CARLA: Combining Cooperative Relaying and Link Adaptation for IEEE 802.11 Wireless Networks

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Abstract—**In this paper, we present a novel design named CARLA which combines Cooperative Relaying and Link Adaptation for IEEE 802.11 wireless networks, in order to maximize spectral efficiency and hence improve the throughput of the network. Unlike previous studies assuming that accurate channel information is available for relaying and link adaptation, the novelty of our approach is to use the expected packet transmission time (ETT) and RTS/CTS exchange to estimate the quality and level of contention for the current channel. By taking into account the quality of the direct channel from source to destination and the relay channel between relay and destination, CARLA enables both source and relay terminals to adjust their transmission rates so that not only the reliability of the transmission but also the bandwidth efficiency can be improved, hence fully utilizing the diversity gain. CARLA is a simple, distributed and rate-per-link adaptation protocol requiring no modification on 802.11 PHY and MAC. Simulation results show that CARLA can achieve significant performance improvement in terms of end-to-end throughput and energy efficiency for different network conditions.**

Keywords: cooperative relaying, link adaptation, IEEE 802.11, medium access control

I. INTRODUCTION

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] and it has been reported in [2] that cooperative diversity could yield significant performance gains over conventional protocols. Cooperative hybrid automatic repeat request (HARQ) techniques are applied to take advantage of the cooperative diversity to achieve efficient transmission in [3]. However, most of these studies focus on the information theory and signal processing aspects without specifying how the relays participate in the cooperation and realize the achievable gains.

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 auto link adaptation algorithms at the medium access control layer (MAC) have been proposed. The link adaptation algorithms can be classified into two categories: SNR based or packet transmission (loss) based [5] [6][7]. 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. Receiver Base Rate Fallback (RBRF) [5] is a typical example of such algorithms; it sends back to the sender the receiver RSSI. One drawback for these protocols is that it is not compatible with IEEE 802.11 because both the control and data packet format have to be modified. In the packet retransmission based link adaptation algorithm, 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. Both the ONOE algorithm [6] and Adaptive ARF (AARF) [7] belongs to this category.

Since cooperative relaying provides higher transmission reliability and the link adaptive 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, modulation modes and level of cooperation is proposed in [8]. However, [8] assumes idealized multiple access schemes where transmissions among terminals are perfectly coordinated and the protocols are evaluated in simplified topologies, i.e. three-node-source-relay-destination. Base on RBAR, a cooperative relay-based auto rate scheme (CRBAR) is proposed in [9] 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. In [9] the perfect channel state information (CSI) is required to achieve the maximum performance.

The main contribution of this paper is the design and evaluation of a practical MAC protocol which combines cooperative relay algorithm with link adaptation capability (CARLA) for IEEE 802.11 WLAN networks. A few advantages of CARLA are provided below to illustrate the opportunities for performance improvement enabled by it.

- CARLA does not require a-priori CSI for cooperative relaying and link adaptation, which results in no modification on MAC messages.
- CARLA does not require any reliable signal strength estimation from the radio interfaces which is difficult to obtain in real world. By using the combination of transmission time and channel contention estimation, CARLA is capable of accurately estimate the channel state.

- CARLA is based upon the existing IEEE 802.11 Distributed Coordination Function (DCF) and it is therefore a completely distributed medium access protocol.

The design of CARLA enables it to take advantage of both cooperative relay and link adaptation algorithms. Therefore the performance gain of CARLA is twofold: first, the improved delivery reliability provided by the cooperative relaying. Second, the improved bandwidth efficiency acquired from link adaptation algorithm. Our simulation results show that CARLA outperforms state-of-art link adaptation algorithms, in terms of end-to-end throughput and energy efficiency. The performance enhancement can be observed for different channel conditions and traffic loads.

The rest of the paper is organized as follows. Section II presents the system model and some background information of our protocol. Section III describes the design of the protocol and is followed by section IV, which presents performance evaluation of our protocol. In section V, we present the future work and conclusion.

II. SYSTEM MODEL AND BACKGROUD INFORMATION

In this section, we will present the system model for 802.11 DCF. The system model is extended from the general model proposed in [10]. Using this system model, the impacts of rate adaptation and packet collision/corruption at both the direct link channel and the relay link channel can also be taken into account. For simplicity of exposition and without losing 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 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. Each terminal has saturated traffic to transmit to one of its neighbors. In total N terminals are deployed in the network. All terminals are identical and stationary. 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.

