A Cooperative Low Power Mac Protocol for Wireless Sensor Networks

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***Abstract*—Over the last decade cooperative communication in wireless sensor networks (WSN) received much attention. A lot of works have been done to propose a MAC layer that supports cooperative communication. However the impact of the association of a cooperative communication technique with a low power listening scheme was not studied in the literature. In this paper we propose CL-MAC, a Cooperative Low power mac protocol for WSNs. CL-MAC implements jointly Low Power Listening and cooperative communication. More precisely, we propose two variants of this protocol: a proactive version CL-MAC(P) and a reactive version CL-MAC(R). In order to evaluate the performances of the two proposed CL-MAC variants, we compare its to those of X-MAC. Simulation results proved that our protocol is able to enhance the use of the channel and to reach promising energy preservation especially in dense networks.**

***Index Terms*—Cooperative relaying, relay selection, energy efficiency, wireless sensor networks, low power listening.**

I. INTRODUCTION

In the last years, the technological evolution in the field of Wireless Sensor Networks (WSN) was impressive. WSNs are composed of small and cheap sensors that can sense, compute and communicate. Their role is increasing in nowadays life. Such technology is used in habitat monitoring, health care applications and security applications. Despite the services they provide and the advantages they bring, WSN have several constraints. A sensor is, most of the time, battery powered and without possibility of scavenging. Moreover, a sensor is equipped with a small antenna having a reduced transmission range. All these constraints motivated a multitude of research efforts around WSNs. In order to preserve energy, the researchers tried to reduce the time spent by nodes in idle listening. Therefore, they proposed some techniques like Low Power Listening (LPL) to schedule regular sleep periods. Furthermore, the energy is not the unique restriction. In general the channel conditions may lead a node to triggers several retransmissions for the same data packet. Consequently, a solution is required to overcome the effect of bad channel conditions and reduce costly packet retransmissions. Cooperative communication [1] is one of the possible solutions. It aims to enhance the network channel conditions and to decrease the number of retransmissions by using the antennas of the neighbors.

This paper aims to combine the two above mentioned concepts, i.e. LPL and cooperative communications, in a MAC protocol so as to preserve more energy and improve the radio resource usage. The remainder of this paper is organized as follows: in Section 2 we discuss related works, followed in Section 3 by the detailed description of our protocol, CL-MAC, and its variants. Section 4 presents and discusses performance evaluation results. Finally, we summarize the main results and presents some trails for future work in Section 5.

II. RELATED WORKS

Low Power Listening (LPL) is conceived to cope with the energy constraints of WSN. LPL saves the energy of the sensor nodes by scheduling cyclic radio sleep periods. The node that has a packet to send, has to wake up its neighbors by sending traffic, called preamble packets, on the channel. When a neighbor wakes up and hears these preamble packets, it realizes that another node wants to send some data packets. Various LPL protocol versions are proposed in the literature. B-MAC [2] uses long preambles to wake up the neighbors. The sender keeps sending a long and continuous preamble, a unique long packet, until all the neighbors wake up. It sends, then, the data packets. X-MAC [3] enhances B-MAC. X-MAC suggests dividing the long preamble into several micro-preambles spaced by *listen* periods and including the destination address. These introduced listen periods allow the destination, when it hears a preamble, to send an early Acknowledgment and to inform the sender to stop sending preambles and start sending data. This scheme reduces the number of sent preambles and preserves further energy. In Wise-MAC [4], a fixed wake-up schedule is maintained by the coordinator. The coordinator sends data packets to the concerned node relevant to the maintained schedule.

A different LPL approach was presented by RI-MAC [5]. On the contrary to B-MAC [2] and X-MAC [3], where the sender initiates the data transmission, RI-MAC proposes a receiver initiated low power listening MAC protocol. The goal of RI-MAC is to reduce the channel occupancy time. Unlike B-MAC or X-MAC, the sender in RI-MAC does not transmits preambles in order to wake up its neighbors, but remains silent until the receiver sends a beacon to express its ability to receive the data packets. If a sender is ready the data transmission starts.

