Comparative Study on Cooperative Communications in the Upper Layers of Ad Hoc Networks

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***Abstract*—In this study, we compare the cooperative MAC protocols, the routing protocols, and the transport protocols, all of which support cooperative communications. Numerical results and comparisons of three cooperative MAC protocols with reactive helper node selection mechanisms are presented. Research trends, as well as the advantages and disadvantages of related research, on cross-layer cooperative MAC protocols, cooperative routing, and transport protocols are described.**

***Index Terms*—Ad hoc, cooperative, cross-layer, helper node, MAC**

I. Introduction

THE goal of wireless communications is to attain a high transmission rate and end-to-end communication reliability by combating wireless channel impairments and a limited radio spectrum. By employing space diversity, cooperative communications were introduced in the physical layers of mobile ad hoc networks to overcome these limitations. The idea of space diversity being used in cooperative communications, also called cooperative diversity, is slightly different from the traditional space diversity (e.g., MIMO) because in cooperative communications single-antenna mobile nodes transmit cooperatively as a virtual antenna array. Figure 1 explains the concept of cooperative communications. As shown in Figure 1, there are three communication nodes in a sample network: the source, the destination, and the helper node. The source node sends data to the destination node; however, due to a bad wireless channel, the source node can only send data at 2 Mbps. If any communication node that is located between the source node and the destination node accepts a role as a helper node, then the source node and the helper node can send data at 11 Mbps. As a result of this helper node's contribution, system throughput has been increased. In addition, since the destination node receives data from both the source node and from the helper node, it gains space diversity [1].

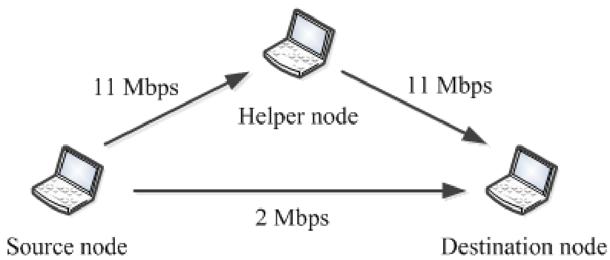

Fig. 1. Example of a cooperative communication.

Since the first studies on cooperative communications in physical layers, numerous studies have examined the physical layers' aspect. However, study results on MAC protocols and upper layers are scant, particularly when compared to research on physical layers. Therefore, a systematic study of these areas is required [12]. Instead of examining physical layers, this paper will conduct a trend survey of related research on cooperative communications in upper layers.

Section II is a survey of related studies, while Section III provides a comparative analysis of cooperative MAC protocols, routing protocols, and transport protocols that are used for cooperative communications. Section IV provides the conclusion.

II. Related Work

To date, the majority of cooperative MAC protocols that have been studied have been based on the IEEE 802.11 wireless LAN standard with various transmission rates. Determining how to decide which helper nodes to use in cooperative MAC protocols is one of the most important issues. According to when source nodes select helper nodes, the helper node selection mechanisms can be classified into two schemes: proactive and reactive schemes. The rDCF scheme [3] uses a proactive helper node selection scheme. Every mobile node

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should maintain its relay table by overhearing control frames. The source node, which has data to send, first searches for one proper helper node from the relay table, and then transmits data to the destination node using two-hop communication through the helper node. The CoopMAC scheme [4] has many points of similarity to the rDCF scheme and maintains its CoopTable for selecting helper nodes in a proactive manner. However, these two schemes only use a merit of MAC protocol, but not cooperative diversity from the physical layer.

