Cross-layer energy-aware protocol for wireless sensor networks

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Abstract— The resource limited nature of WSNs requires that protocols implemented on these networks be energy-efficient, scalable and distributed. In this paper, we present a novel combined routing and MAC protocol. The protocol achieves energy efficiency by minimizing signaling overhead through stateless routing decisions that are made at the receiver rather than at the sender. The protocol depends on a source node advertising its RSSI to its neighbors, which then contend to become the receiver of the packet, by measuring their local optimality index, and map this into a timer value. More optimal nodes have smaller timer values and so respond before less optimal nodes. The proposed solution is assessed through simulations. Performance results show the advantages of the proposed solution when compared to RBF protocol, a recently proposed cross-layer approach with similar goal.

Keywords— Wireless sensor networks, Cross-layer protocols, Energy conservation, Network life time, RSSI.

1. INTRODUCTION

In the last few years, Wireless Sensor Networks (WSN) have become a hot topic not only for researchers but also for the industry. A WSN consists of a big set of lightweight and cheap devices with many integrated sensors and wireless communication interfaces. Nodes use their wireless radio to communicate the information acquired with their sensors. When the destination is out of the radio range of source node, other nodes are used as relay stations [6].

Geographic Routing (GR) is one of the schemes which have gained most momentum in the recent years. In GR, each node needs to know the position of its neighbors. To do that, they send periodic HELLO messages called beacons including the identifier of the sender and its position. These packets are not forwarded; therefore only one hop neighbors can receive them. The packets include the identifier of the sender and its position.

However, although geographic routing in general is highly desirable, the beaconing mechanism has some issues, such as generating interferences with regular data transmission and consuming bandwidth and battery power. In particular in those sensors not taking part in any routing process, the energy and bandwidth consumption represent a total waste of resources. To overcome such issues, a new routing protocols class that exploits the cross-layer interactions was proposed, i.e., receiver-based forwarding. Receiver-based routing protocols are highly scalable and robust against frequent topological changes [12]. They can reduce/avoid communication and processing overhead by minimizing neighborhood information exchange, and can minimize memory usage by not maintaining routing tables.

2. RELATED WORKS

In [7] and [8], the performance analysis of the geographical random forwarding (GeRaF) algorithm is presented. This algorithm introduces receiver-based routing for cross-layer interaction between MAC (Medium Access Control) and routing layers. However, the GeRaF algorithm requires a sensor node with two radios for signaling, which may not be feasible in some scenarios. In [14], the MAC protocol is modified for a single radio node. However, the solutions in [14], [7] and [8] consider a perfect channel model and are based purely on geographical relations. In [9], a receiver-based routing protocol, whose performance is analyzed based on a simple channel model and lossless links, is proposed. Moreover, the latency performance of the protocol is presented based on different delay functions and collision rates. Also, the effects of the physical layer are not considered in the protocol operation.

A cross-layer module (XLM) proposed in [1] incorporates initiative determination, receiver-based contention, local congestion control, and distributed duty cycle operation. Decision is made whether a node should participate in a communication when the conditions of RTS threshold, local congestion control threshold and remaining energy threshold are satisfied but also uses location as a parameter that determines the routing level of each node that makes progress of forwarding the packets. The basic Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) MAC, as proposed for the sensor networks, provides carrier sensing prior to message transmission. The arising issues as the hidden terminal problem with current transmissions are addressed by using the Distributed Coordination Function (DCF) in IEEE 802.11 [11] four-way RTS-CTS-DATA-ACK handshake when transmitting a Unicast packet. Network Allocation Vector (NAV) timers are used to monitor the expected channel occupancy during transmission and exponential backoff window is used to handle contention.

Receiver-based contention techniques have also been adopted in several cross-layer MAC and routing protocols. The adaptive load balanced algorithm (ALBA) described in [2], [3] and [4], is based on the GeRaF framework in [7]. In addition to the location of the nodes, the traffic load on each node is considered for route establishment. More specifically, each potential node computes two values: geographic priority index (GPI) and queue priority index (QPI), which indicate the progress of the node towards the destination and its traffic load, respectively. Accordingly, if a node has a packet to send, it sends several RTS packets to scan QPI and GPI values of its neighbors. Each neighbor responds to this packet by CTS packets if their values match the requested values. The source node then selects one of the neighbors if the requested value is found. Moreover, ALBA-R proposed in [4], enhances the original protocol to avoid local minima in routing through a coloring scheme called Rainbow. Based on its previous success in finding relays, each node assigns itself a different color, which is used to participate in communication. While ALBA-R employs a cross-layer MAC/routing technique, the route selection is performed at the sender node, which incurs high overhead due to the QPI and GPI scanning.

