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Metrics for Optimal Relay Selection in Cooperative Wireless Networks

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Abstract—**A key design issue in relay based cooperative wireless networks is the metrics used for relay selection. Internal operational parameters and network sensing parameters are two categories recently considered as decision factors for cooperation strategies. We focus on the impact of these potential sensing parameters as indicators of the effective cooperation, from the perspective of the network layer, namely: movement, medium access delay and medium delay ratio. Simulation results indicate a strong correlation between network performance and the proposed cooperative metrics. Novel solutions for cooperation should take these metrics into consideration in order to provide better network performance.**

Keywords-cooperation loop;metrics; cooperative protocol;sensing parameters

I. INTRODUCTION

Cooperative communications as a transmission strategy has recently attracted significant attention in the design of future wireless networks [1-8]. The broadcast nature of the radio medium, long considered as a relevant waste of energy, because of the interference caused to others, is now regarded as a potential resource for possible performance improvement. This implies that neighboring nodes eavesdrop other messages and potentially help by relaying information. Cooperative communications efficiently take advantage of the broadcast nature of wireless networks, making possible for all network nodes to transmit cooperatively, thus providing diversity that can significantly improve system performance.

In cooperative scenarios, there are two main questions to be answered: a) how to determine the optimal relay (helper) node to cooperate with and b) how to determine when to cooperate. The answer to these questions is directly related to the parameters sensed and decisions that are taken based on the each parameter value, as well as the characteristics of the traffic being transmitted. Therefore, the selection of sensing parameters affects the overall system performance. The main objective of this paper is to propose and to evaluate the impact of several sensing parameters that can be used for improving performance in cooperative protocols for wireless networks. It should be pointed out that we aim to improve performance as perceived by user applications using the TCP/IP communication stack.

The rest of the paper is organized as follows: Section 2 discusses the state-of-the-art of cooperation techniques and associated metrics. The concept of cooperation loop and the associated relevant parameters are described in Section 3. In Section 4, we evaluate how the relay selection based on various sensed parameters can impact the performance of cooperative networks. Section 5 concludes the paper and presents future directions.

II. RELATED WORK

The first concepts leading to cooperative communication can be traced back to the groundbreaking work of Cover and El-Gamal on the information-theoretic properties of the relay channel [1]. This work analyzed the capacity of a three-node network consisting of a source, a destination, and a relay. In most research publications in the area of cooperative communications, the improvement of using cooperation techniques has been analyzed from a fundamental point of view, considering different cooperation schemes at the link layer [2-4]. When we consider cooperation at the network level, we find fewer proposals. It seems reasonable to believe that, compared with previous works focused in the radio level (PHY), cooperative schemes analyzed at a network level will pose different requirements and design parameters to take into account for designing new protocols for cooperative networks.

Most importantly, few steps have been taken in the field of identifying and characterizing metrics that meet actual network requirements and make use of cross layer parameters. Most of publications [5-8] consider only the initial parameters of the physical layer achieved at the MAC layer regardless of the higher layer impact on cooperation schemes. In [5], the Cooperative MAC (CoopMAC) protocol is designed in the context of 802.11b wireless networks in which stations transmit first to an intermediate station and then to the access point. According to this proposal, the sensing parameters are comprised by the acquired bit rates from overheard packets and the decision parameter is restricted to the delay ratio calculated over the direct and cooperative paths. Within the context of 802.11e networks, and in order to increase performance while providing enhanced Quality of Service (QoS) mechanisms, both the Cooperative-MAC (CMAC) and FEC-CMAC (FCMAC) protocols were presented in [6]. In these solutions, cooperation is triggered when a station detects (or senses) an erroneous packet transmission, between any other pair of source-destination neighbor stations, and decides to cooperate by retransmitting a copy of the overheard transmission, as long as the received packet has no errors. The CD-MACA protocol [7] proposed within the framework of wireless ad-hoc networks, makes use of information included in the Request-to-

Send (RTS), Clear-to-Send (CTS), and Data frames (DATA) of 802.11 in order to enable cooperative relaying, thus improving overall performance. CD-MACA authors proposed that when a source terminal fails to receive the CTS packet, if any other station had received it properly, this other station will take the place of the source terminal and retransmit the data packet. Sadek *et al.* [8] proposed a new approach for designing TDMA (Time Division Multiple Access) based protocols for relay-based wireless networks, and the results indicate a relevant increase in the maximum stable throughput by applying the solutions to pure TDMA. In this solution, potential relay nodes store packets sent to the Access Point in a queue, and if no reply is received they use the empty time slots in a TDMA allocation method to retransmit the failed transmitted packets.