It is assumed 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. Backgroud information

We first briefly describe here the incremental decode-and-forward with selection capability (SIDF) protocol that is a widely studied and a benchmark in the research field of relaying. 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. More details will be presented in section III.

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. 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 either none of the transmissions were 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 retried during the previous observation interval, and incremented otherwise. If the credit count reaches a threshold then ONOE shifts to a next higher rate. ONOE is widely used in 802.11 device driver for Atheros cards in Linux and FreeBSD and it achieves averagely good performance for widest range of network conditions. Finally, ONOE does not suffer the design fault of AARF mentioned in [10]. When congestion occurs, the performance of AARF dramatically drops due to packet collisions.

It has been reported that some types of link adaptation algorithms do not work properly in multiple-user environment and their performance can degrade drastically due to the inability of differentiating losses between wireless noise and contention collisions. Based on this observation, there have been a few attempts to aid rate adaptation algorithms in dealing with the collision effect. One of the ideas is to exploit the RTS/CTS exchange to filter only wireless losses into rate decision process. CARA (collision aware rate adaptation) [11] dynamically enable the RTS/CTS mechanism upon loss with the assumption that an acknowledge timeout following a successful RTS/CTS exchange is likely to be due to channel-based error. CARA further proposes to selectively turn on RTS/CTS exchange only after data frame transmissions fail at least once without RTS/CTS to save the extra RTS/CTS overhead.

III. DESIGN

In this section, we give details of the proposed CARLA protocol. The key function of CARLA 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 carefully protocol design across the several layers of the protocol stack. CARLA also adopts a mathematical model in [12] to calculate ETT on the fly as well as a rate selection mechanism similar to [11] to combat the collision related issues.

A. Motivation and challenges

The major motivation of our work is to design a simple cooperative relay algorithm with explicit link adaptation capability so that the theoretical performance gains can be realized. CARLA consists of two modules, one responsible for the cooperation 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.

For the cooperative module, due to its bandwidth efficiency, we choose to use aforementioned SIDF 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 the condition of the current channel efficiently. 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, the cooperation diversity is not fully utilized. Second, because of the nature of SIDF, relay may decide to relay or not to relay periodically. For packet-retransmission based link adaptation algorithms like ONOE and CARA, the counting of the outcome of retransmission may be not successive. Therefore conventional link adaptation methods are not suitable for this task. Thirdly, 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 via matching the rate with the underlying channel condition and the time costs of seeking this rate.

B. CARLA Protocol Modules

TABLE I. NOTATION USED IN CARLA

Notations	Comments
Slot	duration of a time slot
DIFS, SIFS, ACK	duration of DIFS, SIFS and ACK frame
HEAD	duration of MAC/PHY header
N_{try}	The number of retry
w_i	backoff window for *ith* retry
L_{data}	number of bits in the data frame
f_d	Consecutive failure count for direct transmissions
f_r	Consecutive failure count for relay transmissions
T_{th}	RTS/CTS On/Off threshold

The CARLA protocol consists of the following modules:

1) Cooperative relaying: Since we assume source and relay nodes operate in half-duplex mode, the cooperation is done in two phases. In the first phase, the source transmits and both the relay and the destination listen. In the second phase, if the destination does not receive correctly it will broadcast NACK to ask for cooperation. 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. If the destination also fails in receiving the relayed packet, it sends no feedback and the source retransmits again. Conversely, an ACK is sent back to the source. In this case, the source transmits a new packet, while the relay resumes its normal activity.

2) Relay selection and coordination: In the first phase of SIDF, if multiple relay candidates have correctly decoded the data from the source, they start a distributed contention on channel acces. At the beginning of the second phase of SIDF, each candidate then randomly selects a backoff timer, which is uniformly chosen from the set {0, 1 , ... , DIFS}. During the backoff time, the canditate keeps monitoring the channel, if it senses a transmission going on the channel, the candidate assumes that another node is relaying and stops channel contention process. Otherwise, the node finishes the countdown, and sends a copy of data at the end of the backoff.