In [16], an integrated MAC/routing (MACRO) protocol is developed. It integrates MAC and routing layer functionalities in order to support geographic forwarding in wireless sensor networks. In MACRO, a competition is triggered to select the best next relay node while forwarding information to the destination. The competition is based on the evaluation of a weighted progress factor representing the progress towards the destination per unit of transmission power. MACRO also employs the receiver-based contention scheme but considers only energy efficiency and geographical locations for communication.

In [5], authors have proposed RSSI-Based Forwarding (RBF), a cross-layer integrated medium access control/routing protocol for multi-hop WSN. Without using prior knowledge of nodes' geographical locations and without maintaining neighborhood routing tables, the next-hop node for data forwarding task is determined at the same time as the contention process among the possible forwarding nodes is solved. For an arriving beacon signal transmitted by the sink, received power levels are computed for each sensor node in the network and these levels are then used as the decision parameter for the nodes to contend for the forwarding task of the data packets. RBF protocol is very simple; the localization of the nodes is done by a simple broadcast by the sink. Nevertheless, the nodes taking part in the contention process have all the same probability of being selected for forwarding the packet, which generates a significant number of hops in the routing process. Moreover, the authors proposed to increase the power of transmission to overcome the problem of holes. This solution is really not possible in sensor networks, because the increase in transmission power causes more collisions and consumes more energy.

Most of the receiver-based routing protocols reported in the literature assume knowledge of nodes' geographical locations for routing the sensed data toward the sink node. With the WSN's characteristics that require a large number of low-cost and energy-efficient sensor nodes, equipping a GPS on every sensor node may not be practical. Furthermore, the cost of a GPS chip is much more expensive than the sensor node itself [13]. In this work, we propose CLEAP (Cross-Layer Energy-Aware Protocol) that exploits cross-layer interactions between routing, MAC and physical layers. CLEAP does not require nodes to maintain neighborhood state information and location awareness. Our protocol has some similarities with the schemes proposed in RBF; we employ a received power of a beacon signal broadcasted by the sink for nodes-sink estimating distances. The remainder of this paper is organized as follows. In section 3, we give a detailed description of the protocol. Section 4 presents some simulation results and provides an analysis of the data collected. Finally, in section 5, we conclude this paper with a summary of our findings and future work.

3. PROTOCOL DESCRIPTION

CLEAP protocol runs in two phases: the network setup phase and the data communication phase.

3.1 Network setup phase

The sink initiates the connection by broadcasting a Beacon frame. Transmission power of the sink must be large enough so that the Beacon signal reaches all nodes in the network. Each node in the network stores the Received Signal Strength Indicator (RSSI) in a variable *my_RSSI* to use as a routing parameter.

3.2 Data communication phase

The main role of this phase is to transmit data collected by the sensor nodes to the sink. It consists in choosing the next node that will receive the data to transmit in its turn to others. This process is repeated until data reach its destination. This phase is executed in two steps: one for the transmission initiation and the other for the contention process.

2.1.1. Transmission initiation

This step is based on the CSMA/CA mechanism of IEEE 802.11 [11]. It is triggered when a node has data to transmit. In this case, it puts his value *my_RSSI* in a field RSSI of RTS (Request To Send) packet and performs the CSMA/CA algorithm to broadcast it. Then, the node starts a timer *CTS_Wait* to wait for a CTS (Clear To Send) response. If *CTS_Wait* expires without having received a CTS response, the node performs Backoff and retransmits an RTS. For each RTS retransmission, a counter of retransmissions number, *Short_Retry_Count*, is incremented. In this case, the RTS retransmission will take place if this counter is below a predefined threshold *Short_Retry_Limit*. When a CTS is received, the counter is reset to zero.

Each node receiving the RTS packet determines which region it is as follows: if the value *my_RSSI* is strictly greater than that included in the RTS packet, the node is considered in the relay region *F*, otherwise it is considered in F^c. Nodes that are within the relay region will participate in the contention process, while other nodes will go to sleep for the duration of *NAV* (Network Allocation Vector) specified in RTS packet.