Nevertheless, none of these methods takes in consideration that transmissions between different nodes can be very differently due to the multi rate adaptation algorithm: it is actually an essential feature of current wireless systems, the capability to dynamically change its transmission rate according to current radio link conditions. Any cooperation strategy to be effective at the network level needs to consider this aspect as well; otherwise the potential improvement will be restricted to only a small set of situations.

III. COOPERATION LOOP ANDSENSING PARAMETERS

All systems that are able to adjust their operation according to changes in their environment are based on feedback information. While some of these concepts are associated with Autonomic Systems [9], cooperative systems are no exception in this respect: they also require a feedback loop.

This cooperation loop can be structured as depicted in Fig.1, consisting of three phases: sense, decide and act. In our view, the cooperative protocol will employ sensing methods to sense the environment and neighbor nodes (Sense). The observations captured by the sense action will be further used for decision (Decide) when the cooperation policy determines the strategies to be followed based on the observations and cooperation purposes. For instance, if the cooperation aims for minimizing delay, the sensing parameters and decision methods differ from the case where cooperation is concerned about power issues. The final phase is carried out by the sending control messages for initiating the cooperative transmission (Act). Different environments such as Wireless LANs (WLANs), Wireless Sensor Networks (WSNs) and Wireless Mesh Networks (WMNs), have particular requirements which can be mapped to the operation of all states in this reference model.

One of the main motivations for cooperative communication is to optimize the resource allocation at the user and network levels. As illustrated in Fig. 1, the sensing phase performs as the initiation for the cooperation loop. Thus, the accurate selection of the appropriate sensing parameters (and its relative weight), play a crucial role in system performance. In the following, we illustrate key important metrics to help relay decision, which we categorize in internal operational parameters and network sensed parameters. These parameters can be used by a myriad of algorithms for cooperative communication, combined differently depending on the overall system objectives.

A. *Internal operational parameters*

Internal operational parameters include the main characteristics of every node, which are relevant for its own behavior in a cooperative scenario, most commonly related to energy and load. The energy source, if running from battery, and its remaining charge, are basic parameters that should be considered in every cooperative scheme. Nodes plugged to the grid have little energy constraints. When powered by a battery, if the remaining energy level is low, its cooperation with the other nodes in the network will lead to an inefficient use of the equipment, as it reduces network survivability (and potentially reduces overall capacity in the long term). Also, the transmission power selected by the candidate relay node will be a key factor in the total energy consumption of each node and overall network performance, together with sleep intervals. Thus, one node with low energy level has less opportunity to be selected as a relay even though its other metrics may suggest a potentially good performance increase.

The effectiveness of each node to cooperate can also be evaluated by the input and output traffic. One node with too much input traffic cannot be a good candidate for the cooperation since its participation in the cooperation can reduce network performance, due to its inherent performance limitations in packet processing and medium access. So we consider load as a decision parameter for cooperation process. Note that internal operational parameters have high relevancy, since the willingness of one user to participate in cooperation is the first step toward this end. Of course, incentive mechanisms may be in place to promote increased cooperation [13].

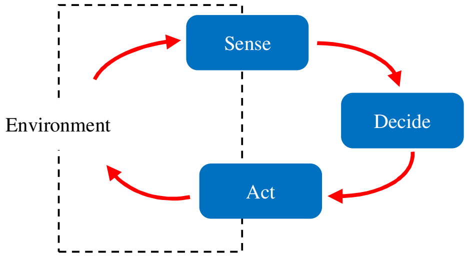

Figure 1. Feedback loop for the cooperative relay process

B. *Sensing parameters*

This category comprises the set of parameters sensed of the neighbors, network topology and wireless medium, which can have impact on the gain of cooperative solutions. Some of these parameters are obtained from sensing the environment and others are acquired by some computation based on sensing the user information itself. These parameters are the following: delay ratio, access delay, and movement direction. In order to provide a better understanding about these parameters, we choose one scenario relying in 802.11 to illustrate this relevance.