References [5]-[7] demonstrate cooperative MAC protocols with a reactive helper node selection scheme; in particular, references [5][6] are particularly cross-layer cooperative MAC protocols that receive support from the physical layer. The reactive scheme fulfils its role only after source and destination nodes exchange their RTS and CTS frames. In a cross-layer triple busy tone multiple access (CTBTMA) scheme [5], candidates for helper nodes calculate the utility function after overhearing the RTS and the CTS frame, at which point they send a busy tone. The utility function implies the effective transmission rate through the current wireless channel; thus, the bigger the utility function, the longer the busy tone. Therefore, the candidate node whose utility function is the largest is chosen as the final helper node and the node sends the ready to help (RTH) frame to both the source node and to the destination node. Reference [6] proposed a cross-layer cooperative MAC protocol where the candidate helper nodes calculate the composite cooperative transmission rate (CCTR) and then are classified into several groups according to the value of the CCTR. The contention procedure to select the best helper node is a two-step procedure: the first step takes place among different groups and the second step takes place among different members of one group. This competition procedure is known as the timer-based selection: the bigger the CCTR, the shorter the timer. Therefore, the candidate whose CCTR is the largest is defined as the helper node. After overhearing the RTS and the CTS frame, the cooperative relay-based auto rate (CRBAR) MAC protocol [7] uses a p-persistent back-off scheme to choose the helper node.

Numerous projects have researched cross-layer design. Reference [8] extended the CoopMAC to the cross-layer cooperative MAC protocol. The source node divides its channel slot in two and transmits only half the data in the first half. If the helper node receives the correct information, then it re-encodes and sends the rest of the data in the second half. Thus, the destination node gains space diversity by receiving half the coded data from the source node and the remaining half from the helper node. Reference [9] uses the CoopMAC as the fundamental access mode. According to the transmission rates between the source node, the helper node, and the destination node, there are four different transmission modes: basic access, RTS/CTS direct transmission, source-helper-destination transmission, and receiver maximal ratio combining. The receiver maximal ratio combining scheme is based on the cross-layer design between the physical layer and the MAC protocol. Reference [10] proposed the sender initiating concurrent cooperative MAC (SI-CCMAC) protocol for wireless LANs. This scheme is designed for the downlink of the AP's one-hop region and supports concurrent transmissions with the help of two-hop relaying. As is demonstrated in references [3][4], AP is required to maintain the helper table. The basic idea is that AP sends multiple data packets, which are used for different destinations, to multiple helper nodes; after this, the helpers simultaneously relay the data to the corresponding destinations.

In addition to studies on the cross-layer design of the physical layer and the MAC protocol, there have also been studies on cooperative routing and transport protocols. Reference [11] suggested a cooperative path access control (PAC) scheme that reserves the whole path, from the source node to the distant destination node, and then begins a pipeline communication. Reference [12] insisted that, in order to support various kinds of cooperation, network and transport layers are also needed to support cooperative communications.

Reference [13] proposed a cross-layer multilayer approach for supporting virtual multiple input single output (MISO) links. It includes a MAC layer any-cast protocol to find appropriate relay nodes, between which virtual MISO links are established. The primary path is constructed with the traditional ad hoc routing protocol, such as DSR or AODV, and relay nodes for establishing virtual MISO links are selected to shorten the primary path.

III. Analysis and Comparison

This section presents a comparative analysis of previous related works, which are described as three different topics. For each topic, the problems and benefits of each proposed scheme are explained in detail.

A. Helper node selection mechanism

There are two classifications of helper node selection mechanisms: a proactive mechanism and a reactive mechanism. The proactive mechanism is complex, causes lots of traffic in the network, and does not guarantee that the selected helper node, which is determined before the RTS transmission, is the best option for a time-varying wireless channel. In order to work properly, every mobile node should share the information in its helper table with its neighbours. However, no communication protocol has been suggested to make such sharing a possibility and any communication protocol that enables the possibility of this sharing may unnecessarily cause a heavy traffic load. Thus, the reactive mechanism is chosen as our study topic, and three cooperative MAC protocols using reactive mechanism are chosen for performance comparison.

The first protocol is the CTBTMA scheme [5]. It modifies the traditional dual busy tone multiple access (DBTMA) proposed for ad hoc networks into a cooperative MAC protocol by adding one additional busy signal. After exchanging the RTS and the CTS frame, the helper node candidates compute the proper channel transmission rate from the received SNR value in the channels between itself and the source or the destination node. If they find they can reduce the frame transmission time, then they participate in the selection of the helper node. Every participating candidate calculates the following utility function U and sends a busy signal during a period that is proportional to its utility value.

$$U = W/(T_O + T_P) \quad (1)$$
$$T_P = W/r_{sh} + W/r_{hd} \quad (2)$$

After these helper node candidates finish sending the busy tone, they should monitor whether any other candidate continues sending a busy tone. If there is any continuing busy signal in the wireless channel, then these candidates are excluded from this helper node selection contest. In the end, the candidate whose utility value is the largest survives and this node sends the RTH frame to the source and the destination node. If the number of mobile nodes increases, then there will be more than one mobile node with the same utility value. Then there will be continual collisions in the helper node selection contest, which will consume both resources and time.

