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CORELA: A Cooperative Relaying Enhanced Link Adaptation Algorithm for IEEE 802.11 WLANs

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Abstract—One of the key challenges for cooperative relaying multi-rate wireless networks is the integration and interaction of relaying with link adaptation algorithms, in particular under incomplete and/or imprecise channel state information conditions. In this paper we propose a practical cooperative relaying link adaptation medium access protocol that considers the historical link quality to enable the relay terminal to adjust its transmission relaying rate by estimating the error probability based on past packet transmission history. Simulation results show that this protocol achieves significant performance improvement in terms of end-to-end throughput and energy efficiency for different network conditions compared with other link adaptation algorithms. It also has the best performance of the direct transmission without perfect knowledge of current channel condition.

Keywords - cooperative relay, link adaptation, MAC, 802.11

I. INTRODUCTION

Recently a significant amount of research effort has gone into exploring cooperative techniques in the domain of wireless communications, where multiple wireless terminals assist each other in transmission to overcome fading and interference in wireless environments. Different cooperative diversity schemes are proposed in [1]. The simplest form of relaying is the amplify-and-forward (AF) scheme, where the relay terminal simply amplifies and forwards the signals that are acquired from the source. In the decode-and-forward (DF) scheme, the relay terminal decodes the received signals and forwards the re-encoded signals to the destination. Using the latter method, [2] proposes using space-time coding techniques among cooperating nodes to implement cooperative relay. Cooperative automatic repeat request (ARQ) techniques are applied to take advantage of cooperative diversity to achieve efficient transmissions in [3].

The IEEE 802.11 wireless media standard supports multiple data bit-rates at the physical layer (PHY), where the terminal may transmit at higher rate than the base rate if channel conditions so permit [4]. In order to choose the most appropriate transmission rate, various link adaptation algorithms at the MAC layer have been proposed. The link adaptation algorithms can be classified into two categories: SNR based or packet transmission (loss) based [5][6][7][8]. In the SNR based link adaptation algorithms, the received signal strength information (RSSI) is used as an indication of link quality, and then a transmission rate is selected based on the average or instantaneous RSSI from a predetermined SNR-rate table. In the packet retransmission based link adaptation

algorithms, the transmitting terminal counts the outcome (either successful or failed) of each transmission attempt. Based on the packet transmissions history, the transmitting rate can be adaptively adjusted. Auto Rate Fallback (ARF) is the first documented bit-rate selection algorithm [6].

Since cooperative relaying provides higher transmission reliability and the link adaptation protocols enable terminals to adapt their data rates to match the channel conditions, both techniques can contribute to improve network throughput. The idea of joint adaptation of coding rates and level of cooperation is proposed in [9]. Results from [9] show that coded cooperation with adaptation provides substantial improvement over direct transmission and conventional multi-hop connections. Authors of [10] first derive the outage capacity for Selection DF (SDF) cooperative relaying with N relays with ideal rate adaptation schemes for typical topologies. Then an offline heuristic for computing Signal-to-Noise Ratio (SNR) thresholds aimed at reaching the derived bounds is proposed. Base on RBAR (Receiver-Based AutoRate), a cooperative relay-based auto rate scheme (CRBAR) is proposed in [11] in which the relay candidates adaptively select themselves as the relay nodes and determine the relay scheme and transmission rates based on the instantaneous channel measurements. CRBAR also uses frame combining at the receiver side to combine the copies of the same packet from a source and a relay to ensure a higher data rate being likely supported between the relay and the destination.

The motivation for our protocol is to solve two issues in current link adaptation protocols. Firstly, when the channel condition of direct channel is so poor that only lower data rates can be supported, link adaptation algorithms only consider the direct transmissions, hence still achieving a low throughput. Secondly, the data rates supported at the PHY layer are limited in numbers, for example, 802.11a supporting eight transmission rates up to 54 Mbps. Therefore, no link adaptation algorithm can adapt the data rate to perfectly match the exact channel condition, which results in frame errors at the reception.