Average delay ratio: In wireless networks, effective delay is one of the most important parameters for the design of every protocol. Therefore, in cooperative schemes we need to include delay ratio as a metric parameter. This parameter is defined as the ratio of the transmission delay in the cooperative path (through the relay node), over the transmission delay in the direct (non-cooperative) path. In Fig. 2, the delay ratio sensed by node C is defined as:

$$DR_{acb} = (D_{ac} + D_{bc})/D_{ab} \qquad (1)$$

where, the D_{ab}, D_{ac} and D_{bc} are the corresponding delay between the three nodes as calculated from the inverse of the current transmit rate ($D_i=1/R_i$).

Processing delay in node C is neglected, but can be included if the node C characteristics are known, or processing delay can be obtained. The relevance of this metric is due to the fact that data rates will potentially differ in these three links: in 802.11 data rates are automatically adjusted based on Signal to Noise Ratio (SNR). Node C, as a potential relay, can discover the potential bitrates between itself and node A and B by overhearing control frames (RTS and CTS). Node C can find R_{ac} and R_{bc} from the signal strength of RTS and CTS frames. Node C can also obtain the actual data rate achieved between A and B (R_{ab}) from overhearing data frames exchanged between node A and B. The 802.11 MAC header (or in more detail, the PLCP sub-header), contains a field named SIGNAL, which denotes the bit rate of every data packet sent to the network. By taking in consideration of delay ratio, senders can predict the gain of using a relay over using the traditional direct communication scheme. Clearly, the value of delay ratio less than 1 points towards improving network performance, due to a resulting higher bandwidth for end-to-end transmission by using the relay path.

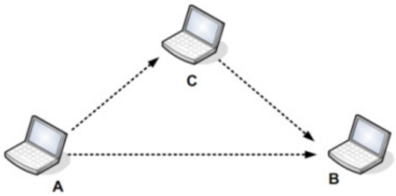

Figure 2. Example of cooperation with one relay node

Table I shows all possible delay ratio values for the scenario depicted in Fig.2 when end-to-end data rate of direct transmission between node A and B varies from 1Mbps to 11Mbps. Analysis is limited to 802.11b for simplification, but it can be extendable to 802.11a, g or n. The minimum delay ratio (=0.18) indicates the situation with the best performance gain when using cooperation. In this case, transmission delay is reduced by 72% if the direct data rate is 1Mbps and the data rate between source to relay and relay to destination is 11Mbps. As the data rate between A and B increases, the usefulness of using a relay decreases. Still, even when the end-to-end data rate of the direct path is 2Mbps, performance can be improved if a relay path is chosen. From our analysis, we can conclude that relay selection algorithms are only useful when end-to-end data rate is near the lower limits allowed by the standard. For instance, if the A to B data rate is 5.5 Mbps or 11 Mbps, cooperation will not present any benefit and actually it will degrade network performance.

Average access delay: Access delay is defined as the average time from the moment the frame is held in the transmission buffer queue, until the time the frame is actually transmitted. In cooperative schemes, this parameter influences the transmission delay and can be one of the most important metric for a relay selection algorithm. Access delay represents the load in the network caused by its own traffic, by interference, as well as by traffic produced by other nodes in the neighborhood. If nodes present high access delay, they should not be used as a relay as their surrounding wireless medium has little free capacity. And this will be true independently of the delay ratio presented. None of the proposals described in the related work takes in consideration this parameter as a parameter for triggering cooperation.

Movement direction: This parameter is particularly important in environments with mobility, and it can be estimated also by overhearing control traffic (by node C). Considering that the speed of a radio transmission is close to $2.998\text{x}10^8$m/s, each meter between sender and destination will imply an additional delay of 299.8ns in any transaction. As presented in [10], current hardware can use this method to estimate distances with high precision (<1m). Even without dedicated hardware, by averaging multiple transactions, similar conclusions can be achieved (although with higher error) [11]. Absolute distance is not really relevant for the cooperation decision process, however direction is. If a node is approaching a relay, the sender can expect that the communication characteristics of the channel between relay and destination will improve (better delay ratios). The opposite will be true if a node is increasing its distance from the relay. In the case of 802.11 wireless networks, direction can be estimated by calculating the variation of time between the reception of RTS and CTS control frames. When a relay node listens to the source's RTS, it sets up a timer (called RTS-CTS timer) internally that will be stopped as soon as it receives the CTS from the destination. The greater the distance between the three nodes, the greater will be the time measured. If RTS-CTS frames are not enabled, the same concept can be extended to DATA-ACK frames even when the DATA frame size varies. If we assume the scenario depicted in Fig. 2, node C can measure the RTS-CTS delay for packets sent from node A to node B, thus estimating if B is approaching or departing from C.