2.1.1. Contention process

This step is based on the routing priority of each node; the priority is determined by two parameters: the packet progress and residual energy. To do this, each node calculates its optimality index *Iop*, determines its priority class corresponding *my_classe* and starts a timer *CTS_Response* to wait before responding by CTS.

$$Iop = \frac{E_r * (my\_RSSI - RSSI)}{E_{ini} * (RSSI\_max - RSSI)} \quad (1)$$

Where E_r is the residual energy of node and *RSSI* is the value *my_RSSI* of the node sending the RTS (that is included in the RTS). *RSSI_max* is the maximum value of the parameter *my_RSSI* that can have a relay node; it represents the RSSI value at a distance of (*D-r*) of the sink, where *D* is the distance between the source node of RTS packet and the sink. *r* is the radius of transmission. To reduce the likelihood that multiple nodes simultaneously send their CTS, the relay region *F* is divided into N_c[1] priority classes as shown in Figure 1. A node determines its class by the following equation:

$$my\_class = \begin{cases} \left\lfloor N_c * \frac{last\_Iop - Iop}{last\_Iop} \right\rfloor & , last\_Iop \geq Iop \\ 0 & , last\_Iop < Iop \end{cases} \quad (2)$$

Where *last_Iop* is a parameter included in the RTS (set to 1 by default), it represents an estimate of the largest value *Iop* of nodes belonging to the relay region. In this way, we obtain a relay region divided into N_c priority classes. Class 0 contains the most optimal nodes towards the metric *Iop* and class N_c*-1* contains the nodes less optimal. Once the priority class *my_classe* is determined, the node starts a timer *CTS_Response* before responding by a CTS.

$$CTS\_Response = \left(\sum_{j=1}^{my\_class} \frac{CW}{2} \right) + Random\left(1, \frac{CW}{2}\right)$$

Random (1, cw) is a function that generate a timeslot between 1 and cw (Contention Window). It's obvious that the nodes of class N_i have a waiting time strictly less than the waiting time for node class N_i+1. In addition, the nodes of the same class may have different waiting times thanks to the function *Random ( ).*

After *CTS_Response* expire, the node responds with CTS by setting its value *Iop* in the field *last_Iop* of the CTS. To avoid multiple responses CTS, each node listens to the channel during his waiting time *CTS_Response*. If a CTS is heard, the node concludes that another node has sent his CTS, in this case it cancels its timer, updates its *NAV* and goes to sleep. If a data packet is detected, the node cancels its timer, updates its *NAV* and goes to sleep. In the case where two nodes send their CTS simultaneously, the Backoff mechanism is used to resolve the collision problem. After receiving the CTS packet from the initiator node, it updates its value *last_Iop*, transmits the data packet and starts a timer *ACK_Wait = SIFS* to wait for an acknowledgment (ACK). If this timer expires

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[1] This number has been tuned via extensive simulation and selected to obtain better performances in terms of energy consumption and latency.

without receiving an ACK, the source node assumes a packet loss and retransmits the data packet again. For each DATA retransmission, a counter *Long_Retry_Count* of retransmissions number is incremented. DATA retransmission will take place if this counter is below a predefined threshold *Long_Retry_Limit*, otherwise the packet will be dropped. After receiving the ACK packet, the counter is reset. The amount of time set for the *CTS_Wait* timer corresponds to the maximum time allowed to send a CTS response, i.e., N_c*(CW/2)*time_slot.

In Figure 1, node 1 sends an RTS packet and initiates a contention process in its neighborhood. Nodes in the relay region determine their priority classes as shown in the figure. Node 15 waits less time than other nodes to respond by CTS, as shown in Figure 2, nodes 9, 8, 5, 45 and 7 hear the CTS of node 15 and goes to sleep. After receiving the CTS packet by node 1, an exchange DATA/ACK will take place.