3) ETT computation: ETT takes into consideration the mixed effects from wireless channel condition and collisions. Therefore it is a suitable metric to describe the quality of channel condition and can partially indicate the congestion in the channel as well. ETT for a particular data rate *R* is calculated by [12]:

$$ETT_r = DIFS + Slot\sum_{i=0}^{N_{try}} \frac{w_i}{2} + (N_{try} + 1)(SIFS + ACK + HEAD + \frac{L_{data}}{R_r}) \quad (1)$$

then the average ETT for data rate *R* can be calculated by:

$$AETT_r = \alpha AETT_r + (1-\alpha)ETT_r \quad (2)$$

4) RTS/CTS loss differentiation: The consecutive failure count f_d and f_r record the number of failed transmission 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. Therefore, CARLA 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 tranmission.

5) Rate probing: let S_{smp} denotes a set of candidate smapling bit rates which have a loss-free frame transmission time smaller than the current $AETT_r$, when the total number of transmissions is a multiple of 10, the algorithm will choose a data rate in S_{smp} with less than 4 consecutive packet error failures. Therefore higher data rates can potentially be used.

C. CARLA protocol description

CARLA starts with the highest possible data bit rate. Once the transmission in the direct channel begins, the relay candidates continuously monitor the communications between the source and the destination. If the destination sends out NACK to indicate an error in reception, all the relay candidates with fully decoded source signal will starts the relay procedure. After a relay wins the channel access, it will transmit a copy of data frame to the destination.

After each transmission of a data frame with rate R_r, frame delivery statistics are collected and processed, then ETT_r can be calculated by (1) based on the collected statistics and $AETT_r$ and the number of successful/failed transmissions of each data rate are updated accordingly. The ETT of the current data rate is constantly compared with that of other data rates. With loss differentiation and rate probing described in the above modules, CARLA has the ability to make correct estimation of the current channel condition and congestion level. Therefore it can always find and hence switch to the best data rate for both direct and relay transmission, which in turn yields the highest possible throughput.

IV. PERFORMANCE EVALUATION

In this Section, we validate our proposed protocol CARLA under various scenarios with different channel conditions and traffic loads in MATLAB. We consider a one-hop wireless LAN which has various numbers of nodes. Nodes can be classified into two groups: namely source and relay. We consider a circular network topology such that each of nodes has two adjacent neighbors with d meters apart. Each node has saturated traffic to transmit to its clock-wise neighbor. The transmission is affected by flat Rayleigh fading so that the receiving power at the receiver side is proportional to $Pd^{-\alpha}$, where P is the transmitting power and α is the path loss exponent.

For simplicity, we assume that there is always a dedicated relay node located in the exactly half way from the source and the destination for each traffic flow. Moreover, we have considered some idealized aspects of relay coordination. It is assumed that always the best relay among the available candidates wins the contention and takes part in the relaying for a certain transmission and there is no contention and collision among relay candidates. The rationale behind this assumption is that we focus on exploring relationship between cooperation and link adaptation and providing an insight on the potential gains achieved by implementing the protocol we proposed. Therefore, our simulation represents an upper bound of proposed protocol.

The aggregated throughput is computed by dividing the total sum of successfully transmitted packet bits by the total duration of transmission time. The energy efficiency is calculated by dividing the total number of successfully received bits by the total amount of power consumed in transmitting.

A. *Simulation Configuration Description*

As shown in Table II, the set of core parameters used in the simulation are listed.

TABLE II. PARAMETERS USED IN SIMULATION

Data packet size	2000 bytes
Transmission power	1 Watt
Number of source nodes	2, 8, 16, 20, 26, 32, 36
Number of relay	2, 8, 16, 20, 26, 32, 36
Distance between source destination pair (meters)	10, 50, 100, 150, 200
Distance between source and relay (meters)	5, 25, 50, 75, 100
Path loss exponent α	3.5
Slot/SIFS/DIFS	9/16/34 µs
HEAD/ACK	20/42 µs
Parameters used in link adaptation algorithm	
Data rate	[6 12 24 36 54]Mbps
α	0.9
T_{th}	1

To characterize the performance that a combination of cooperative relaying and rate adaptation acquires, we compare our scheme with ONOE and CARA in terms of aggregated throughput and energy efficiency. Due to the lack of space, only some typical performance results are presented here.

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 increasing, the likelihood of collision also increases. In the plots, the distance value denotes how far the source and the destination apart. The larger the value, the less receiving power reaches the reception side.

