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ECAR: an Energy/Channel Aware Routing Protocol For Cooperative Wireless Sensor Networks

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***Abstract*—The proliferation of low power networks like Wireless Sensor Networks (WSN) rose up new challenges. Power conservation and channel quality become the most important parameters. Obviously, hop count based routing protocols are no more adapted to such networks having power limitations and channel problems. Several alternatives were suggested to cope with these constraints. In MAC layer for example, cooperative protocols were designed to enhance the channel use: the neighbor nodes help the source to retransmit its packets. However, if the path proposed by the routing protocol contains poor channels, the cooperative communications will not save all the packets. Therefore, the design of new routing protocol becomes compulsory. In this paper we propose ECAR, a routing protocol that optimizes two objectives at the same time: energy and Channel State Information (CSI). Compared to AODV, ECAR provides considerable enhancements in delivery ratio, end-to-end delay and power consumption.**

***Index Terms*—Cooperative relaying, biobjective routing protocol, energy efficiency, wireless sensor networks.**

I. Introduction

In Wireless Sensor Networks (WSN), the physical limitations of the sensors (i.e. limited antenna size and limited power capacity) affect the conditions of the channels constituting the network. Depending on time and space, these conditions can differ, more or less randomly, from an instant to another and from a channel to another. The channels are thus considered unreliable. However, if we look at this problem from another corner, we can consider it as an opportunity rather than as a drawback. The channels of a network do not sustain the same changes at the same time. A spatial diversity exists. Therefore, we can design a different sort of protocols that exploit this spatial diversity. Actually, a wireless sensor node I may fail to transmit frames to a receiver-node J because of the poor channel conditions. Due to spatial diversity, the neighbors of I and J overhear an independently faded copy of the frame and help the transmitter to retransmit it towards the receiver. This diversity was exploited at different levels. At the physical layer, Space Time Coding (STC) [1], [2] was proposed. It allows several nodes to transmit the same frame at the same time and to the same destination. STC aims to strengthen the transmitted signal and to reduce the outage probability. It requires an excellent level of synchronization between nodes, which is difficult to guarantee in large networks. In order to avoid synchronization problems, alternative works proposed asynchronous version of STC [3], [4]. It requires high computation capacities which are not available to small network devices such as wireless sensors.

At the MAC layer, the competitive medium access methods were modified to set up cooperative communication schemes. In general, the cooperative communication runs in three phases [5]–[8]. First, the transmitter I sends its packet on the direct channel and the neighbors overhear it. Next, a relay is selected. It is the neighbor having the best two channels: from the transmitter I to the relay R (we call it I-R) and from the relay to the targeted receiver J (we call it R-J). Finally, the relay retransmits the packet to the targeted receiver. These access methods have proved their efficiency in reducing the outage ratio and enhancing the number of delivered packets. However, as they act at the MAC layer, this optimizes the communications on a link by link basis. A network layer solution is thus needed in order to have optimized end-to-end communications (i.e. from the network point of view).

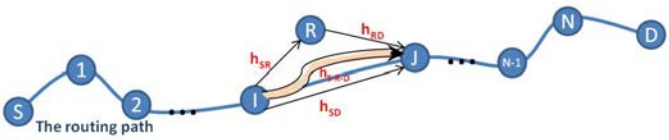


Fig. 1. Cooperative Link

In this paper, we propose to route packets through paths that optimize at the same time two essential parameters in WSN: energy and Channel State Information (CSI) . Our contribution can be resumed in the following points:

- In order to benefit from the cooperation, the cooperative links (i.e. the links I-R and R-J) must have good conditions; otherwise, the cooperation is sub-optimal or even useless in some cases. So, our idea is to take

into account this statement while designing the routing protocol (i.e. choosing only cooperative links with good quality). Therefore, we design ***ECAR***: a routing protocol that computes the routing path using the CSI of the whole cooperative link (C_CSI) (see Fig .1) as a first metric. ECAR searches for paths having at the same time the best direct and cooperative channels. As far as we know, this work is the first one that exploits such information in the network layer,

- Furthermore, in parallel to using C_CSI, ECAR optimizes the consumed energy of the paths it selects. In the optimization problem, we model the wireless sensor network as a graph and the route search problem as a multi-objective shortest path problem.

The remaining of this paper is organized as follows: Section 2 proposes an overview of the proposed channel aware routing protocol existing in the literature. Section 3 describes the channel model, the network model and formulates the routing problem. Section 4 details the different aspects of the bi-objective routing protocol. Finally, section 5 presents the simulation results before concluding in section 6.