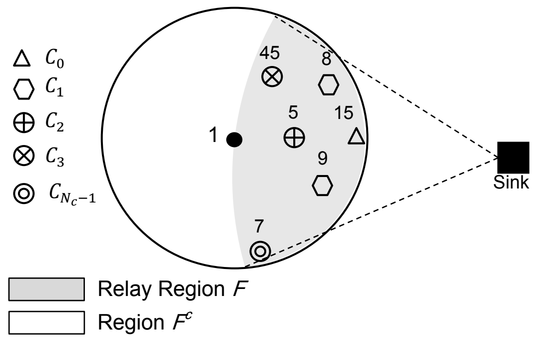

Figure 1: *Sample assignment of class's priority*

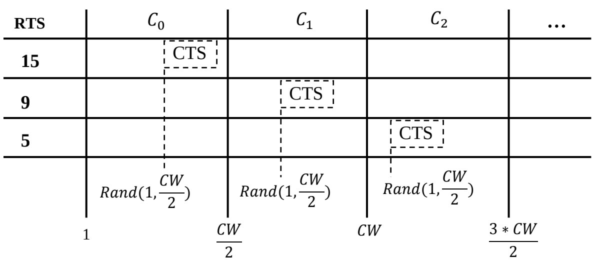

Figure 2: *The mechanism of timers*

Our protocol CLEAP also includes a mechanism for dealing with dead ends, i.e., with those nodes that cannot find relays in the direction of the sink. Originally, all nodes are labeled 'green'. They route information according to the CLEAP operations described above. Whenever a node x has reached a number of attempts equal to *Short_Retry_Count*, it considers itself a dead end. Being a "bad relay," x stops proposing himself as relays for other nodes [4]. A node which cannot advance packets toward the sink switches its color to 'red'. Red nodes handle a packet that they generate or that they receive according to a different rule: the packet is sent away from the sink selecting as relay green or red nodes in F^c. This process is repeated until a green node is reached. Starting from the green node, CLEAP operations' are resumed. The packet is forwarded to the sink along a route which goes only through green nodes. If a red node is unable to find relays in F^c, it progressively stops proposing itself as relay for other red nodes, eventually discarding the packet.

4. PERFORMANCE EVALUATION

4.1 Simulation models

In this section, we illustrate the performance evaluation of CLEAP. The existing sensor network simulation platforms are not suitable for cross-layer communication suite design due to their layered architecture [1]. For this reason, we evaluate CLEAP and RBF in our simulator developed at our laboratory in C#. Our simulator consists of a channel model and an event-driven simulation engine. The simulations are done in random topologies with different sets of 50 to 130 nodes. Each simulation lasts for 100 seconds, and the results are the average of 30 trials for each of five different random topologies. Sensors are deployed in a square area with side L=150 m.

Table 1 show some parameters used in the simulation. To not penalize RBF, we have chosen, as recovering strategy, to increase the transmission power at *14 mW* when meeting a hole.

Table 1: *Simulation parameters*

Table column heading	Table column heading
Time_slot	*20 µs*
SIFS	*10 MS*
Sensor transmit power	*7 mW*
Sensor sensivity	*-95 dBm*
Sink transmit power(Beacon)	*1 W*
Sink transmit power(cts/Ack)	*7 mW*
Paquet generation rate	*5 packets/s*
PL(d_0)	*55 dBm*
η	*3*
Eamp	*100 pj/bit/m^2*
Eelec	*50 nj/bit*
CW	*32*
N_c	*10*
E_{ini}	*0,5 joules*

We assume the path loss of the signal varies according to the log-normal propagation model as in [10]. Equation (4) gives the path loss *PL* at a distance *d* from the transmitter node where $PL(d_0)$ is the path loss at a reference distance d_0, η is the path loss exponent.

$$PL(d) = PL(d_0) + 10\,\eta\,log_{10}\left(\frac{d}{d_0}\right) \quad (4)$$

According to this model, the *RSSI_max*, explained in section three for *Iop* calculation, is obtained by:

$$RSSI_{max} = P_t - \left[PL(d_0) + 10\eta \log_{10}\left(10^{\left[\frac{P_t - RTS.RSSI - PL(d_0)}{10\eta}\right]} \mp r\right)\right] \quad (5)$$

Where P_t is the transmission power of the Beacon signal transmitted by the sink. Note that when the forwarding node is searched among nodes in relay region *F*, these nodes use the sign (-) in the equation, otherwise they use the sign (+).

The energy consumed by the nodes is calculated through the first rder energy model described in [15]. More specifically, the energy for receiving a bit, E_{RX}, is assumed constant, whereas the energy required transmitting *pk* bits, $E_{TX}(r)$, is computed as follows:

$$E_{TX}(r) = E_{elec} * pk + E_{amp} * pk * r^2 \quad (6)$$

$$E_{RX} = E_{elec} * pk \quad (7)$$

Where E_{elec} is the energy needed for the transmitter circuitry, and E_{amp} models the energy required to cover the transmission range *r*. The energy spend by a node in idle mode is set to 2/3 of the cost of receiving.

4.2 Simulation results and discussion

In Figure 3 (a) and (c), we present the average residual energy (ARE). Results in (a) shows that CLEAP improves average residual energy in the network compared to RBF protocol. This improvement can be justified by the mechanism used by CLEAP protocol that tries to route the packet through the optimal path in terms of energy consumption. For cons, RBF protocol routes packets through a path chosen randomly, which can be costly in terms of energy consumption and especially when there is a hole. However, when the network is less dense (70 nodes), RBF has better performances than those obtained with CLEAP. This energy saving is obtained through the recovering mechanism applied by RBF, which is to increase the transmission power for out of a hole. In fact, this mechanism is not effective in denser networks. From Figure 3 (c), we can see with RBF, nodes deplete their energy quickly compared to our protocol CLEAP. And this proves the effectiveness of our mechanism applied during the timers' calculation, taking into account the residual energy of nodes participating in the contention process.