In addition to the energy constraints, bad channel conditions affect the performance of WSN. The nodes may be constrained to perform several transmissions to successfully deliver a packet. Cooperative communication proposes to the source to use the best channels, available in the neighborhood. In fact, when the channel between a source S and a destination D is poor, cooperative communication [1] may be a solution by finding a better transmission path through the neighbors of S and D. Instead of retransmitting on the same poor channel and risking an additional retransmission, the node (S or D) looks if the channels of the neighbors are better and uses them for possible retransmission.

The most important step in a cooperative communication is the selection of the neighbor that will retransmit the packet on behalf of the source. Hereafter, we call this neighbor a relay node. The relay (R) selection is usually based on the Channel State Information (CSI) of the channel between S, D and R [6], [7]. Additional information like residual energy can also be used [8], [9]. The relay selection requires additional signaling overhead compared to non-cooperative schemes. For example, Core-MAC [10] uses RTS/CTS for channel reservation and relay selection and it relays the packet only when required.

LPL and cooperative communication have proved their efficiency in reducing the power consumption and enhancing the channel conditions. The objective of this paper is to conceive a protocol that implements LPL and cooperative communication so as to take advantage from their benefits. As far as we know, this work is the first one that combines this two concepts.Our proposed protocol and its two variants use LPL to schedule sleep periods for the nodes and cooperative communication to get over bad channel conditions. The combination of the two techniques is presented in the following section.

III. CL-MAC: A COOPERATIVE LPL MAC PROTOCOL

In this section, we propose two variants of CL-MAC; a proactive variant CL-MAC(P) and a reactive variant CL-MAC(R). The two variants implement LPL and cooperative communication. CL-MAC(R) implements a reactive relay selection, in which the relay is selected after data transmission by the source CL-MAC(P) implements a proactive relay selection. In this variant, the relay is elected before data transmission by the source. The two protocol variants use the same set of mechanisms for activity management, preamble collision avoidance and relay selection.

A. Activity Management

In both protocol variants, the nodes practice a sleep and activity period of fixed lengths. Each node sleeps for a period P, then wakes up for a short duration Wp then returns to sleep and so on. When a source node has a packet to send, it must wakes up its neighbors. Therefore, it sends a sequence of micro-preamble packets spaced by listen periods. This allows to reduce the energy consumed in sending excessive preambles as practiced by other protocols [2]. The length of this sequence of micro-preambles must be sufficient so as to reach all the neighbors. Each preamble contains the destination address and the Rendez-vous-point (RDV). The RDV point is the time on which all the neighbors have to wake up.

When a node wakes up, it listen to the channel for a period of an inter-preamble to verify if there is any activity. After the reception of the preamble, the node reads from it the destination address and the RDV point information. If the node is the destination, or if the destination of the preamble is known as a neighbor (i.e. the node is a potential relay), it schedules to wake up, in such a way to reach the RDV. In the other cases, the node is not concerned by the transmission and returns to sleep. Therefore, at the RDV point, we have three types of nodes that are awake: the source, the destination and possibly one or more potential relays (a part of the neighbors). Once the relay is selected and data transmitted successfully, the nodes return to sleep mode and so on.

B. Preamble Collision Avoidance

When a Sender (S) have a packet to send, it wakes up its neighbors by transmitting a sequence of preambles (PR in Fig. 1). In the case we have several senders on the same neighborhood there is a possibility that the preambles collide with other packets. In order to avoid these collisions, the sender has to perform some verification. Before sending any preamble, S checks the status of the channel (free or not) using CCA (Clear Channel Assessment). It listens to the channel for a period of an inter-preamble. If an is detected, S delays its packet transmission until the end of the ongoing one.

