Cooperation Metric for IEEE 802.11 Wireless Networks

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***Abstract*— A key design issue in relay based cooperative wireless networks is the design of an appropriate metric for relay selection algorithms. In most cooperative protocols designed for IEEE 802.11 networks, the relay selection metric is based on reducing the transmission delay of relay links. The bandwidth efficiency provided by this metric is beneficial for applications communicating at high data rate, however not all applications will benefit from this simple approach. In this paper, a novel cooperative metric is proposed, which in addition to bandwidth, also considers link reliability and link stability, especially useful in mobile scenarios, and for time sensitive service applications. The proposed metric is applied to the well-known CoopMAC protocol. Simulation results indicate a strong correlation between network performance and proposed cooperative metric.**

Keywords—Cooperation, metric, MAC protocol, IEEE 802.11.

I. INTRODUCTION

Cooperative relaying communications have recently emerged as a novel approach beyond the classical paradigms of point-to-point and point-to-multipoint communications. The key idea of cooperative communication is based on having nodes cooperating to transmit their messages, instead of operating independently and competing among each other for channel resources, as is done in conventional networks. Cooperative relaying achieves this purpose by allowing intermediate nodes (also called relays or helpers) to retransmit the sources' messages towards the destination thereby splittinga single lower speed transmission into multiple, but faster transmissions. Inspired by the attractive features and potential benefits of cooperative relay based communications, there have been many efforts to exploit cooperative techniques in IEEE 802.11 networks [1].

Considering this approach, many authors have proposed various cooperative schemes applied to the MAC layer of the IEEE 802.11 standard [4]-[10]. These schemes mostly focus on offering bandwidth efficiency by using a metric defined based on minimum transmission delay [2][3]. The cooperative protocols with improved bandwidth efficiency can be beneficial for application generating traffic at high data rate, or when throughput is the key issue. However, there are some application services such as real-time Video On Demand (VOD) and Voice over IP (VoIP) which require low jitter, and low packet loss, combined with high link stability and high link reliability, sometimes in detriment of bandwidth. Moreover, mobility can remarkably impact on relay links and subsequently on cooperation performance, and must be considered. In this work, we focus on the development of a cross layer metric, which is able to take in consideration additional communication characteristics, with the aim of providing enhanced overall performance to real applications.

The remaining part of this paper is organized as follows: In Section II, we present existing cooperative MAC protocols in IEEE 802.11 standards. Section III presents a novel metric and system model of cooperative IEEE 802.11 MAC protocols. Simulation and results are also presented in Section IV and Section VI concludes the paper and relates the future directions.

II. RELATED WORK

There have been considerable research efforts devoted to spectrum efficiency by using cooperative techniques at IEEE 802.11 MAC protocols. Improved spectrum efficiency can be obtained by reducing transmission delay between source and destination nodes. In order to reduce transmission time while exchanging data frames, two fast transmissions (Source-Relay and Relay-Destination) are replaced instead of a slow direct transmission. Due to shared medium of wireless channel and by overhearing the packets exchanged between the neighbors, every node can monitor the data rates and maintain a neighborhood mapping in the form <*source, destination, bitrate*>. This mapping is performed at MAC layer of IEEE 802.11 to determine the optimum combination of source-relay-destination. This mechanism were suggested originally by rDCF [4] and CoopMAC [5] protocols. In CoopMAC, the neighborhood mapping function is executed by source nodes. The source node selects the best relay node which provides the minimum transmission delay to destination. After exchanging modified control packets, a data packet is sent from source to relay and then is forwarded from relay to destination. In rDCF, potential relay nodes perform the neighborhood mapping function and the cooperation phase is similar to CoopMAC.

Besides the rDCF and CoopMAC protocols, there are several other protocols that exploit special techniques and features to improve bandwidth efficiency. Network coding [11] is explored by the CODE protocol [8] in order to support bidirectional traffic and further improvements to throughput. The approach of concurrent cooperative transmissions, allied to a store and forward approach, used in the CCMAC protocol [7] provides improved performance when compared to the original CoopMAC. In the CoopMACA protocol [6], the authors employ packet aggregation and distributed contention based relay selection

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algorithm to provide a robust adaptation instantaneously for variation of network topology especially in a general mobile scenario. The author of the EMR protocol [8] proposes the use of a priority-mapping scheme of available throughput and integrates the information into the control packets in order to select the optimum relay node. The approach of using opportunistic channel time reservations is another cooperative technique which was proposed in ORP protocol [10] for infrastructure WLANs. A solid review of cooperative MAC protocols and techniques was presented in [12].