II. Related Works

In multi-hop wireless networks, traditional routing protocols [9]–[11] compute the routing paths based on the number of hops crossed by the packets. An optimal path is defined as the one having the minimal hops from a source to a destination. An example of such routing protocols is the Ad hoc On-demand Distance Vector (AODV) [11] reactive routing protocol. In this protocol, the source broadcasts a Route Request Packet (RReq), which is propagated over the network until reaching the destination. The destination sends a Route Reply (RRep) towards the source, to establish the path.

With the proliferation of the energy limited wireless devices like wireless sensors, traditional routing protocols do not respond any more to the requirements imposed by these networks (i.e. not just establishing optimal paths in terms of number of hops). The definition of an optimal path has changed. The optimal path is redefined as the one that costs the least energy or provides best channel qualities[1] . Therefore, multiple researches proposed new routing protocols to cope with these new challenges.

In the energy aware routing protocol proposed in [12], the routing decision is taken locally by combining the residual energy level and the environmental energy supply. The protocol was compared to other routing protocols and was proved to be energy efficient. In addition to limited energy, WSN suffers from random channel conditions. Consequently, cooperative routing protocols was also proposed as a solution. The authors in [13] proposed to combine the transmission of the nodes in order to enhance the radio range of the transmitters and to strengthen the network connectivity.

The channel capacity is introduced as a routing parameter in the protocol proposed by [14]. The protocol computes the routing path that optimizes the routing cost. In addition, it obliges the nodes to respect the capacity of the channels. The problem is formalized using the minimum cost low problem. A comparison between 6 energy based routing metrics was presented by [15]. The authors show that, in their case, the routes computed based on the residual energy provides best results in term of power conservation. Furthermore, a power aware sensor selection method was proposed in [16]. The sensors autonomously evaluate the sensing quality, the communication cost, and the required power level. Afterwards, a header node selects the sensor that provides the best data. In [17], the authors proposed a routing protocol that uses VMISO (Virtual Multi-Input Single Output) to profit from the spatial diversity. The routing algorithm uses clustering techniques to define a set of nodes from which it can select the relay nodes. These are few examples of routing protocols that tries to find optimal routes in terms of either energy or channel conditions.

In this paper, we propose ECAR, a routing protocol that takes advantages from the protocols proposed in the literature. At the one hand, it reduces the power consumption of the sensor nodes. At the other hand, it considers the channel qualities and includes the channel enhancement provided by the cooperative relaying in the route computation. Therefore, ECAR has two objectives while selecting the routing paths: minimizing the energy consumption and optimizing the C_CSI within the selected routing paths. The C_CSI is defined as a metric reflecting not only the quality of the direct link but also of the cooperative links. The details of our bi-objective routing protocol are presented in the following sections.

III. Bi-objective Routing Problem Statement

In this section we describe the different models that we use to conceive a bi-objective routing protocol. We present the channel model, the cooperative communication model and the network model. All these models are used by the following to formulate a bi-objective shortest path problem.

A. Cooperative Communication and Channel Model

In classical Medium Access Control (MAC) protocols, the nodes compete to access to the channel. However, while using cooperative communications, the nodes cooperate with their neighbors to access to the medium. In our case we consider this later case while using more precisely COSMIC [7] as cooperative MAC protocol. Let us take the one-hop network illustrated in Figure 1 to explain the cooperative communication mechanism. A transmitter node I sends a packet towards a target receiver J . The common neighbors of I and J overhear this transmission. In some cases, the direct link (from I to J) is poor and the packet arrives corrupted to J. The channels of the neighbors, from the transmitter and to the targeted receiver, may have better conditions than the direct one. Therefore, instead of retransmitting the packet from Ion the poor direct channel, one of the neighbors (denoted R for Relay) forwards the packet to J on its channel that has better quality. In our model, only one relay retransmits the overheard packet. It uses the Decode-and-Forward technique (DF): it

[1]Other metrics are also considered but these two metrics are those that concentrate the most attention

decodes the packet, then re-encodes it before forwarding it to D. The signal received by the destination D (Y_{SD}) and overheard by the relays (Y_{SR}) can be modeled by the following formula 2:

$$Y_{SR} = \sqrt{P_{SR}} \cdot h_{SR} \cdot X_s + n_{SR} \quad (1)$$

$$Y_{SD} = \sqrt{P_{SD}} \cdot h_{SD} \cdot X_s + n_{SD} \quad (2)$$

Where P_{SR} (respectively P_{SD}) is the power of the signal received by the relay (respectively by the destination), X_s is the signal transmitted by the sender and h_{SR} and h_{SD} are the Rayleigh distributed fading coefficient of the channels between the source and the relay and between the source and the destination (see Fig .1). Furthermore, n_{SR} and n_{SD} are additive white Gaussian noise of the corresponding channels. We suppose a quasi-static fading channels, i.e. the fading coefficient *h* is constant during the transmission of one packet and independently changes from one packet to another.