The design of our protocol enables it to take advantage of both cooperative relay and link adaptation algorithms. Therefore the performance gain of the proposed protocol is two-fold: first is the improved delivery reliability provided by cooperative relaying; and second is the improved bandwidth efficiency acquired from the link adaptation algorithm. The contribution of this paper is the design and evaluation of a practical cooperative relay enhanced link adaptation (CORELA) protocol for IEEE 802.11 WLAN networks. A few advantages of CORELA are summarized below:

- CORELA does not require a-priori channel state information (CSI) for link adaptation, which results in no modification on MAC messages defined in IEEE 802.11 standard.
- CORELA is based upon the existing IEEE 802.11 Distributed Coordination Function (DCF) and it is therefore a completely distributed media access protocol.

Our simulation results show that CORELA outperforms both cooperative relay and link adaptation algorithms, when each of them works alone, in terms of end-to-end throughput and energy efficiency. The performance enhancement can be observed for different channel conditions and different traffic loads as well.

The rest of the paper is organized as follows. Section II presents the system model and background information. Section III describes the design of the protocol and is followed by Section IV, which presents analysis of simulation results. In Section V, we draw the conclusion.

II. SYSTEM ASSUMPTIONS AND BACKGROUND INFORMATION

In this section, we will present the system model for IEEE 802.11 DCF. The system model is extended from the general model proposed in [12]. Using this model, the effects of rate adaptation and packet collision/corruption at both the direct channel and the relay channel can be considered. For simplicity of exposition and without loss of generality, we introduce a notion of virtual time slot and assume that system time is slotted with each time slot of t second. This enables us to assume that channels are separated in time and to use terms such as slots or phases in the remaining of the paper.

A. System Assumptions

We assume a single hop wireless LAN with fully connected topology, where all the nodes are in radio range of each other. In total, N terminals are deployed in the network. All terminals are identical and stationary. Each terminal has saturated traffic to transmit to one of its neighbors.

Here we only consider single-relay scenario, such that for each source-destination pair, it is assumed that there is always one and only one relay to help the transmission. Accordingly, we assume there is always a specified channel resource dedicated to the relay. Therefore we do not consider any relay selection and relay channel allocation mechanisms here. Our algorithm can be extended to multi-relay environment. Due to the much smaller size of MAC control messages compared to the data packet, the error of the non-data packets is considered negligible.

We assume single transceiver at each node and simultaneous transmissions from more than one node will result in collision. Once a source gains the channel access and starts transmitting, other sources will not transmit until the transmission is over.

B. Background Information

We first briefly describe here the incremental decode-and-forward with selection capability (SIDF) protocol that is going to be used as the cooperative scheme in our simulation. In such

a strategy, feedback from the destination in the form of ACK or NACK is utilized at the relay node to decide whether to transmit or not.

Since we assume the source and relay nodes operate in half-duplex mode, the cooperation is done in two phases. In SIDF, the first phase is exactly the same as DF, where the source transmits and both the relay and the destination listen. In the second phase, if the destination does not receive correctly it will send NACK to the source. If the relay overhears this, and if it is able to fully decode the source signal correctly, it forwards the re-encoded signal to the destination and the source will not retransmit in this phase. If the destination also fails in receiving the relayed packet, the source retransmits again. It can be seen that such a strategy is more bandwidth efficient than DF because the relay only transmits if necessary.

The basic link adaptation protocol we use here is ONOE. ONOE [7] is widely used in 802.11 device drivers for Atheros cards in Linux and FreeBSD. Furthermore, ONOE achieves averagely good performance for a wide range of network conditions. ONOE is a credit-based link adaptation algorithm where it maintains credits for the currently used rate on a per-destination basis to aid in the decision to increase the data rate. Initially, ONOE sets the bit-rate to 24 Mb/s in 802.11a/g and 11 Mb/s in 802.11b with zero credit for that rate. The value of the credit is then determined by the frequency of successful, erroneous transmissions and retransmissions accumulated during a fixed invocation period of 1000 ms. ONOE steps down to a next lower rate if none of the transmissions was successful in the previous interval, or more than ten frames were transmitted with average retry exceeding one. Consequently, the credit count is decremented if more than 10% of the frames are retried during the previous observation interval and incremented otherwise. If the credit count reaches a threshold then ONOE shifts to a next higher rate.