The main metric for relay selection in existing cooperative IEEE 802.11 MAC protocols is computed based on the minimum transmission delay of direct transmission and relay links. This metric can be achieved according to physical layer information which is available at MAC layer. Nonetheless, there are some aspects of wireless networks such as application services requirements and mobility impact that have not been taken into consideration. To address these aspects in cooperative scenarios, a novel metric should be defined. In this paper, we provide a cross layer metric for cooperative IEEE 802.11 MAC protocol in which mobility aspects and spectrum efficiency are key components.

III. Cooperation issues in IEEE 802.11 MAC protocol

Bandwidth efficiency is mostly introduced as a main challenge for application services in wireless networks, however, there are some applications may benefit from link reliability and link stability more than bandwidth efficiency. As an example, for a real-time VoIP traffic, jitter reduction and low packet loss have a high order of importance. In fact, VoIP traffic is usually characterized by a relatively low bitrate, while the codecs used are extremely sensitive to reordering, loss and jitter. When nodes are mobile, or objects move in the environment between nodes (e.g., shopping center), greatly induce fluctuations in the communication characteristics of any two nodes, resulting in instability. Therefore, in order to improve communication in jitter and loss sensitive environments, and to improve overall bandwidth efficiency in perfect scenarios, we propose the use of a new cooperative metric, which we call the CoopMetric (CM). This metric can take in consideration information from applications, or directly from the traffic generated and be used to select the best relay node for each individual flow.

A. CoopMetric

CoopMetric (CM) has three main components representing communication delay, reliability and stability of the cooperative path. These components are Delay Ratio (DR), Reliability (RE) and Stability (ST), and can be used to rank candidate relays in order to maximize the performance of a specific application. It should be noticed that the method we propose can be used for multiple, simultaneous applications as relay selection is considered per flow. In this section, we explain how to compute these components.

1) Delay Ratio

All protocols that aim to provide bandwidth efficiency employ a common metric for relay selection. Generally, this metric can be related to the delay of direct and cooperative paths. For the simple scenario depicted in Figure 1, node R_i is a candidate relay between source (*S*) and destination (*D*). The MAC header of IEEE 802.11 frames or in more specifically, the PLCP (Physical Layer Convergence Procedure) sub-header contains a field named SIGNAL, which denotes the bit rate of every data packet sent to the network. Thus, R_i can effectively obtain the actual data rate between *S* and *D* from overhearing data frames exchanged between them. R_i can also estimate the potential data rate between itself and source-destination pair. Node R_i can measure the Signal to Noise Ratio (SNR) of control frames sent by nodes S and D, and compute the corresponding data rates of obtained SNR(s). This estimation can be obtained even for a single unidirectional communication as every transmission implies an acknowledgement from the destination. After obtaining the three data rates between these three nodes, a general metric of Delay Ratio (DR) can be defined. DR is the ratio between the transmission delay of relay path, and that of the direct path. If the relay node supports data rates of B_{SR_i} and B_{R_iD} respectively to *S* and *D*, and the direct transmission data rate between *S* and *D* is B_{SD}, the delay ratio estimated by R_i can be expressed as (1):

$$DR_i = \frac{\left(B_{SR_i}\right)^{-1} + \left(B_{R_iD}\right)^{-1}}{\left(B_{SD}\right)^{-1}} \qquad (1)$$