Figure 3 (b) shows the average delivery rate (ADR) results. From the figure, we can observe that the delivery rate is proportional to the number of nodes in the network. It can also be noted that when the number of nodes is less than or equal to 70 nodes, the average delivery rate of RBF protocol is better than that of our protocol CLEAP because of the number of nodes disconnected (note that we did not impose any constraint on the connectivity of the network when generating topologies). However, beyond 70 nodes, our protocol gives better delivery rate than the RBF protocol.

We note from Figure 3 (d) that when the number of nodes is less than 60 nodes, the average latency (AL) obtained with the RBF protocol is better than that obtained with our protocol, and this is reflected by the low density of the network. In fact, when the network is less dense, increasing the transmission power is better suited than the perimeter routing. However, when the number of nodes is greater than 60, the average obtained with our protocol is better than that obtained with RBF. The reason is that our selection mechanism takes into account the packet progress which minimizes the number of hops when routing data packets.

5. CONCLUSION AND FURTHER WORK

Conceiving energy-efficient protocols is a critical issue in energy-constrained wireless sensor networks. In this paper, we proposed an integrated cross-layer MAC/routing protocol; named CLEAP. By exploiting interaction with the physical layer, our proposed scheme does not need a localization protocol which eliminate the costly techniques to determine the sensor nodes' locations; the estimate of the distance which separates each node from the sink, is done by broadcasting a beacon signal from the sink, the measured RSSI is then combined with the remaining energy in the contention process. Energy consumption and latency has been considered as the important indicators to analyze the effectiveness of the protocol in event-driven WSN, and the protocol has been shown to have low latency and low energy consumption as well as robust data delivery rate.

Much further research remains to be done on how to add local parameters, such as interferences level and buffer occupancy, to the CTS_Response without altering basic system behavior. Furthermore, we want to study the error measurement impact of the RSSI on the performances of the protocol.

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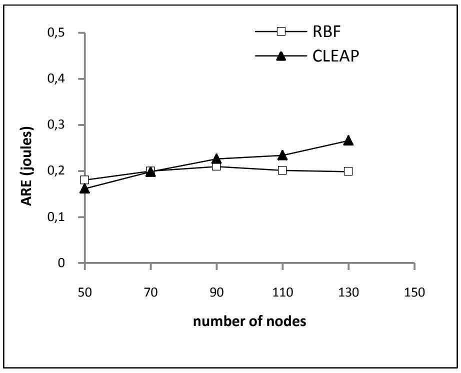
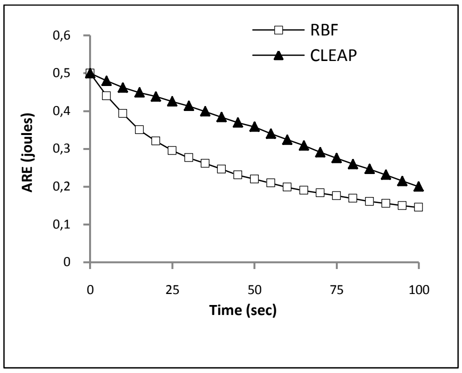
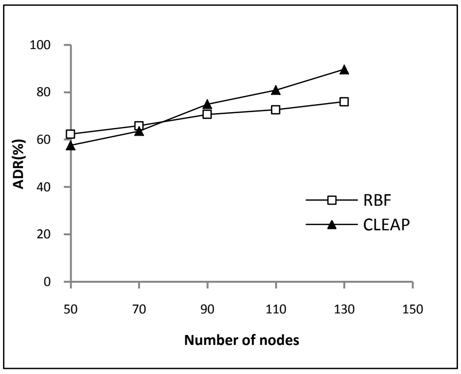


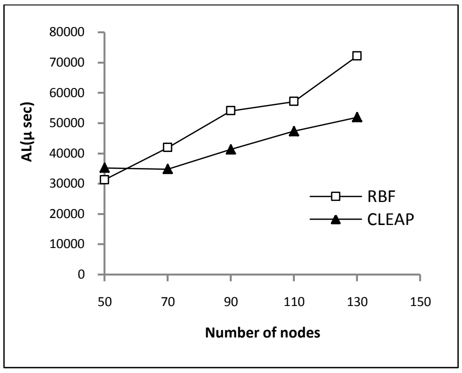
(a)



(c)



(b)



(d)

Figure 2: *Simulation results. (a) Average residual energy vs. number of nodes; (b) average delivery rate vs. number of nodes; (c) average residual energy vs. time; (d) average latency vs. number of nodes*

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