The cross-layer cooperative MAC protocol [6] also proposed a timer-based reactive helper node selection scheme. After overhearing the RTS/CTS frame transmitted by the source and the destination node, respectively, helper node candidates check whether they can contribute to increasing the effective transmission rate or not. When it is concluded that they can be helpful, they send a helper indication (HI) signal. They calculate CCTR R_h using equation (3), and they are then divided into several groups according to the value of the CCTR.

$$R_h = \frac{W}{W/R_{C_1} + W/R_{C_2}} = \frac{R_{C_1}R_{C_2}}{R_{C_1} + R_{C_2}} \quad (3)$$

This scheme uses a two-step contention mechanism. The first contention is inter-group and the second contention is intra-group or among the members within that group. This contention is carried out with mobile nodes' timers whose values are inversely proportional to their CCTR. Each helper node candidate triggers its timer after the CCTR calculation is finished. As soon as its timer expires, the candidate checks whether there is any signal, such as a group indication (GI) or a member indication (MI) signal. If any signal is found, then the candidate is excluded from this helper node selection contest. Otherwise, it sends a GI or an MI signal. If this transmission is successful, the candidate sends the RTH frame. In order to avoid a possible collision with other RTH frames, the related candidates retransmit their RTH frames in a mini-slot chosen randomly among succeeding K mini-slots.

The CRBAR scheme proposed in Reference [7] uses a reactive helper node selection mechanism in order to decide the proper helper node. First, after overhearing the RTS/CTS frame, all helper node candidates calculate the received SNR. After this, they begin the helper node selection process in each of the following time slots, using the p-persistent back-off scheme, where the probability p is decided using the following equation:

$$p = \frac{\delta}{1/r_{sh} + 1/r_{hd}} \quad (4)$$

In the above equation, δ is the system parameter and is closely related to system performance. However, a *p*-persistent back-off scheme does not guarantee that the selected helper node will be the best mobile node.

Reference [9] proposed a reactive helper node selection scheme, which is similar to the CTBTMA. The difference is that helper node candidates, which are determined to have smaller expected transmission times than those in the direct transmission, participate in the helper node selection procedure with an RTH frame rather than a busy signal. Therefore, this mechanism has the same problem, i.e. continuous collisions, when there is more than one candidate with the same expected transmission time.

Three different cooperative MAC protocols, suggested in references [5]-[7], are compared using a computer simulation. The simulation code is implemented in C++ language with the SMPL simulation tool [15]. For this performance evaluation, the IEEE 802.11b wireless LAN with an ad hoc mode is used as a sample network, and the system parameters used in the performance evaluation are described in Table 1. All mobile nodes are assumed to be randomly distributed in an 100m × 100m square communication area, and every mobile node is assumed to move independently in a random waypoint model [14]. It is also assumed that every source node always has packets to transmit in its buffer, which is called the saturated traffic model. This saturated traffic model is commonly used to derive the maximum system performance. In this paper, it is assumed that there is no frame transmission error for all frames, including the control and data frames. As performance measures, system throughput and channel access delay are used; system throughput is defined as the number of bits transmitted successfully during the whole simulation time and channel access delay is defined as the time period from the instant when the source node sends the CRTS frame to the instant when the source node receives the ACK frame successfully. The relation between the rates and the ranges is shown in Table 2 [5].