The cooperative channel of a cooperative communication involving one source, one destination and one relay are constituted by the channels from the source to the relay and from the relay to the destination. It can be modeled by an equivalent channel as follows [18] :

$$Y_D = W_{SD} \cdot Y_{SD} + W_{RD} \cdot Y_{RD} \quad (3)$$

with $W_{SD} = \sqrt{P_{SD}} \cdot h_{SD}$ and $W_{RD} = \sqrt{P_{RD}} \cdot h_{RD}$ are the combining coefficient. More details about the computation of the equivalent channel are given in [18]. We can model the equivalent channel by Formula 3 because in the conventional DF protocol, the relay decodes the received signals and forwards it either as is or re-encoded to the destination regardless whether the relay can decode correctly or not [18]. The relay node can also forward the received packet only when it coorectly received it. This version of DF is called Selective Decode and Forward [18](S-DF). This version is out of the scope of the current paper.

In our model, the COSMIC MAC protocol aggregates the CSI of the equivalent cooperative channels and communicates it to the network layer. It is used, later on, to compute routing paths.

B. Network Model

The problem of searching for an optimal route between two nodes in a wireless sensor network can be modeled by an equivalent optimization problem: the bi-objective shortest Path Problem [19].

The wireless sensor network is modeled by a graph G = (V , E). V is the set of nodes of the graph representing the n sensors of the wireless network. E is the set of edges of the graph representing the different radio links between the sensors. An edge linking two nodes V_i and V_j is characterized by a couple of costs: ($E_{(V_i,V_j)}$, $C_CSI_{(V_i,V_j)}$) where $E_{(V_i,V_j)}$ is the average power consumed by the two nodes (V_i and V_j) to exchange a packet and $C_CSI_{(V_i,V_j)}$ represents the average of the quality of the best potential relays and is computed as follows :

$$C_CSI_{V_i,V_j} = \begin{cases} \frac{\sum_{k=0}^{n_r} CSI_{(V_i,V_j,V_k)}}{n_r} & \text{if } V_k \in E_{br}(V_i,V_j) \\ D_CSI_{(V_i,V_j)} & \text{if } E_{br} = \emptyset \end{cases} \quad (4)$$

where $CSI_{i,j,k}$ is the CSI of the cooperative link in which V_i is the source V_j the destination and V_k is the selected relay and n_r is the number of potential relays.

$E_{br}(V_i, V_j)$ is the set of potential relays having a C_CSI higher than the D_CSI, $E_{br}(V_i, V_j)$ = {V_k, where $(V_i, V_k) \in$ E, $(V_k, V_j) \in$ E and C_$CSI_{(V_i,V_j,V_k)} >$ D_$CSI_{(V_i,V_j)}$ }. In the best of our knowledge, this is the first work that proposes to use such cooperative CSI information in parallel to the energy in the aim to design a routing protocol.

C. The bi-objective routing Problem Formulation

The bi-objective routing problem is modeled by a bi-objective shortest path problem. It searches for a set of efficient paths that optimize the couple of objectives (E(p),C_CSI(p)). The problem that we consider can be modeled by :

$$Min \sum_p E_{(V_i,V_j)} \quad V_i \; and \; V_j \; \in p \quad (5)$$

$$Max \; (Min \; C_CSI_{V_i,V_j}) \quad V_i \; and \; V_j \; \in p \quad (6)$$

where p is a path joining two distant wireless sensor nodes S and D and belonging to $P_{s,d}$ the set of possible paths between S and D. E(p) is the sum of the consumed energy by the nodes of the path to deliver the packet from S to D. C_CSI(p) is the minimum CSI value of the different cooperative links constituting the path. In multi-objective optimization the notion of optimality is relative. It is so rare to find a solution that has the optimal values for both objectives at the same time (E(p) and C_CSI(p) in our case). In general, a path P is efficient (means optimal in the case of multi-objectives optimization) if it does not exist another path P' such that CSI(P) $\leq$ CSI(P') and E(P') $\leq$ E(P), with at least one strict inequality. In other words, if another efficient solution P' exists and the energy of P' is better than the energy of P, , then necessarily the CSI of P' is worse than that of P. This problem is known to be NP-Hard [19] and the number of alternatives to explore can be of an exponential number. Therefore, in order to efficiently solve this bi-objective routing problem and find an efficient path in a reasonable time, we use a resolution algorithm that aims to avoid exploring the alternatives that do not lead to an optimal solution. The details of how our algorithm perform that are described in the next section.