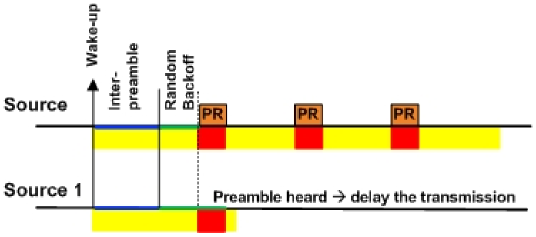

Fig. 1. Preamble Collision Avoidance

Furthermore, another medium access problem remains. If two senders want to send data packet at the same time, they wait for the inter-preamble, find that the channel is free and starts the preamble transmission. In this case, the senders do not realize that the preambles had collided. In order to avoid these collisions, the senders have to wait for an additional random backoff after the inter-preamble. This backoff will reduce the probability of simultaneous access to the channel and reduce collisions.

C. Relay Selection

The relay selection consists in determining, among the common neighbors of the source and the destination, which one can have the best conditions (energy, channel state) to retransmit the packet on behalf of the source. Relay selection is made for each packet anew since the environment can change from one moment to another. The potential relays decide autonomously which one is the Relay. The conditions of a potential relay are evaluated using a utility function called TOPSIS (Technique for Order Preference by Similarity to Ideal Solution [11]). The potential relay deduces the state of the channel to the destination from the last received packets and read its own residual energy. The values of these parameters are injected into the utility function to produce a score (NodeScore in Formula. 2). This score is converted into a backoff timer (SelectionBackoff in Formula. 2). α and β in Formula 2 are respectively the coefficients of the CSI and RE (the Residual Energy). This coefficient are set following the importance given to RE and CSI. The neighbor that computed the smallest backoff responds first to the relay selection request and becomes a Relay.

$$NodeScore = \alpha \times CSI + \beta \times RE \quad (1)$$

$$SelectionBackoff = \frac{1}{NodeScore} \quad (2)$$

Also, some of the potential relays may not take part in this relay selection for one of the following reasons. When the energy of a node is under a critical threshold, the node prefers to preserve its energy to send its own traffic. In addition, if the channel conditions between the potential relay and/or source/destination do not enhance the global channel conditions the node retires from the relay selection.

D. CL-MAC(P): Proactive low power cooperation

In this variant of the protocol, the relay selection is always made for each packet, even if there is no outage. Besides, cooperative relaying is invoked only when an outage occurs. On the RDV point all the nodes (S, D and the potential relays) are awake. At first, D sends a Begin Relay Selection (BRS) packet (see Fig. 2). The potential relays receive the BRS and measure the Signal-to-Noise ration (SNR) of the channel to the destination and recover their residual energy. They compute a backoff timer using these two values as explained earlier and contend for the channel. The potential relays that have not correctly received BRS or that detected that the SNR of the packet is under a threshold, do not participate in the selection.

The potential relay that has the shortest backoff announces its selection as relay by sending a Relay Reply (R-R) packet. The destination responds with a Relay ACK (R-Ack). The remaining potential relays cancel their backoff and return to sleep. Once the relay has been elected, S sends its data packet. If D has correctly received it, D sends an ACK. Otherwise, the relay detects the absence of the ACK and retransmits the Data. Then, if the retransmitted packet is correctly received, D sends the ACK.

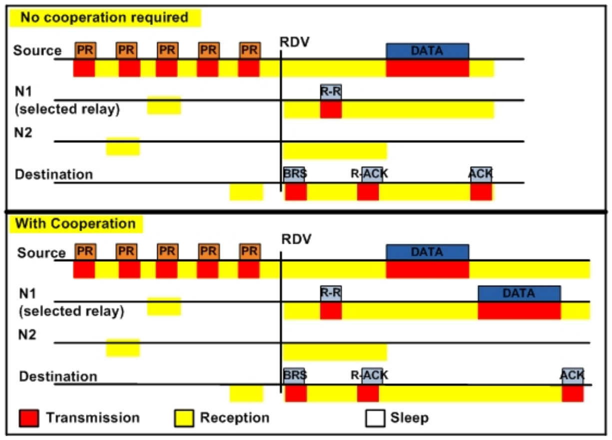

Fig. 2. Proactive protocol variant CL-MAC(P))

E. CL-MAC(R): Reactive low power cooperation

In this variant of the protocol, both the relay selection and the relaying of the data packet are made on demand.