TABLE I
SYSTEM PARAMETERS

Parameters	Values	Parameters	Values
RTS	160 bits	SIFS	10 μs
CTS	112 bits	DIFS	50 μs
RTH	164 bits	CWmin	32 slots
ACK	112 bits	CWmax	1024 slots
DATA	1024 bytes	Basic rate	1 Mbps
Slot time	20 μs	MAC header	28 bytes
GI (MI)	3 (3)	K	4
δ	0.06	CRBAR mini-slot	6
Simulation time		1500 sec	
Transmission rate		1, 2, 5.5, 11 Mbps	

TABLE 2
TRANSMISSION RATES AND RANGES

Data rate	11 Mbps	5.5 Mbps	2 Mbps	1 Mbps
Range ($BER \leq 10^{-5}$)	48.2 m	67.1 m	74.7 m	100 m

Figure 2 and Figure 3 show the system throughput and the channel access delay of the CTBTMA scheme, respectively. It is shown in Figure 2 that the CTBTMA scheme has the best performance when the number of source nodes is five. This is because five source nodes with the saturated traffic model are enough to make this communication area completely saturated, thus when there are more than five source nodes the probability of transmission collisions increases, which results a the decrease of system throughput. Figure 2 also shows that the CTBTMA scheme has the best system throughput when the number of helper nodes is two. Since the number of supportable transmission rates is limited (ex. 1, 2, 5.5, and 11 Mbps here), utility function defined in equation (1) for helper node candidates has a limited number of values. Therefore, as the number of helper nodes increases, the probability that there is more than one helper node candidate with the same value of utility function increases. This causes repeated collisions of helper node candidates in a helper node selection contest, which results in reduced system throughput.

It is shown from Figure 3 that channel access delay is closely related to the number of source nodes but not to the number of helper nodes. This means that the contention among source nodes with CRTS frames to seize a wireless channel is a more dominant factor to channel access delay than that among helper node candidates with RTH frames.

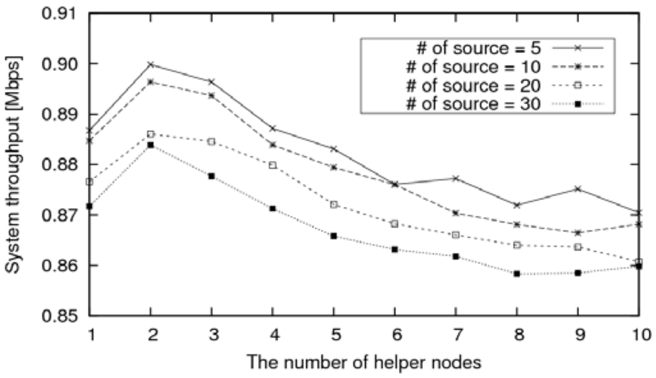

Fig. 2. System throughput of CTBTMA

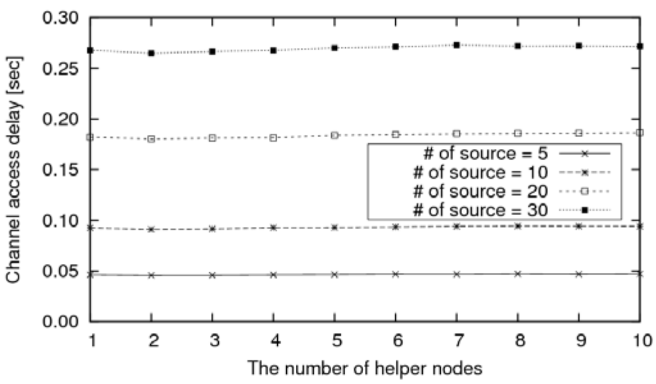

Fig. 3. Channel access delay of CTBTMA

Figure 4 and Figure 5 show the system throughput and the channel access delay of the cross-layer cooperative MAC protocol (for the sake of simplicity, called the cross-layer MAC from here on) suggested in Reference [6], respectively. It is shown in Figure 4 that this cross-layer MAC protocol has the best system throughput performance when the number of helper nodes is between 5 and 20, which is greater than the value 2 in the CTBTMA scheme. In addition, system throughput performance is greater than that of the CTBTMA scheme over its whole gamut. It is shown in Figure 5 that the channel access delay of the cross-layer MAC performance is slightly lower, but it has a pattern similar to the CTBTMA scheme.