TABLE I. DELAY RATIO VALUES LESS THAN 1 FOR 802.11B

Delay ratio	*A to B Data rate(Mbps)*	*A to C Data rate(Mbps)*	*B to C Data rate(Mbps)*
0.18	1	11	11
0.27	1	11	5.5
0.36	1	5.5	5.5
0.59	1	2	11
0.68	1	2	5.5
0.36	2	11	11
0.54	2	11	5.5
0.72	2	5.5	5.5
1.5	5.5	11	5.5
2	11	11	11

IV. SIMULATION AND RESULTS

In this section, we evaluate every described sensing metric in one scenario using IEEE 802.11b as the communication protocol. Even though the number of nodes and the resulting medium access contention can affect on the overall system performance, our evaluation is focused on the impact of the sensing parameters in the characteristic of end-to-end application data delivery through a relay node. Note that this is very different from previous works, based on radio link metrics. We consider the impact at network level, with the rate adjustments mechanisms, automatically performed as in real systems. We assume that all relay nodes have the same internal operational parameters which means their willingness to participate in cooperation is equal. Simulation experiments were performed using OMNeT++, version 4.0 [12] in an Ubuntu environment. Simulations are configured as an 802.11b indoor scenario with duration of 20 seconds, transmitted power of 100mW, packet size of 1024 bytes generated at a constant bit rate (CBR) of 2 Mbps UDP. 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.

A. Scenario 1:Delay Ratio

In the first scenario, we consider the performance of a cooperative communication using potential relay nodes presenting different values for delay ratio. To do this, we need to know the relative distances between source, relay and destination nodes. In order to find the data rate versus transmission range, firstly, we setup a simple scenario with two nodes using 802.11b. Table II indicates the data rates of different transmission ranges for BER < 10^{-5} achieved from a simulation using OMNET++: as distances changes, data rate will be adapted accordingly. Then we configured a simulation scenario as depicted in Fig. 3, wherein two communicating nodes (*A* and *B*) located at the distance of 180 meters, and five relay nodes (*R1* to *R5*) located at different locations between *A* and *B*. The distance between nodes *A* and *B* is such that the effective data rate between these two nodes is 1Mbps. In Fig. 3, different types of lines indicate the different bit rates (2Mbps, 5.5Mbps and 11Mbps) achieved between every relay node and each nodes of *A* and *B,* which are the result of the different locations. In this scenario, every relay node receives packets from node *A* as the source and can forward them to node *B* as the destination.

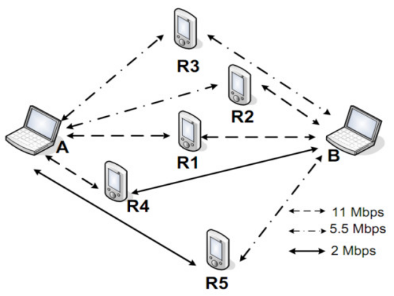

Figure 3. Cooperation scenario for two nodes with direct transmission of 1 Mbps

TABLE II. IEEE 802.11B TRANSMISSION RANGES

Data rate(Mbps)	11	5.5	2	1
Range(meter)	100	130	150	180

Table III depicts the average delay ratio that is computed at each relay node (all nodes overhear all transmitted packets). As illustrated in Table III, the minimum delay ratio is reported by *R1* while it has the minimum and equal distances to *A* and to *B*. The maximum delay ratio is presented at *R5,* which is at the greatest distance from source and destination. For better understanding the effect of delay ratio as a key metric of cooperative wireless networks, we have measured the average service throughput and average end-to-end delay for different values of delay ratio, when using the cooperative path. As shown in Table III and Fig. 4, the values of throughput and delay measured are strongly related to the computed delay ratio. In particular, throughput of the cooperative path tends to decrease with increasing values of delay ratio, while the end-to-end delay is directly proportional to delay ratio.