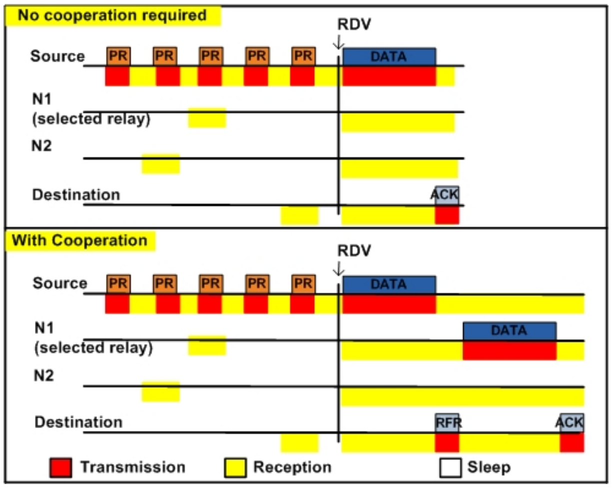

Fig. 3. Reactive protocol variant (CL-MAC(R))

On the RDV point all the nodes wake up. The source directly sends a data packet (see Fig. 3). D receives it and the potential relays overhear it. If D is able to decode the packet, it sends an ACK to S. In this case, the potential relays return to sleep. Otherwise, when the packet is lost, a relaying is required. At this step, only the potential relays that correctly overheard the data packet participate in the relaying process. D sends a Request-For-Relay packet and starts the relay selection. The potential relays that correctly received the RFR with an SNR higher than a given threshold, continue the relay selection. The others give up and go to sleep. The remaining potential relays compute a backoff timer relative to the SNR of the RFR and to their own residual energy. The relay for which the backoff timer expires first, retransmits the data packet to the destination. When hearing the beginning of this data packet, the other potential relays return to sleep mode.The destination sends an ACK to confirm the correct reception of the retransmitted packet and the other potential relays return to sleep.

F. Discussion

The two protocol variants have some differences. In the proactive variant, the relay selection is always performed before data transmission, while it is performed only when needed in the reactive variant. Furthermore, in the reactive variant all the relays tries to hear the data packet, while in the proactive version only the selected relay stay awake trying to hear the data packet. These two points make a difference in the power consumption behavior of the two protocol variants. In the other side, in the reactive variant, the relay selection is made after the reception of the data packet. In this case we are sure that the selected relay dispose of a correct copy of the packet, while in the proactive variant, the reception of a correct copy of the data by the selected relay remains probabilistic. This fact can also affect the behavior of the two variants. Moreover, the introduced low power listening mechanism helps to decrease the power consumption of the nodes in the two variants of CL-MAC. At the RDV point and after the relay selection, the nodes that do not participate in the cooperative transmission switch to sleep mode to preserve their energy.

IV. SIMULATION

A. Simulation Environment

In order to evaluate the impact of the combining of LPL and cooperative communications, we simulate the two variants of CL-MAC using the Opnet Simulator [12]. All the protocol variants run the same LPL parameters: 0.09s for sleep period, 0.01s for wake up period and 0.005s for the intepreamble length. Furthermore, in order to evaluate the impact of LPL on CL-MAC, we deactivate LPL, in each scenario, and measure the produced performance.

The simulated network is composed of a sink, a number of sources (varying from 1 to 5), and a number of potential relays (varying from 0 to 4).

At each simulation run, we vary either the number of sources or the number of potential relays. Each source node sends a periodic traffic: 1 packet/s. The size of the used data packets is 127 bytes, the size of the BRS, Ack, PR, R-R, RFR and R-Ack packets is 20 bytes. We suppose that the signal at a receiver r is described by the following formula:

$$Y_r = h \cdot X_s + n_C \tag{3}$$

Where X_s is the signal transmitted by the sender, h is the Rayleigh distributed fading coefficient of the channel and n_C is an additive white Gaussian noise. We suppose a quasi-static fading channels, i.e. the fading coefficient h is constant during the transmission of one packet.