IV. ECAR: OUR BI-OBJECTIVE ROUTING PROTOCOL

In the current section we describe the algorithms that we developed to design a distributed efficient path search. The optimal paths are found by solving the bi-objective shortest path problem described in section III. A classical resolution of this problem requires important computation capacities. Such

resolution methods can be found on the literature [19] and are out of the scope of this paper.

Our routing protocol is inspired from the distributed algorithm proposed in [19]. It solves multi-objective shortest path problems having among its objectives a MinMax one. It presents a simple procedure to solve a complicated problem. The efficient routing paths are found after the propagation of labels from a source node towards all the nodes of the network until reaching the destination. Indeed, when a source node (S) has a packet to send to a destination D, S initializes a label, includes it in a Route Request packet (RRep) and broadcasts it.



Fig. 2. The structure of a label

The structure of a label is described in Fig .2. It contains five fields. The two first fields are reserved for the values of the CSI and of the energy. These two fields describe the performance of the sub-path from the source to the current receiver of the label. A third and a fourth fields contain two label IDs, which are required to identify the label in the current node and in the previous one. The last field contains the address of the previous node (the last forwarder of the RReq). S begins by putting its address in the *previous node id* field and the current id of the label in the *previous label id* field. It affects zero to the *CSI* field. Finally, it puts, in the *Energy* field of the label, the average quantity of energy used to send a packet.

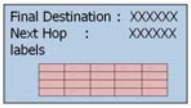


Fig. 3. An example of a routing entry

The route request is relayed from a node to another until reaching the destination. The executed algorithm is described in Figure .4. Every time an intermediate node receives a RReq, it extracts the label from the RReq and searches for a corresponding routing entry (see Fig .3) to the same destination. If there is no entry, a new one is created and the label is added. Whereas, when a routing entry exists the node checks if the new label is optimal. Therefore, it compares the new label to the existing ones. Suppose that L_1 is the received label, corresponding to a sub-path (from the source to the current node) $P_1(CSI_1, E_1)$ and that L_2 is one of the existing labels corresponding to another sub-path. The sub-path represented by L_1 is better than the one represented by L_2 if one of the conditions of Table .I is true. In this case L_1 is preserved and added to the routing entry (L_2 is then dropped).

Alternatively, L_1 and L_2 are both considered as efficient if one of the conditions of Table .II is verified. Here, both labels are preserved and added to the routing entry. In the previous two cases the new label is updated by the cost of the current nodes. Then it is included in a route request and relayed to the destination.

CSI	Energy
$CSI_1 = CSI_2$	$E_1 < E_2$
$CSI_1 > CSI_2$	$E_1 = E_2$
$CSI_1 > CSI_2$	$E_1 < E_2$

TABLE I
OPTIMALITY CONDITIONS

CSI	Energy
$CSI_1 > CSI_2$	$E_1 > E_2$
$CSI_1 < CSI_2$	$E_1 < E_2$

TABLE II
EQUIVALENCE CONDITIONS

Finally, if L_1 does not verify any of the conditions of Table .II or I, it is not an optimal label and cannot lead to an optimal path, so, L_1 is dropped.

At the destination, a label is considered as optimal only if it verifies the conditions of Table .I. In this case, D sends a Route Reply packet (RRep) to the source. This route reply packet will pass through all the nodes that generated the received label. Therefore, the destination sends a Route Reply packet to the node whose address is in the *Previous Node Id* field. We restrict the optimality conditions at the destination in order to reduce the number of route reply transmission.