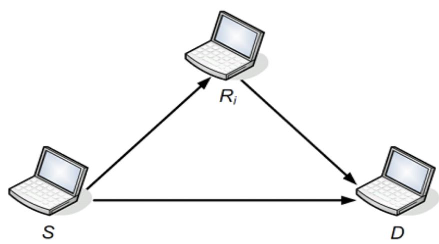


Fig. 1. Example of cooperation with one relay node

TABLE I. Delay ratio of 802.11b

B_{SD} $(Mbps)$	B_{SR_i} $(Mbps)$	B_{R_iD} $(Mbps)$	DR_i
1	11	11	0.18
	11	5.5	0.27
	5.5	5.5	0.36
	2	11	0.59
	2	5.5	0.68
2	11	11	0.36
	11	5.5	0.54
	5.5	5.5	0.72

The value of DR_i can be obtained by each of the relay, source and destination nodes. Clearly, if the value of the calculated delay ratio is less than 1, the relay channel may provide better transmission characteristics than the direct channel, due to the resulting effective higher bandwidth and lower transmission delay for end-to-end communication. Table I summarizes all possible delay ratio values less than one in the cooperation scenarios of Figure 1 when IEEE 802.11b is used (the same values can be calculated for other amendments of IEEE 802.11). As the data rate of the direct transmission increases, the cooperation opportunities will decrease. Thus, there is no other cooperation scenario with delay ratio less than one for high data rate of 5.5 Mbps and 11 Mbps between S and D in IEEE 802.11b.

2) Reliability

Besides the transmission delay, a parameter is needed to determine the reliability of the cooperative path including source-relay and relay-destination links. The reliability of cooperative path of S-R_i-D is the product of source-relay reliability (RE_{SRi}) and relay-destination reliability (RE_{RiD}).

$$RE_i = RE_{SRi} \, . RE_{RiD} \quad (2)$$

Where, $RE_{SRi} = \frac{N_{ACK-SRi}}{N_{T-SRi}}$ and $RE_{RiD} = \frac{N_{ACK-RiD}}{N_{T-RiD}}$. By using a practical sensing method, the total number of transmitted packets (N_T) and acknowledgment packets (N_{ACK}) can be overheard and computed for each link.

3) Stability

When a source node has a data packet to send, it should determine which relay node has less variation of delay ratio and reliability. The IEEE 802.11 communication medium is highly dynamic and it is assumed that the values obtained for *DR* and *RE* parameters will vary over time, especially when considering mobility. Low variations of delay ratio may indicate lower mobility of the relay node with respect to the source and destination locations, or alternatively higher stability between source, relay and destination nodes. Similarly, a relay node with low variation of reliability presents a cooperative path with more stable links having constant values of packet loss. If σ_{DR_i} and σ_{RE_i} are selected as standard deviation of delay ratio and reliability for a relay node of R_i, $(1 - \sigma_{DR_i})$ and $(1 - \sigma_{RE_i})$ refer to the stability of the relay node in terms of delay ratio and reliability. Therefore, we can define the link stability as (3).

$$ST_i = (1 - \sigma_{DR_i}) \, . (1 - \sigma_{RE_i}) \quad (3)$$

In order to select the best relay node, the source node needs to evaluate the delay ratio and reliability values of all neighbors in a table called *RelayTable*. The *RelayTable* contains instantaneous value of DR_i and RE_i for a specific period of observation window (W_{obs}). In order to calculate the average of delay ratio and reliability, the source node calculates the exponential moving average (EMA) of DR_i and RE_i as expressed in (4) and (5).

$$(DR_i)_t = \alpha(DR_{i-obs.})_t + (1-\alpha)(DR_i)_{t-1} \quad (4)$$

$$(RE_i)_t = \beta(RE_{i-obs.})_t + (1-\beta)(RE_i)_{t-1} \quad (5)$$

Where, $(DR_{i-obs.})_t$ and $(RE_{i-obs.})_t$ are the observed values at time t, $(DR_i)_{t-1}$ and $(RE_i)_{t-1}$ are EMA values obtained by the previous sample, and α and β are the constant values. The EMA values provide the decision based on the overall variation trend of delay ratio and reliability values. According to the above discussion, it is concluded that the CM metric is directly proportional to reliability (RE) and inversely proportional to delay ratio (DR). CM is also directly proportional to the stability of a relay node including reliability and delay ratio values. All these relations are expressed as (6):