Nodes are equipped with only one antenna and the senders do not have any information about the CSI of the channels. Furthermore, nodes are equipped with an AA alkaline battery and the power consumption is supposed to be linear. We suppose that the major part of the power consumption of the nodes is due to radio communications and that the processor's power consumption is negligible. The current draws of the radios are : 17.4mA for transmission, 19.7mA for reception and 10^{-3}mA when the node is sleep mode. Besides, the channels are half-duplex: a node cannot send and receive data at the same time.

For each of the measured parameters, we compare the performance of the two CL-MAC variants to those of a modified version of X-MAC [3]. In fact we added to this latter a backoff timer used to eliminate senders' simultaneous access to the channel and thus avoid preamble collisions

B. Simulation Results

Outage Ratio: Fig. 4 depicts the outage ratio defined as the ratio of packets that was retransmitted at least one time to the total number of sent packets. We fix the number of sources to 5, we vary the number of potential relays and measure the outage ratio of the source node. X-MAC does not use potential relays, therefore its outage ratio remains stable. For CL-MAC and its variants, the outage ratio decreases with the increase of the number of potential relays. The presence of relays increase the diversity order of the system and creates more transmission paths to the destination. The selected relay transmits the packet instead of the source which allows avoiding retransmissions. This is what makes the performance of CL-MAC are better than those of X-MAC.

We can notice that the reactive version of CL-MAC presents better results than the proactive one. In fact, in the reactive version, the relay selection is done after the reception of the data packets, so the relay already dispose of a correct copy of the packet to retransmit. However, in the proactive version the relay selection is made before data transmission. So, there is a probability that the channel conditions change and that the relay fails to receive a correct copy of the packet.We also notice from Fig. 4 that the deactivated LPL CL-MAC variants have the same performance as the activated LPL one.

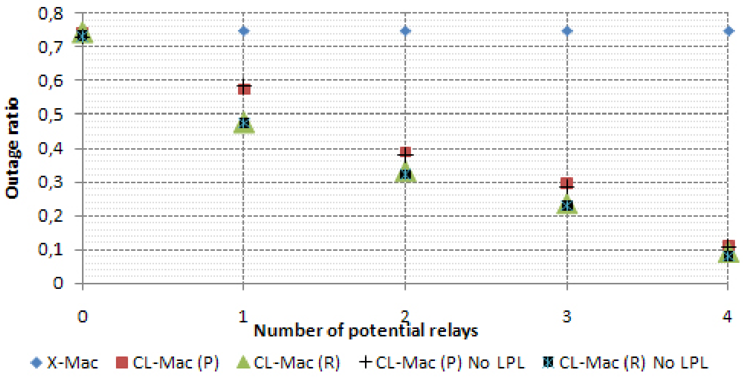

Fig. 4. Outage Ratio Vs Potential Relays

Delivery Ratio : Fig. 5 shows the delivery ratio defined as the ratio of the received packet to the total number of sent packets. In this case we vary the number of sources and fix the number of relays to two. Since all the protocols are CSMA/CA based, the delivery ratio decreases with the increase of the number of sources. Our proposed protocol, CL-MAC, and its variants lead to better delivery ratio since they propose better transmission paths thanks to the use of cooperative relaying. The reactive version gives better delivery ratio than the proactive one for the reasons described above. Here also, and for the same reasons given previously, we notice that the deactivated LPL CL-MAC variants have the same performance as the activated ones.

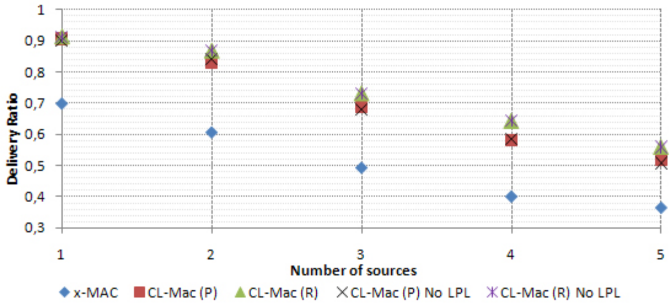

Fig. 5. Delivery Ratio Vs Number of Sources

Power Consumption Fig. 6 gives the average energy consumed by the nodes to successfully deliver a packet (total of energy consumed by all the sources, relays and destinations to send/receive the packets divided by the number of sources and the number of packets). In this case, we fix the number of sources to 5 and vary the number of potential relays (from 0 to 4). X-MAC preserves energy by sending a reduced number of preambles and if an outage occurs it proceeds with a retransmission from the source node.