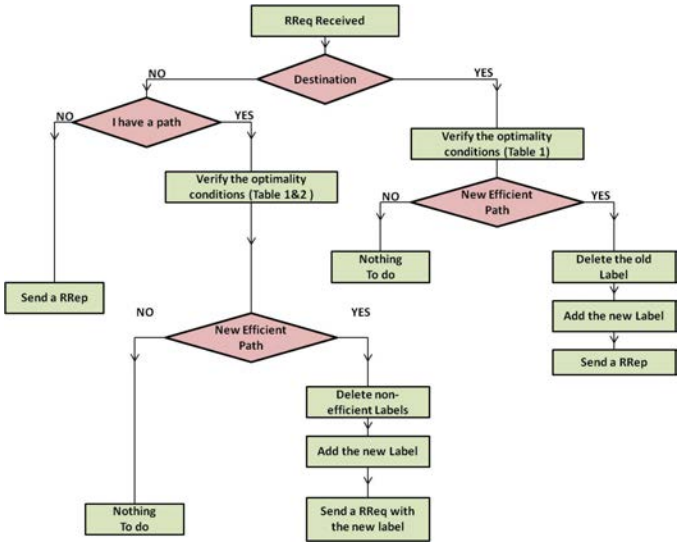


Fig. 4. The algorithm executed at the reception of a Route Request

When an intermediate node receives a RRep packet, it searches among its labels for the one whos ID corresponds to the ID stored in the label of the RRep. It determines the ID of the next node to the source and the ID of the same label on this node and sends a route reply to it. All the intermediate

nodes execute the same procedure. When the source receives the route reply, the route is established.

V. Simulation Results

A. Simulation Environment

In order to evaluate the performance of our protocol, we implemented it in OPNET 15 Simulator [17]. In our simulations we use different network sizes. Initially we start with a network composed of ten nodes: a source, a destination plus a number of intermediate nodes. Then, we increase this number by ten more nodes at a time and we measure the obtained performances. We compare 4 different configurations as mentioned in Table III.

	MAC Layer	Network Layer
Configuration 1	802.15.4	AODV
Configuration 2	COSMIC	AODV
Configuration 3	COSMIC	ECAR (D_CSI)
Configuration 4	COSMIC	ECAR (C_CSI)

TABLE III
Simulation Configurations

COSMIC [7] is a cooperative MAC protocol, 802.15.4 is an IEEE MAC layer for wireless sensor network and a well known routing protocol AODV [11]. The Signal to noise Ratio (SNR) is used as the CSI of the channels and is distributed randomly and independently. Each channel is Rayleigh faded with quasi-static fading (i.e. the SNR is the same for a packet and may change randomly and independently for the following one). The current draw of the radios are 17.4mA for transmission, 19.7mA for reception and 10^{-3}mA in idle mode. Furthermore, in order to compare the impact of the use of the C_CSI, we compare ECAR running with this parameter to a ECAR running with the CSI of the Direct channel. We call this parameter D_CSI. The details of the simulation results are given in the following section.

B. Simulation Results

Delivery Ratio Figure .5 depicts the delivery ratio defined as the ratio of the received packet by the final destination to the total number of sent packets. AODV does not care about the quality of the links it uses. Therefore, some bad links may be introduced in the path, which increase the possibility of outage and packet loss. Moreover, when we increase the number of nodes in the network, we increase the number of hops between the source and the destination. The packet should pass through more bad links and the possibility of loss increases. When we use COSMIC with AODV, the former set up cooperation and reduce the losses, which explains the enhancement of delivery ratio by 20% on average.

Indeed, with ECAR the delivery ratio is enhanced by more than 80% in all the cases. Finally, one should note that the use of C_CSI with ECAR increases the delivery ratio compared to the case where the D_CSI Is used. The difference between both can reach 15% in some cases.