TABLE III. AVERAGE SERVICE THROUGHPUT AND DELAY RATIO OF RELAYS IN FIGURE 3

Relay	**R1**	**R2**	**R3**	**R4**	**R5**	**No Relay**
Delay ratio	0.18	0.27	0.36	0.59	0.68	-
Average service throughput (Pkt/s)	184	180	169	120	109	93

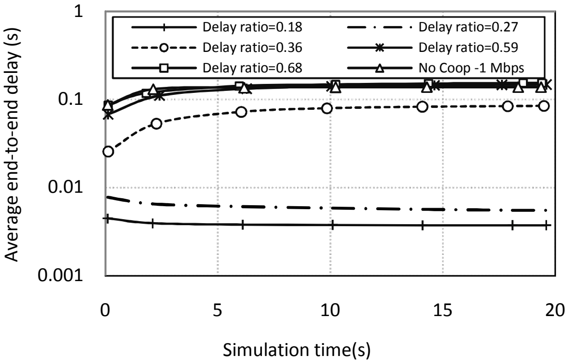

Figure 4. Average end to end delay versus delay ratio

Another simulation scenario is depicted in Fig. 5 where two nodes *A* and *B* have a direct transmission of 2Mbps at the distance of 150 meters while three relay nodes (*R1* to *R3*) are sensing different delay ratio values. Table IV and Fig.6 illustrate the result of this cooperation scenario. As expected, the cooperative gain achieved for the end-to-end direct transmission of 1Mbps is more than the case of 2Mbps. In both scenarios depicted (Fig. 3 and Fig. 7), the optimum relay (*R1)* has the delay ratio of 0.18 and 0.36. The results indicate that the average service throughput gain of cooperation by using *R1* in Fig.3 increases up to 200% (Table III) while Table IV shows an average service throughput gain of 10% for *R1* in the simulation scenario depicted in Fig. 5. In addition, even though average end-to-end delay of the direct transmission path is less than or equal to the delay provided by some cooperative relay transmissions (R4 and R5 in Fig. 4 and R3 in Fig. 6), the values of the corresponding average service throughput (Table III and Table IV) reveal that all cooperative transmissions perform better than direct transmission, because of an higher number of dropped packets in direct transmission.

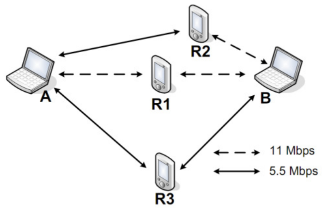

Figure 5. Cooperation for two nodes with direct transmission of 2Mbps

TABLE IV. AVERAGE SERVICE THROUGHPUT AND DELAY RATIO OF RELAYS IN FIGURE 5

Relay	R1	R2	R3	No Relay
Delay ratio	0.36	0.54	0.72	-
Average service throughput (Pkt/s)	184	180	169	164

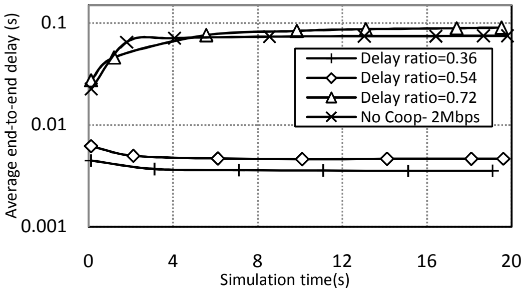

Figure 6. Average end to end delay versus delay ratio

B. Scenario 2: Access Delay

To consider the influence of medium access delay on the cooperation process, we set up another scenario (see Fig. 7) in which two nodes (*C* and *D*) create background traffic at different rates, from 0 to 20 Mbps. Background traffic interferes with the relay node *R* by increasing its delay accessing the wireless medium. The data rate between these three nodes is 11Mbps. Similar to the scenario depicted in Fig. 3, node *R* is placed at several different coordinates in order to experience different values of delay ratio. The data rate between sender and receiver nodes (*A* and *B*) is 1Mbps. As depicted in Fig. 12, access delay experienced by relay nodes has a strong impact on throughput for cooperation with high delay ratio (0.36, 0.59 and 0.68) while relays with low delay ratio (0.18 and 0.27) are not remarkably affected by interference generated by nodes *C* and *D*. The results also illustrate that one relay with higher delay ratio (e.g. 0.68) but no interference (when there is no background traffic) performs better than another one with less delay ratio (e.g. 0.36 or 0.59) and higher interference (when background traffic varies between 2 and 20Mbps). The importance of considering access delay is highlighted when we have delay sensitive application (e.g. VoIP).