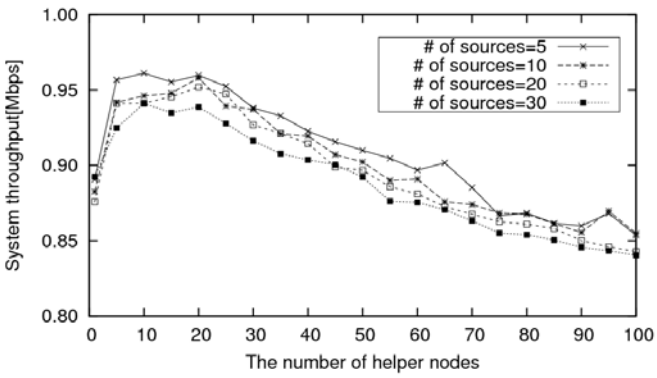

Fig. 4. System throughput of the cross-layer MAC [6]

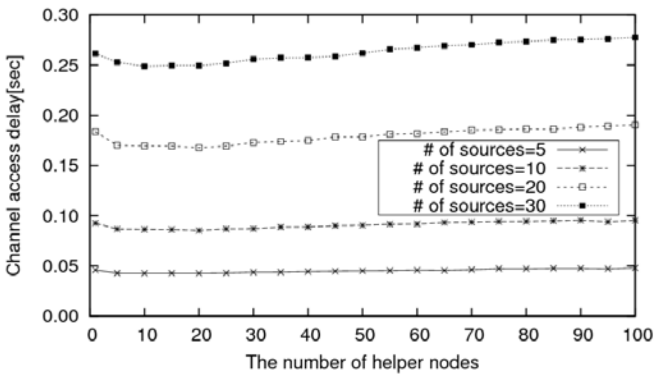

Fig. 5. Channel access delay of the cross-layer MAC [6]

Figures 6 ~ 8 show the system throughput and the channel access delay of the CRBAR MAC protocol suggested in Reference [7], respectively. The system parameter δ in equation (4) used to derive numerical results in Figure 6 and Figure 7 is 0.02. It is shown in Figure 6 that the system throughput of the CRBAR scheme tends to decrease rapidly compared to Figure 2 and Figure 4. It is also shown in Figure 7 that the channel access delay of the CRBAR scheme tends to increase a little more rapidly than the CTBTMA scheme and the cross-layer MAC scheme. Since the CRBAR scheme makes use of the p-persistent back-off scheme to select an appropriate helper node, its performance is greatly dependent on the system parameter δ in equation (4). The relationship between the system throughput and the system parameter δ is shown in Figure 8 when the number of helper nodes is 5 and 20, respectively. In this figure, no cooperation means the traditional IEEE 802.11 wireless LAN protocol without cooperation. It is shown in Figure 8 that the CRBAR has the best system throughput when the system parameter $\delta = 0.06$.

Therefore, the system parameter with $\delta = 0.06$ for the CRBAR scheme will be used for performance comparison of these three cooperative MAC protocols.

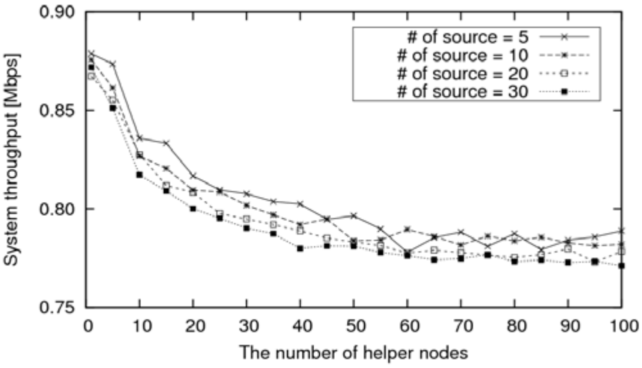

Fig. 6. System throughput of CRBAR ($\delta = 0.02$)