III. CORELA DESIGN

In this section, we provide details of the proposed CORELA protocol. The key function of CORELA is to enable relay nodes to adapt data bit-rate efficiently by considering both the direct channel (source to destination) and relay channel (relay to destination), which requires careful protocol design across the several layers of the protocol stack. CORELA also adopts a rate selection mechanism similar to [13] to combat the collision related issues.

A. Motivation and Challenges

The main motivation of our work is to design a simple link adaptation algorithm with explicit cooperative relay capability so that the theoretical performance gains can be approached. CORELA consists of two modules, one responsible for the cooperative relay and the other for link adaptation. We require the de-coupling of each module to be considered in design, i.e., keep interaction between two modules as little as possible. Therefore, each module can be designed independently and individually and any combinations of cooperative relay and link adaptation schemes can work on the relay. The advantages of this design are flexibility and simplicity. The disadvantage is that each module loses the opportunity to utilize feedbacks

from the other module while such feedbacks may contain useful information for its counterpart to make better decisions.

For the cooperative module, due to its bandwidth efficiency, we choose to use SDF with additional link adaptation capability described in the following. The major task of the link adaptation module is to find a data rate to match efficiently the condition of the relay-destination link. The design of this module faces three major challenges. First, the algorithm at relay must consider multiple channel conditions, i.e. both source-destination and relay-destination. Without the former, the relay may take longer time to find a suitable data bit-rate. Without the latter, cooperation diversity is not fully utilized. Second, because of the nature of SDF, the relay may decide to relay or not to relay periodically. For packet-retransmission based link adaptation algorithms like ONOE and ARF, the counting of the outcome of retransmission may be not successive. Therefore conventional link adaptation methods are not suitable for this task. Third, in realistic systems where CSI is not available a-priori, one opts to use the past history of performance as the criteria to decide the data bit-rate for relaying. As a result, it may take a longer time to find the right rate for transmission. Thus, in order to maximize the gain in the performance, it is critical to balance the trade-off between the gains through matching the rate with the underlying channel condition and the time costs of seeking this rate.

B. CORELA Protocol Description

TABLE I. NOTATIONS USED IN CORELA

Notations	Comments
s_d	Consecutive success count for direct transmissions
f_d	Consecutive failure count for direct transmissions
s_r	Consecutive success count for relay transmissions
f_r	Consecutive failure count for relay transmissions
S_{th}	Consecutive success threshold
F_{th}	Consecutive failure threshold
T_{th}	RTS/CTS ON/OFF threshold
N_{min}	Minimum number of data samples

Table I presents the notations used in CORELA. N_{min} is the minimum number of data samples that is necessary for the decision making. The default value is 8. The IEEE 802.11 standard defines the retry limit for short messages as 7, i.e., data message is allowed to retry 7 times in transmitting until dropped. With N_{min} set to 8, it is guaranteed that CORELA can at least record the transmission history of every data message for a particular data rate.

The consecutive failure count f_d and f_r record the number of failed transmissions in direct channel and relay channel respectively. s_d and s_r record the number of successful transmissions in direct channel and relay channel respectively. By default, all data including relaying data are transmitted without RTS. When the consecutive failure count f_d or f_r reaches RTS/CTS switch threshold T_{th} , the RTS/CTS exchange is activated. From now on, CORELA knows that a data transmission failure following a successful RTS/CTS exchange must be due to packet errors because the successful RTS/CTS messages guarantee no collision to the subsequent data

transmission. If the consecutive failure count further reaches the consecutive failure threshold F_{th} , the transmission data rate is reduced to the next lowest level if possible. On the other hand, if the consecutive success count further reaches the consecutive success threshold S_{th} , the transmission data rate is increased to the next highest level if possible.