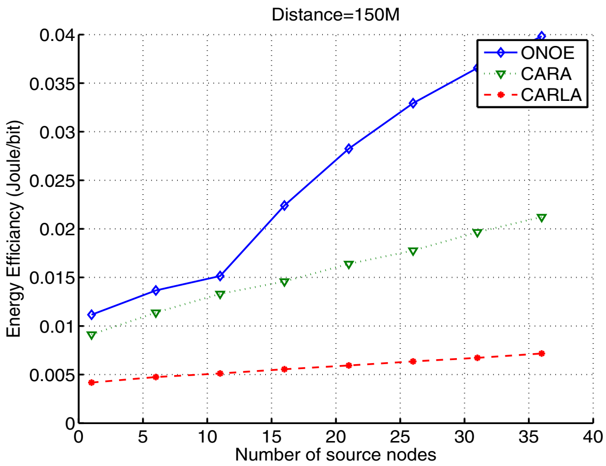

Figure 1. Energy efficiency vs. number of source nodes

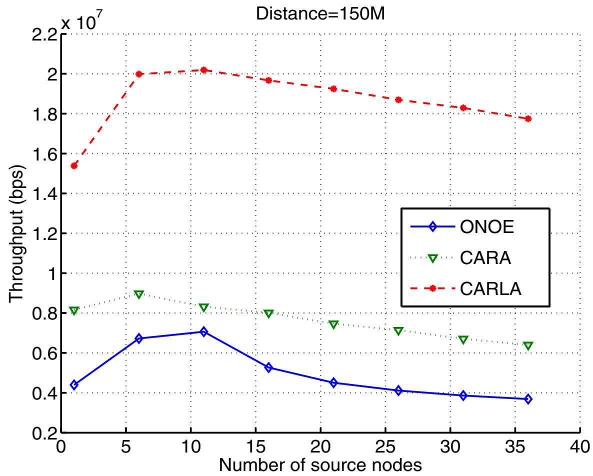

Figure 2. Throughput vs. number of source nodes

B. *Performance Analysis*

Fig. 1 and Fig. 2 show the overall performance of CARLA against ONOE and CARA in direct communication in the scenario with fixed distance and various traffic loads. In this scenario, the source is far away from the destination which leads to a poor quality of direct channel. The transmission rate will finally settle at a fairly low rate because of the high packet error rate. It is noticed that all schemes maintains a steady throughput regardless of number of source nodes, which shows that all protocols are equally capable of distinguishing the channel errors from the collisions. The performance gain of

CARLA thus mainly comes from the cooperation. By using cooperative relaying, more data packets can be correctly received at destination via the much better relay channel, which enables CARLA to use a higher data rate in relaying. Besides, the cooperation also increases the reliability in transmission. Higher reliability and higher data rate results in unnecessary retransmissions in the direct channel, hence improving both throughput and energy consumption.