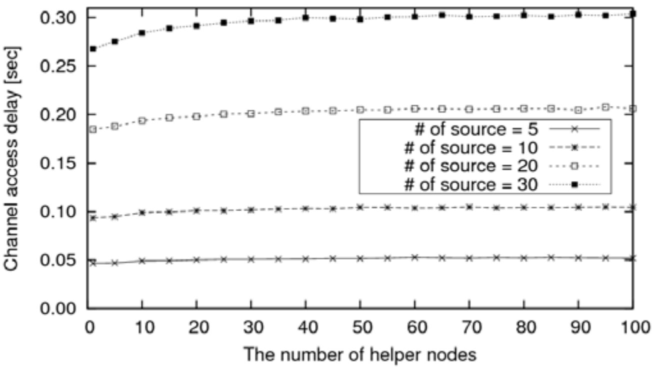

Fig. 7. Channel access delay of CRBAR ($\delta = 0.02$)

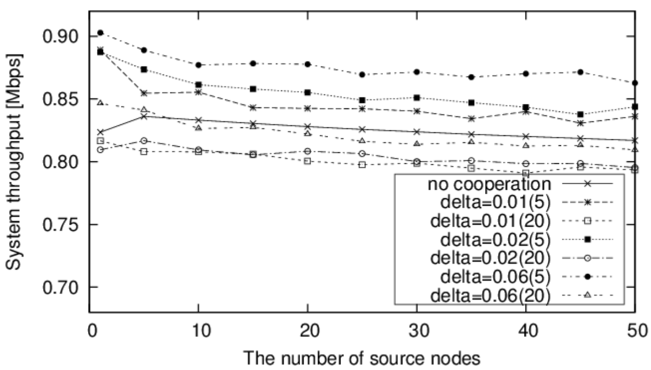

Fig. 8. System throughput of CRBAR for various δ

Figure 9 and Figure 10 show system throughputs for three cooperative MAC protocols in a different environment. First, system throughputs in Figure 9 are derived when there are five source nodes and δ=0.06, as is the case with the CRBAR scheme. This figure shows that the cooperative MAC protocol suggested in Reference [6] has the highest system performance, while the next highest is the CTBTMA scheme [5], and the third highest is the CRBAR scheme [7]. As the number of helper nodes increases, the success probability in choosing the correct helper node decreases because the number of helper node candidates with the same value in equation (1) or equation (3) increases.

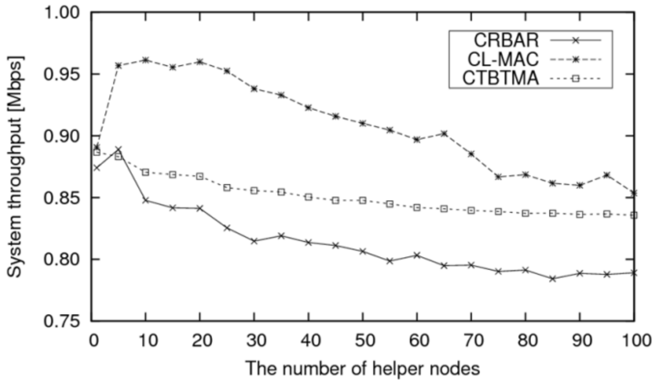

Fig. 9. System throughput of three schemes as a function of the number of helper nodes

Figure 10 shows the system throughput performance for three cooperative MAC protocols and the IEEE 802.11b MAC protocol without cooperation when the number of helper nodes is 10. It is shown that all three cooperative MAC protocols have better system performance than the MAC protocol without cooperation, and the throughput gap between Reference [6] and the others is large. Since, with the saturated traffic model, source nodes always have data frames in their buffers, this figure shows that the total system throughputs for the CTBTMA and the MAC protocol without cooperation reach the maximum value when there are approximately five source nodes.