Once the transmission starts, the relay continuously monitors the communications between the source and the destination. It records each direct transmission in the tuple $\{R_d, T_{suc}\}$, where R_d is the data bit-rate used in the direct transmission and T_{suc} is the number of successful transmissions so far between the source and the destination with rate R_d . When the relay node records an event that one data packet is not correctly received by the destination, the relay prepares to forward this packet by using SDF. The relay first checks if it can correctly decode the data. If it can, the relay then checks if it can forward the data to the destination in a data rate R_r . If it is the first time the relay forwards data to this destination, the relay then uses R_d and records each relay transmission in the tuple $\{R_r, T_{suc}\}$ until minimum number of the data samples N_{min} of both the direct and the relay transmission is reached. In our case, each data set must have at least 8 data samples. Only when relay has enough data samples it then follows the procedure described in the previous paragraph. The rate R_d in the direct link is used as a guideline to help determine the rate in the relay link. This results in reduced time for seeking the right data rate for relaying. Before changing the current data rate for relaying, the relay consults recorded past performance of the both direct and relay links.

IV. PERFORMANCE EVALUATION

In this Section, we validate our proposed protocol CORELA under various scenarios with different channel conditions and traffic loads. We consider a one-hop wireless LAN with various numbers of nodes. Nodes can be classified into two groups: namely source and relay. Each source node has saturated traffic to transmit to one of other sources. For each traffic flow, there is a predefined and dedicated relay node to assist the transmission. Apart from different roles in transmission, all the nodes are identical. In order to illustrate the benefit acquired by adopting the cooperative relaying scheme, we require that the quality of the relay channel is always better than that of the direct channel. Also due to the limit of pages, the channel between source and relay is herein error-free.

The aggregated throughput is computed by dividing the total of successfully transmitted packet bits by the total duration of transmission time. The energy efficiency metric is the total amount of energy consumed in transmissions divided by the total number of successfully transmitted bits, which represents the average energy consumed in correctly transmitting one bit.

A. Simulation Configuration and Descriptions

The configuration of the simulation and settings of CORELA parameters are listed in Table II.

TABLE II. PARAMETERS USED IN SIMULATION

Data packet size	2000 bytes
Normalized transmitting power	1 Watt
Number of source/destination pairs	[2, 48]
Number of relay nodes	[2, 48]
SNR of direct channel	[0, 25db]
SNR of relay channel	[2, 27db]
Initial data rate	24 Mbps
Parameters used in link adaptation algorithms	
S_{th}	10
F_{th}	2
T_{th}	1
ONOE initial credit	0

To characterize the performance of the combination of SDF cooperative relaying and rate adaptation, we compare the following schemes in terms of end-to-end throughput and energy efficiency:

- **ONOE**—the transmission on the direct channel (source-destination) has the link adaptation capability by applying ONOE and there is no assist from relay. The scheme achieves best performance for high SNR and suffers loss for low SNR.
- **Direct-Best**—the transmission is still only on the direct channel without relay assisting but with perfect knowledge of the direct channel condition. So it can select the best data rate matching the current channel condition and hence achieve the maximum throughput on direct transmission.
- **CORELA**—in this scheme, SDF is used at relay for cooperative relaying and a link adaptation algorithm similar to CARA [13] is used at both source and relay to decide the best data rate for transmissions. So different transmission rates may be chosen in the direct channel and relay channel for maximum spectral efficiency.

In the following plots, we present some typical performance results of CORELA against various fixed channel conditions and traffic loads. The SNR value denotes the channel condition of the direct channel. RD-SD represents the quality difference between the relay channel and the direct channel. As each source has saturated traffic, the level of contention in the network is changed by varying the number of source nodes. With the number of source nodes increasing, the likelihood of collision also increases.