$$CM_i = \frac{RE_i . ST_i}{DR_i} \quad (6)$$

B. System model

In order to evaluate cooperative schemes using CM metric, a system model based on CM should be presented. The primary condition for cooperation is lower transmission delay of the relay channel ($T_{C(R_i)}$) compared to the direct channel (T_{SD}): ($T_{C(R_i)}(L) < T_{SD}(L)$). The average transmission delay between a combination of source, relay and destination in cooperation and direct links can be then expressed as (7) and (8):

$$T_{C(R_i)}(L) = T_{C(R_i)/DATA}(L) + T_{C(R_i)/OH} + \tau_{RS} \quad (7)$$

$$T_{SD}(L) = T_{SD/DATA}(L) + T_{SD/OH} \quad (8)$$

Where, L is data packet length and $T_{C(R_i)/OH}$ and $T_{SD/OH}$ are overheads of cooperation and direct transmission respectively. τ_{RS} is the average time for relay selection, which varies between different relay selection algorithms. When CM is applied to equation (7), it can be expressed as (9):

$$T_{C(R_i)}(L) = \frac{1}{CM_i} . T_{SD/DATA}(L, B_{SD}) + T_{C(R_i)/OH} + \tau_{RS} \quad (9)$$

Then we need to apply the cooperation condition and determine the range of useful CM values. The lower bound of useful CM values (CM_{LB}) can be expressed as (10).

$$(CM)_{LB} = \left(1 + \frac{B_{SD}(T_{SD/OH} - T_{C(R)/OH} - \tau_{RS})}{L}\right)^{-1} \quad (10)$$

The relay nodes having the CM values less than CM_{LB} should be removed from *RelayTable*. Furthermore, for direct transmission, we need also to compute the equivalent metric of CM called DirectMetric (DM). Therefore, we define DM as equation (11).

$$DM_{SD} = RE_{SD} . ST_{SD} \quad (11)$$

Where, RE_{SD} and ST_{SD} are reliability and stability of direct transmission. These components are computed for direct transmission according to equations expressed in (3) and (5). Clearly, there is no meaning of delay ratio and its stability for DM metric. In order to select the beneficial relay node, the source node should remove the relay nodes having the CM values less than DM_{SD} from *RelayTable*.

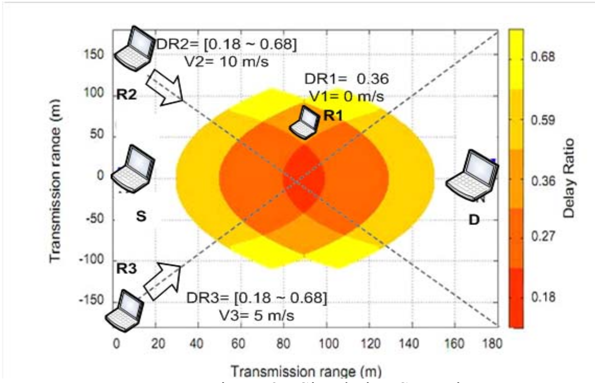
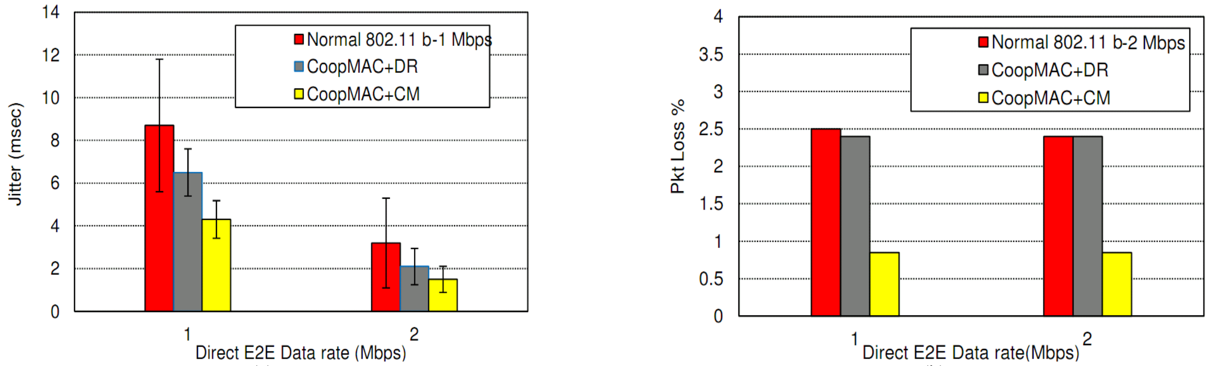