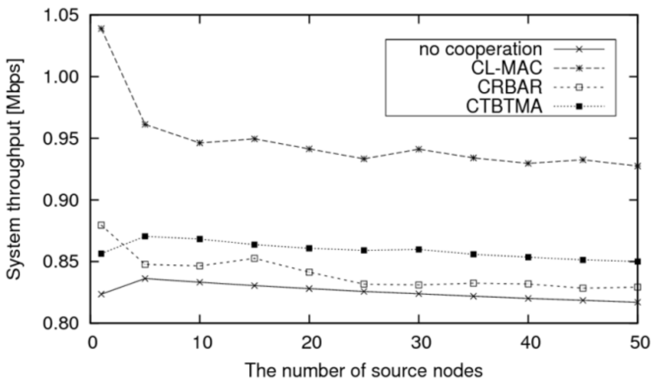

Fig. 10. Comparison of system throughput as a function of the number of sour ce nodes

B. *Cross-layer design*

Since the approach using only the physical layer or the MAC protocol has a limit for maximizing a merit of cooperative communications, the cross-layer design between two layers is required. There have been many studies on the cross-layer design, especially with a physical layer and the MAC protocol. Reference [8] extended the CoopMAC [4] to the cross-layer cooperative MAC protocol in order to enhance system performance. Each channel block, or packet, contains data (B) and parity bits (r), leading to the equation $N = B + r$ coded bits. The source node divides its channel block in two and transmits only half of its coded bits in the first half time slot. These bits are received both by the destination node and the helper node. If the helper node has the correct information, then it re-encodes and sends the remaining half in the second half time slot. Thus, the destination node receives half the coded bits from the source node and the remaining bits from the helper node, creating space diversity. But there are two questions that result from using this approach. The first question is related to the fact that the first half of coded bits, which the helper node receives from the source node, may not contain enough parity bits because it is assumed that $r \geq B$, as is shown in Reference [8]. Thus, the first question is how can the helper node decide whether the received bits are erroneous or not without parity bits in the extreme case? The second question is that separating the assigned transmission period in two time slots is opposite to the design goal of the MAC protocol, the goal of which is to reduce transmission time by raising channel transmission rate.

Reference [9] also extended the CoopMAC scheme to the cross-layer MAC protocol. By using three transmission rates, one for the direct path and two for the two-hop path, this scheme uses four different transmission modes. This approach seems to be as good as the cross-layer design between the physical layer and the MAC protocol; however, mobile nodes should share lots of information with their neighbours. The SI-CCMAC protocol proposed in reference [10] for wireless LANs is designed for the downlink of the AP's one-hop region and supports concurrent transmissions with the help of two-hop relaying. However, it is questionable whether this concurrent transmission in an AP's region is possible, especially when the helper nodes are located near one another.

C. Cooperative approach in upper layers

Compared with current studies about the physical layers and the MAC protocols, studies on cooperative routing protocols or transport protocols are relatively scant. Reference [11] investigated the overheads and challenges that emerge from implementing cooperative communications in a realistic network. Cooperative PAC, which is proposed in Reference [11], is a CSMA-based scheme where the source node sends an RTS-like control frame and then the destination node responds with a CTS-like control frame. This exchange reserves the channel along the entire route for a specified period of time. For route selection in the cooperative PAC, a modified DSR routing protocol, which needs a cross-layer design between the routing and the MAC protocol, is proposed.

Reference [12] insisted that, in order to maximize the merit of cooperative communications, systematic studies on the network and transport layers are required. Compared to traditional one-link based communications, cooperative communications generate a new concept for links, which is a multi-path link between two neighbouring mobile nodes, and this is called a cooperative link. Therefore, cooperative routing protocols handling a sequence of cooperative links should be studied systematically. In this reference, to increase the achieved throughput with cooperation, aggregating the offered resources from different cooperating entities is considered. This kind of cooperative communication can be achieved through cooperative strategies in the network and transport layers. In this scenario, source and destination nodes use several IP addresses. As a result, a new transport layer approach for merging several IP addresses into one network address at each end point should be required, and the typical solution may be a transport layer protocol with a multi-homing feature.

IV. CONCLUSION

In order to maximize the benefits from cooperative communications, systematic research into whole layers is required. At the beginning of this research, a survey on cooperative communications in the upper layers, rather than physical layer, has been described. It includes the helper node selection mechanisms, the cross-layer cooperative MAC protocols, the network layer, and the transport layer supporting the cooperation. Their problems and solutions are described in order to decide future research directions. The performances of three cooperative MAC protocols with reactive helper node selection mechanisms are evaluated and compared to each other using a computer simulation.

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