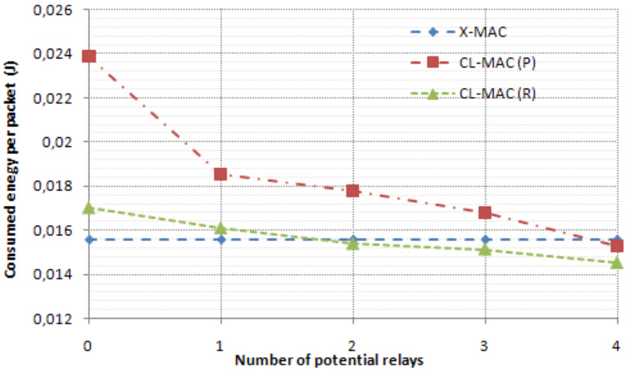

Fig. 6. Power consumption Vs Number of potential relays

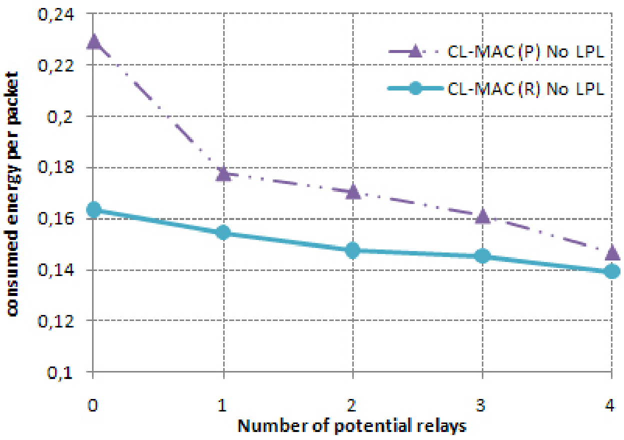

Fig. 7. Power consumption Vs Number of potential relays (CL-MAC No LPL)

CL-MAC and its variants use more preambles than X-MAC (the double on average) and additional signaling packets that are used for relay selection phase. Therefore, X-MAC consumes less energy than our cooperative protocols in the case where no potential relays exist on the neighborhood. The energy consumption of the reactive version become lower than X-MAC when at least 2 potential relays are available in the neighborhood. Also, when 4 potential relays are available, the proactive variant of CL-MAC become less energy consuming than X-MAX. In fact, when the number of potential relays increases, the diversity order increases. Therefore, we have greater possibility to find a good relay and to successfully deliver packets without retransmissions. The proactive version uses more packets so its power consumption is more important than the reactive version. Hence, for dense and lossy networks the energy performance of our protocols are better than of those of X-MAC. Therefore, in comparison to the deactivated LPL version (cf. Fig. 7), the two variants of CL-MAC performs very well. CL-MAC preserves energy ten times more with LPL activated.

V. CONCLUSION

We presented and evaluated in this paper a cooperative low power MAC protocol for wireless sensor network, CL-MAC. Two variants of the protocol are developed, a proactive variant CL-MAC(P) and a reactive variant CL-MAC(R). Our proposed protocol and its variants combine Low Power Listening and cooperative communication techniques in order to enhance the channel use and reduce the energy consumption. Simulation results proved that the cooperative communication enhance the channel conditions, increase the delivery ratio and decrease the outage ratio. Although, reactive CL-MAC and proactive CL-MAC reach promising energy preservation in dense networks. A hybrid approach, combining X-MAC, CL-MAC(R) and CL-MAC(P) depending on the number of available potential relays, is to be considered for future works.

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