Figure 2 - Simulation Scenario

TABLE II. VOIP TRAFFIC CHARACTERISTICS

VOIP	*Voice Payload Size + RTP header +IP+UDP (bytes)*	60	64	70	200	280
	Data packet rate (kbps)	16	64	8	8	6.4/5.28
VOD	*Video Payload Size + Header(IP+UDP) (Bytes)*	500-3000				
	Data packet rate (Mbps)	4				



(a) (b)

Figure 3 - (a) Jitter value of UDP VOIP when CoopMAC using CM and DR in IEEE 802.11b, (b) Packet loss percentage of UDP VOIP when CoopMAC using CM and DR in IEEE 802.11b

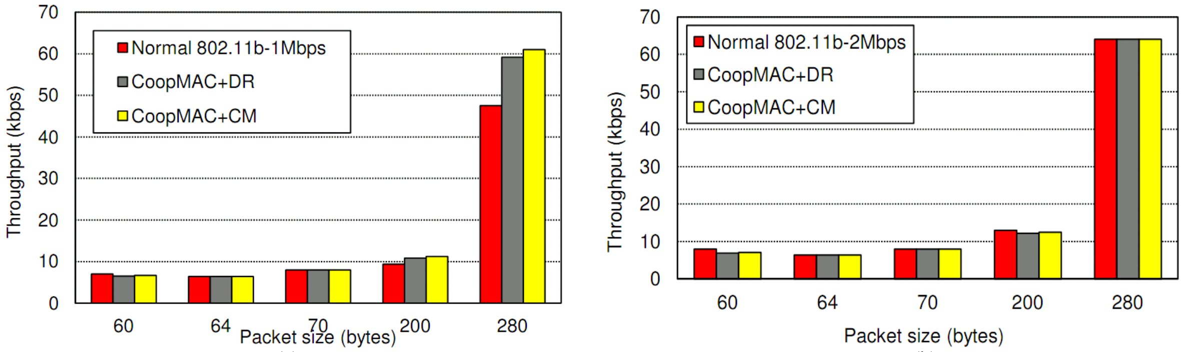
IV. SIMULATION AND RESULTS

In order to consider the impact of CM metric in cooperative MAC protocol, we implemented the well-known CoopMAC protocol [5] in the Mobility Framework (MFw) of the simulation environment OMNET++ 4.0 [13]. Two versions of CoopMAC protocol were implemented in OMNET++: the original CoopMAC which employs the DR metric for relay selection, and CoopMAC enabled by the CM metric. Figure 2 depicts a simple cooperation scenario where one static node (R1), and two mobile nodes (R2 and R3) with speed of 10 m/s and 5 m/s respectively can be the potential relay nodes for a pair of source (S) and destination (D) nodes. Node R1 is placed in an area that provides the delay ratio of 0.36 while R2 and R3 will sense different delay ratios (0.18 to 0.72) due to their movement. We also implemented a random packet drop to provide different values of link reliability.

We select VoIP as a UDP traffic source and Video on Demand (VOD) as a TCP traffic type for applications with the characteristics presented in Table II. It should be noticed that while VOD also might use UDP, that type of traffic would not provide any additional insight to our evaluation. Simulations are configured as an 802.11b indoor scenario with duration of 60 seconds, transmission power of 100mW. We use the Friis free space propagation model with path loss exponent of 4. Results are the average of 50 simulation runs in order to reduce the inherent small random variations of the radio medium.