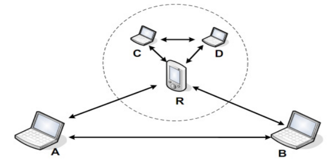

Figure 7. Scenario 2-Access delay

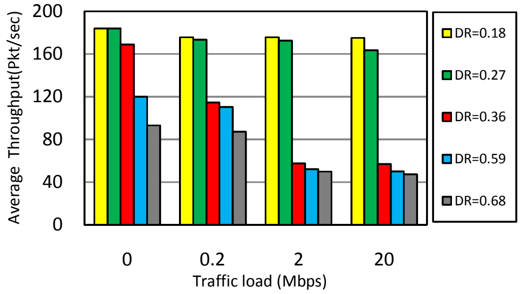

Figure 8. Average service throughput versus traffic generated by node C

C. Scenario 3:Movement Direction

Movement direction estimation can improve the relay selection algorithm, allowing nodes to predict the relative movement direction of the neighbors. Fig. 9 shows the simulation scenario in which node *A* and relay node (*R*) are static, while node *B* moves towards or away from the relay node (*R*), with velocities of 5 and 10m/s. When the relay node *R* receives the RTS sent by node *A*, it starts the timer and when it received the CTS from node *B*, it stops the timer. Fig. 10 depicts the delay measured by a timer at relay node *R*. Since node *A* and node *R* are static, the transmission time of RTS is constant, while based on location of node *B*, the reception time of the CTS will vary. We focus on the average absolute variation of the delay measured in an RTS-CTS transaction. This value increases when node *B* moves away from the relay node *R* in an almost linear way. When node *B* approaches the relay *R*, the opposite trend is observed, with similar values. Moreover, the values observed are in line with the values expected by theory and within reasonable accuracy for current hardware.

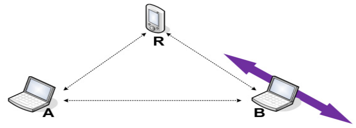

Figure 9. Scenario 3 - Movement estimation

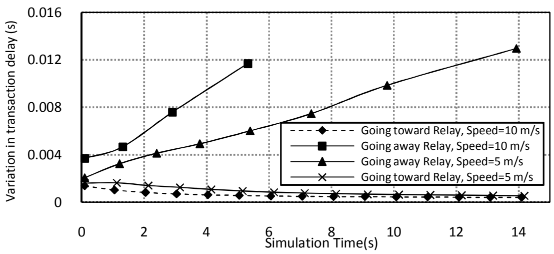

Figure 10. Average transaction delay as measured at the relay node

The major outcome of these results is that they provide insight, pointing that besides the delay ratio, which considered as the main decision factor in relay selection of existing cooperative protocols, the access delay of relay nodes and the movement direction information can also be taken into account for optimized relay selection algorithms.

V. CONCLUSIONS

In this paper, we propose a cooperation loop as a reference model for all cooperative algorithms in relay based cooperative wireless networks. The sense action is an aspect of this cooperation loop, which we considered as the starting point for cooperative scenarios. Instead of link state information, which is considered as a key metric for radio performance aspects, we propose network state information for deciding when to cooperate, with the result of having effective solutions for application data. We discuss access delay, movement, and delay ratio as important metrics for cooperation algorithms, and analyzed their impact in several scenarios. The simulation results, using the 802.11b medium, demonstrate that these metrics strongly impact any cooperation strategy aiming to improve network performance. In our simplified analysis, we were able to show that in which conditions the cooperation will be effective, since rate adaptation is an important phenomenon.

The future work will focus in mapping the associated metrics to the higher layer requirements to improve robust solution for cooperative relaying in wireless networks, and design of optimum algorithms exploiting these metrics. Moreover, by advertising the sensed parameters we hope to improve performance by selecting the most appropriate relay node according to traffic characteristics. In order to exploit the network-centric metrics, we can create a table in every relay node to define its priority value to participate in cooperation. The priority value, which can be obtained based on the internal operational parameters and achieved sensing parameters, is sent to source and destination to fulfill the relay selection procedure.

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