such as: a significant reduction in the interference between ad-hoc cells; with the improvement of the overall throughput, we can reduce the average channel time used by each station to transfer a certain amount of traffic over the network. Hence the SINR between two ad-hoc cells using the same channel can be reduced. Also, a spatial reuse in the sense that neighboring stations can initiate a new transmission earlier than they would otherwise. Furthermore, the stations experiencing bad channel conditions would have probably an important error rate if they choose the direct transmission, but with the cooperative transmission the quality of the signal will be better and hence the error rate is reduced. Moreover, the IEEE 802.11 anomaly [1] caused by low-data rate nodes can be reduced.

IV. CONCLUSION

A significant number of cooperative protocols has been proposed in wireless networks. However, most of the previous works focused on increasing the spatial diversity, or on analyzing the cooperation gain, or on the selection mechanisms, etc., but the rate selection in relaying mode has not been considered in depth. Furthermore, using cooperation in conjunction with a suitable rate adaption algorithm has been addressed only in a few works. In this paper, we proposed a new scheme in which transmitter-receiver pairs that experience bad link quality are assisted by the best intermediate relay node, converting a direct low-rate transmission to a cooperative high-rate transmission. Preliminary results show that it can significantly improve performance of the IEEE 802.11 MAC protocol. The comparison with other schemes is let for future works.

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