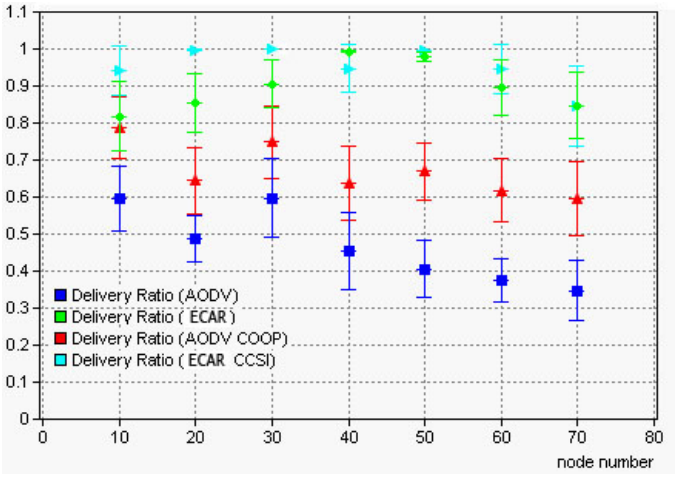


Fig. 5. Delivery Ratio VS Number of nodes

End-to-End Delay Figure .6 shows the end-to-end delay defined as the time required to deliver the packet to the destination. The retransmissions are frequent with AODV which increases the end-to-end delay. By using COSMIC along with AODV, the end-to-end delay is reduced. Indeed, cooperative relaying allows saving some packets and reducing the number of retransmissions. As using ECAR allows choosing more reliable routes, the number of retransmission is reduced importantly. This reduction is more notable when using C_CSI compared to when using D_CSI. Indeed, using C_CSI the end-to-end delay is further reduced by 25% on average compared to ECAR with D_CSI

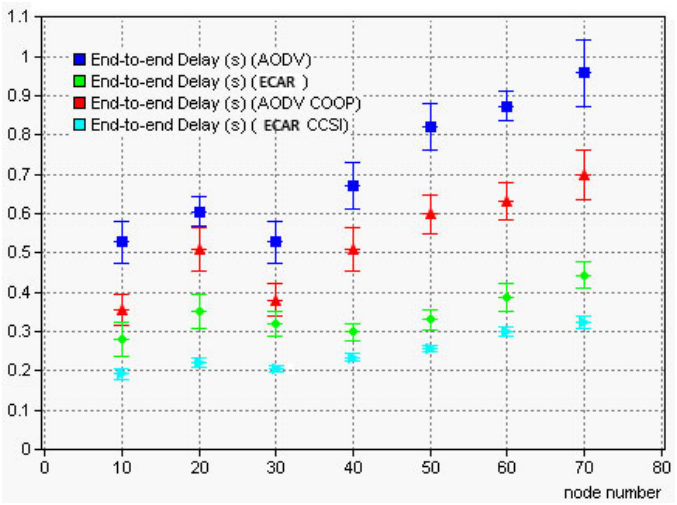


Fig. 6. End-to-End delay VS Number of nodes

Per Packet Power consumption Figure .7 represents the average consumed energy by the nodes composing the path to deliver the packets to the destination. With AODV and with the fact that some bad links composes the established route, several packet retransmissions are needed. This is what makes the energy consumed by AODV the highest. When we run

AODV with COSMIC, the consumed energy is reduced, since cooperative relaying is used. However, the energy consumed with ECAR is reduced by a factor of five to ten times compared to the use of AODV. In fact; ECAR provides paths including the relays that have the best channels. Therefore, when the transmission on the direct channel fails, the relays successfully forwards the packet to the destination, which considerably reduce the power consumption. The difference in energy consumption between ECAR with D_CSI and C_CSI is about 2 to 3%. ECAR provides a better neighborhood with C_CSI.

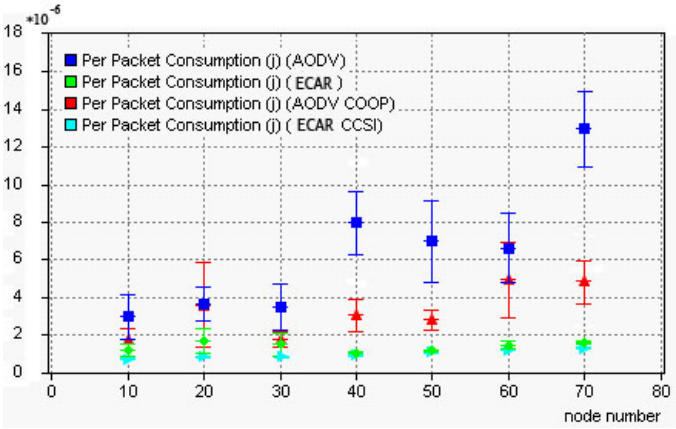


Fig. 7. Power Consumption VS Number of nodes

VI. Conclusion

In the context of WSNs the routing protocols based on the number of hops are out of date. Emerging wireless sensor networks require new protocols that cope with energy constraints and varying channel conditions. In this paper, we proposed a bi-objective routing protocol, called ECAR, which build efficient routing paths in terms of energy and channel conditions. ECAR also assumes the use of cooperative relaying at the MAC layer and tries to take full advantage of that. Simulation results show that ECAR enhances considerably the network performance in comparison to a classical routing protocol. Moreover, the use of the Cooperative CSI (C_CSI) as a routing metric allows enhancing significantly the end-to-end delay, the delivery ratio and at a lower extent the power consumption.

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