B. Performance Analysis

Fig. 1 and Fig. 2 show the overall performance of CORELA against ONOE and Direct-Best transmission without cooperation when channel conditions of direct channel and relay channel are poor (SNR = 1 dB). In this scenario, the transmission rate will finally settle at a fairly low rate because of the high packet error rate. In this case, the main cause of the transmission failure is the packet error due to the poor channel condition regardless of link adaptation algorithms. Therefore the performance gain of CORELA mainly comes from cooperative relaying. The cooperative relaying scheme in CORELA increases the reliability of packet delivery by using a much better relay channel, which results in more consecutive success packet transmissions and hence guaranteeing the rate

adaptation scheme functioning properly. Besides, the better channel quality enables CORELA to use a higher data rate in relaying. Therefore by using cooperative relaying, more data packets can be correctly received at the destination via the relay channel with a higher data rate, which leads to fewer unnecessary retransmissions in the direct channel, hence improving throughput and energy consumption. The above two factors explain why CORELA outperforms Direct-Best even without knowing the exact channel condition of the network. On average, CORELA outperforms Direct-Best by 50%.

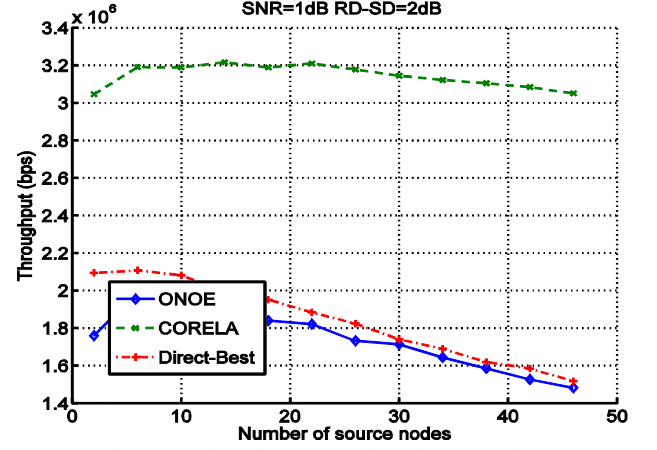


Figure 1. Throughput vs. number of source nodes.

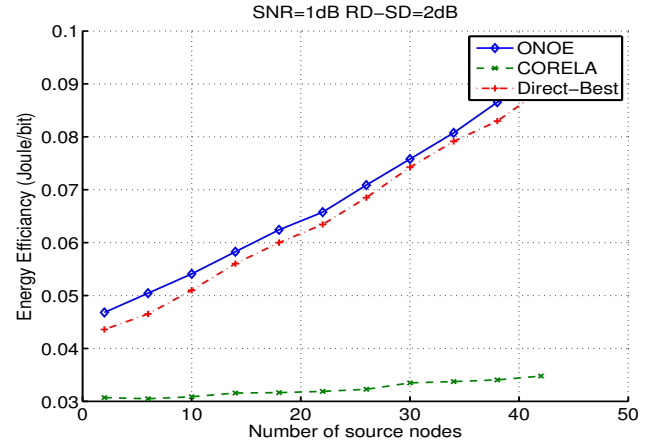


Figure 2. Energy efficiency vs. number of source nodes.

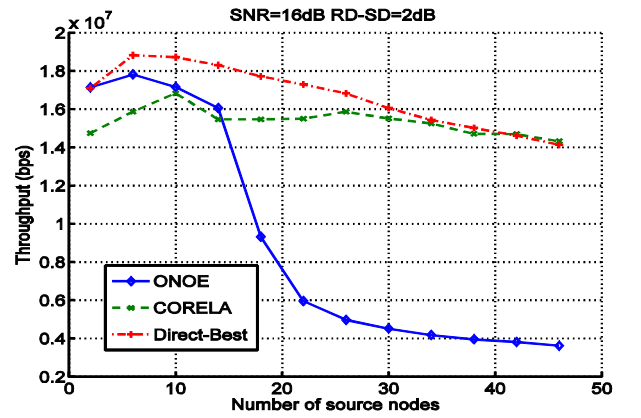


Figure 3. Throughput vs. number of source nodes.