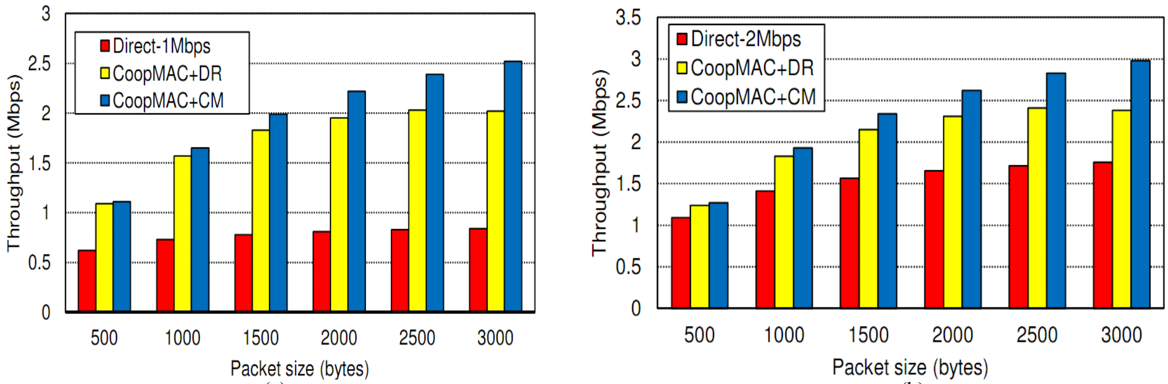
Using UDP-VOIP traffic, parameters such as jitter and packet loss are the two main concerns in performance evaluations. Figure 3 presents the values of jitter and packet loss for the cooperation scenario of Figure 2, where the direct transmission is 1Mbps and 2Mbps. As depicted in Figure 3.a, the average jitter for the CoopMAC protocol when using CM is reduced in comparison to the reference implementation. In addition, the variation range of jitter when using CM is also lower. Considering packet loss, the performance of CoopMAC is improved when using CM as the selection metric. Since CoopMAC using CM selects the relay nodes with higher stability in term of reliability and mobility while CoopMAC using DR selects the relay nodes that only provide lower transmission delay and higher bandwidth efficiency, which are minor aspects to the performance of VOIP traffic. Figure 4 presents the throughput of VOIP traffic when the direct transmission is 1Mbps and 2Mbps. Due to the relevant difference between application service rate (a few Kbps) and the existing bandwidth provided by the physical layer (a few Mbps), it is not expected to have remarkable improvements in throughput when using cooperation regardless of the relay selection metric applied.

In TCP-VOD traffic, throughput is the most important performance parameter as buffers can be used to compensate for jitter and latency. Figure 5 presents the throughput of CoopMAC in the cooperation scenario of Figure 2 when TCP-VOD is traffic type and direct transmissions are 1Mbps and 2Mbps. This figure demonstrates the improvement of using CM especially when the packet size is increased. The stability of relay links are improved by using CM, while using DR selects the relay links without the consideration of stability.



(a) (b)

Figure 4 - Throughput of CoopMAC for VOIP when using CM and DR as metric compared to 802.11 for direct transmission (a) 1Mbps and (b) 2Mbps



(a) (b)

Figure 5 - Throughput of CoopMAC for VOD when using CM and DR as metric compared to 802.11 for direct transmission a) 1Mbps and b) 2Mbps

V. CONCLUSIONS

In this paper, a new metric is discussed for cooperation when higher layer requirements are well suited to lower layer specification monitored by sensing parameters and performance metrics. The concerning parameters in UDP traffic (e.g. jitter and packet loss) and TCP traffic (e.g. delay and throughput) are considered as the main components in CoopMetric. The CoopMetric exploits the geometric model of delay ratio and relay area as providing instantaneous throughput improvement. It also uses monitoring of ACK frames to determine the relative link reliability. The stability of relay nodes is measured by considering the variations of reliability and delay ratio. Therefore, CoopMetric presents a robust criteria comprising cross layer aspects and mobility of IEEE 802.11 networks in order to provide optimum performance in cooperative communications. The future works will focus on adaptive coefficients of CoopMetric to perform mapping of associated cooperative metrics to the higher layer requirements and improve robust solution for cooperative relaying in IEEE 802.11 wireless networks. In order to evaluate the macroscopic impact of CoopMetric, a cooperation scenario will be extended to a large network with random directions and speeds of nodes.

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