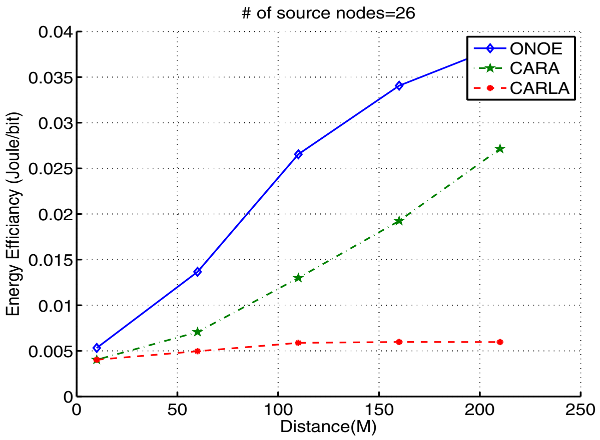

Figure 3. Energy efficiency vs. various distance

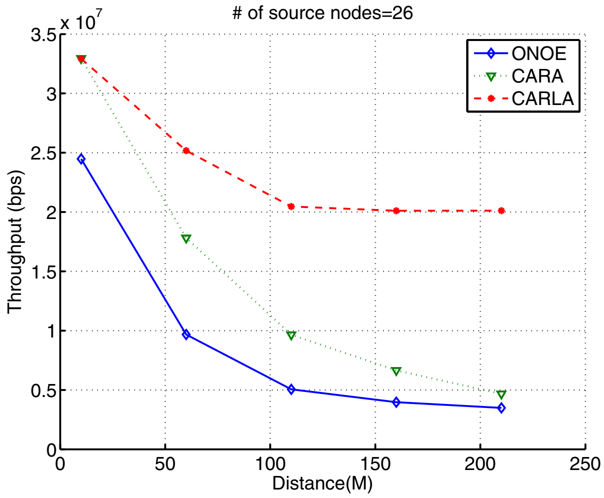

Figure 4. Throughput vs. various distance

Fig. 3 and Fig. 4 display the performance comparison among three schemes when the number of source nodes is fixed but distance between nodes are changing. It is observed that CARLA outperforms other two schemes due to the combination effect of cooperation and link adaptation. The only exception is when the value of distance is too small and CARLA has the same performance with CARA. Under this condition, the direct link is so good that there are almost no packet errors. Therefore the cooperation part of CARLA seldom kicks in and the performance gain of CARLA is mostly from the link adaptation module which is as good as CARA. As shown in Fig.3 and Fig.4, the throughput starts dropping with the value of distance increasing. The performance of both ONOE and CARA keeps dropping steeply while CARLA manages to reach a steady state regardless of changing distance, which again proves the power of combining cooperation and rate adaptation.

In summary, with the various channel conditions and different traffic load scenarios we have evaluated in this section, we observe that our algorithm always yields the best performance when channel is lossy and traffic loads are heavy.

V. CONCLUSION AND FUTURE WORK

In this paper we present a cooperative diversity algorithm with link adaptation capability for IEEE 802.11 WLAN networks, in which all the relays intelligently decide when and how to relay. CARLA enables relay terminal to accomplish the cooperative relaying in an efficient way by adapting the transmission rate to the conditions of the underlying relay link. Our protocol achieves a high and stable performance by taking full advantage of gains from cooperative diversity in wireless communications. Results show CARLA can outperform the other listed approaches in terms of throughput and energy efficiency in either a good or poor channel condition. Furthermore, due to its simplicity for performing joint cooperative relaying and link adaptation, CARLA is quite feasible to implement.

ACKNOWLEDGMENTS

We would like to thank Alistair Munro and Jianhua He for their early discussion with this work. This research is supported by Toshiba Research Europe Ltd.

REFERENCES

[1] J. N. Laneman, G. W. Wornell, and D. N. C. Tse, “Cooperative diversity in wireless networks: efficient protocols and outage behavior,” IEEE Trans. Inform. Theory, vol. 50, no. 12, pp. 3062-3080, Dec. 2004.

[2] G. Kramer, M. Gastpar, and P. Gupta, “Cooperative strategies and capacity theorems for relay networks,” IEEE Trans. Inform. Theory, vol. 51, no. 9, pp 3037-3063, Sept. 2005.

[3] L. Dai and K. B. Letaief, “Throughput maximization of Ad-hoc wireless networks using adaptive cooperative diversity and truncated ARQ,” IEEE Trans on Commun., vol. 56, Issue 11, pp. 1907-1918, Nov., 2008.

[4] IEEE Computer Society LAN WAN Standards Committee. Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, 1999.

[5] G. Holland, N. Vaidya, and P. Bahl, “A rate-adaptive MAC protocol for multi-hop wireless networks,” ACM MobiCom 2001, Rome, Italy, 2001.

[6] Madwifi Project, http://sourceforge.net/projects/i-nadwifi.

[7] M. Lacage, M. hossein and T. Turletti, “IEEE 802.11 rate adaptation: a practical approach,” IEEE MSWiM, October 2004.

[8] Z. Lin, E. Erkip, and M. Ghosh, “Rate adaptation for cooperative systems,” in Proc. IEEE Globecom, Dec. 2006.

[9] T. Guo and R. Carrasco, “CRBAR: Cooperative relay-based auto rate MAC for multirate wireless networks,” IEEE Transactions on Wireless Communications, pp. 5938-5947, 2009.

[10] J. He, D. Kaleshi, A. Munro, and J. McGeehan, “Modeling Link Adaptation Algorithm for IEEE 802.11 Wireless LAN Networks,” in Proc. ISWCS 2006, pp.500-504, Valencia, 2006.

[11] J.S. Kim, S.K. Kim, S.H. Choi, and D. Qiao, “CARA: collision-aware rate adaptatioin for IEEE 802.11 WLANs, ” IEEE INFOCOM, 2006.

[12] J. Bicket, “Bit-rate selection in wireless networks,” MIT, Tech. Rep., 2005.