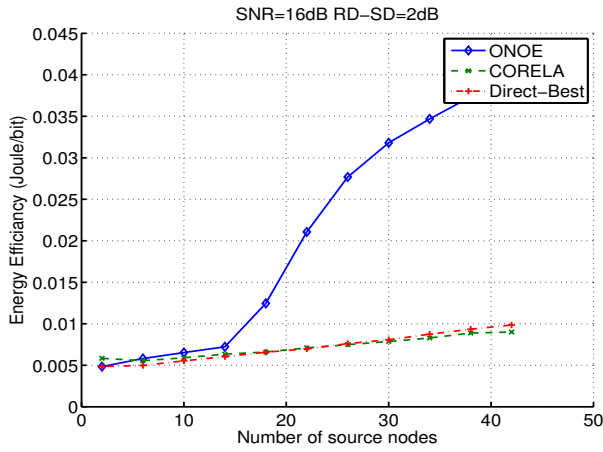


Figure 4. Energy efficiency vs. number of source nodes.

Fig. 3 and Fig. 4 represent the scenario in which channel conditions are relatively good (SNR = 16 dB) so that the channel loss error and packet collisions have a mixed effect on packet transmission failures. In this scenario, the performance of CORELA is also better than ONOE for most of cases, which is mainly attributed to the combination of cooperative relaying scheme and collision-aware scheme. With the collision-aware scheme, CORELA has the ability to distinguish packet errors caused by wireless loss from collision loss, while the cooperative relaying scheme SDF enables CORELA to combat the wireless loss by utilizing spatial diversity, which results in a higher data rate with robust delivery ratio and improved throughput. The improvement in aggregate throughput also translates into a better performance in packet transmission delay, which in turn reduces the energy cost in transmissions.

As shown in Fig. 3, we can see that the performance of ONOE decreases with the increasing number of source nodes, especially a sharp drop can be seen when the number of source nodes goes beyond a certain threshold, i.e., the traffic load exceeds a certain threshold. This is mainly because ONOE does not consider the collision effect; it decreases the transmission rate upon consecutive packet collisions, which results in a lower throughput. It is also observed that ONOE can outperform CORELA when traffic loads are light. This is mainly due to the RTS/CTS overhead introduced by the RTS-based loss differentiation scheme used in CORELA. When the traffic loads are below a certain threshold, the benefits achieved by applying loss differentiation are cancelled by the cost of it.

In this scenario, the direct link SNR is fairly good and there are fewer packet errors. This means that the majority of transmission failures are caused by collisions. Since the cooperative relaying scheme in CORELA is activated only when packet error occurs, CORELA is almost reduced to a normal rate adaptation algorithm in this case. With its two-hop transmission and RTS/CTS overhead, the performance of CORELA is slightly worse than Direct-Best. But CORELA achieves its performance without knowing any channel condition information whereas Direct-Best has perfect knowledge of the direct channel condition.

In summary, with the various channel conditions and different traffic load scenarios we have evaluated in this section, we observe that CORELA yields the best performance for most cases when channel condition is lossy and traffic loads are heavy. In addition, even when channel condition is good enough to accommodate high data rate, the performance of CORELA is close to that of Direct-Best and better than ONOE.

V. CONCLUSION

In this paper we have presented a link adaptation algorithm with cooperative diversity capability for IEEE 802.11 WLAN networks, in which all the relays intelligently decide when and how to relay. CORELA enables a relay terminal to accomplish cooperative relaying in an efficient way by adapting the transmission rate to the conditions of the underlying relay link. Our protocol achieves high and stable performance by taking full advantage of gains from cooperative diversity in wireless communications. Simulation results have shown that CORELA outperforms the other listed approaches in terms of throughput and energy efficiency in various channel conditions and traffic loads. Furthermore, due to its simplicity for performing joint cooperative relaying and link adaptation, CORELA is quite feasible to implement.

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