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***Abstract*—In wireless sensor networks several constraints decrease communications performances. In fact, channel randomness and energy restrictions make classical routing protocols inefficient. Therefore, the design of new routing protocols that cope with these constraints become mandatory. The main objective of this paper is to present a multi-objective routing algorithm RBCR that computes routing path based on the energy consumption and channel qualities. Additionally, the channel qualities are evaluated based on the presence of relay nodes. Compared to AODV and AODV associated to a cooperative MAC protocol, RBCR provides better performances in term of delivery ratio, power consumption and traffic load.**

***Index Terms*—Cooperative relaying, multi-objective routing protocol, energy efficiency, wireless sensor networks, cooperative communication.**

I. Introduction

In wireless sensor networks, the unreliable channels and the restrictions in energy resources make the routing a complex task. In addition, classical routing protocols [1]–[3] are not able to cope with the routing constraint of WSNs. Furthermore, cooperative communication constitutes a potential alternative. It proposes to use the neighbors as helpers in case they have better channels than the source. In fact, due to the broadcast nature of the wireless channel, the neighbors can over-hear the packet of the source, preserve it, then retransmits it to the destination when required. This technique replaces the selfish competitive access to the medium, by a cooperative one. It proved its efficiency in saving energy and enhancing the use of the wireless channel [4].

In this paper [1], we propose to combine cooperation and routing. The contribution of our routing protocol can be summarized as follows:

- In all the cooperative protocols relay nodes are selected anew for each packet, resulting in an important signaling burden. Therefore, it can have a reverse effect, rather than enhancing the channel use, it decreases the channel utilization. Therefore, our routing protocol RBCR, computes the routing path and includes the relay nodes in the routing path. Consequently the relays are known by the intermediate node from the beginning
- Besides, RBCR (Relay selection Based Cooperative Routing) computes the routing paths based on the CSI and based on the consumed energy. For more efficient route computation, it optimizes separately the energy consumed by the intermediate nodes and the energy consumed by the relay nodes.

The rest of the paper is organized as follows. Section II presents and discusses some channel aware and energy aware routing protocols. Section III describes the modeling of our routing problem and formalizes it. Section IV details our relay selection and cooperative Routing protocol. Finally, section V presents simulation results before concluding in section VI.

II. Related Work

The IETF ROLL working group [6] confirmed that none of the existing ad hoc routing protocols is adapted to the requirements of WSNs. In fact, traditional routing protocols like AODV [1], DSR [2], or OLSR [3], define the best path as the path having the shortest number of hops from the source to the destination. Nevertheless, WSNs have several constraints and the optimal path is defined to be the path consuming less energy, having the best channels or both. Several research efforts were conducted during the last few years to conceive routing protocols coping with the WSN energy constraint. An energy aware routing protocols was proposed by the authors in [7]. The routing decision is taken by merging the information about the residual energy of the node and the environmental energy supply. An energy aware, ant colony-based routing algorithm was proposed in [8]. The ant colony algorithm uses three metrics: the distance to the sink, the residual energy of the nodes, and the average energy consumed in the path. Simulation results show that the energy is fairly consumed over the network and network lifetime is extended.

[1]A short version of this work has been presented as poster [5] at IFIP Wireless Days 2011

The second major WSNs constraint is the wireless channel. WSN channels are unreliable and have random conditions. Several nodes are obliged to consume a lot of energy for the retransmissions of their packets. Therefore, channel-aware routing protocols came to fill this gap. In order to increase the transmission range of the nodes, the protocol proposed in [9] considers that sensor nodes are able to transmit packets cooperatively and simultaneously. Simulation results show that this method strengthens the network connectivity. Spatial diversity was exploited by cooperative communication in [10]. The authors propose to enhance the use of the network channels by using neighbors antenna. Spatial diversity is also exploited by VMISO (Virtual Multi-Input Single Output) [11] by organizing the network in clusters in which relay nodes are selected. In VMISO, relay selection is made at MAC layer. To the best of our knowledge, relay selection in cooperative communication has always been performed at MAC layer until now. In this paper, we propose a routing protocol that computes routing paths based on the energy consumption and channel conditions. Besides, it computes the routing path based on channel enhancements brought by relay nodes. The relay node that gives the best channel enhancement with the least energy consumption becomes a part of the routing path. The details of our protocol are presented in the next section.

III. Problem Formulation

In this section we present the models used by RBCR as well as the formulation of the shortest path problem while relays are used. More precisely, we present the used network and channel models and the problem formulation. Our models are based on two studies [12], [13] where the WSN is represented as a graph. RBCR searches for the shortest path in term of three objectives: the energy consumed by the intermediate nodes, the one consumed by the relays and the quality of the cooperative links. The resulting routing path will be formed by intermediate nodes and relay nodes.

A. Network Model

We represent the WSN as a graph G(V,E). V is the set of vertice of the graph representing all the sensors of the network. E is the set of edges of the graph representing the real wireless links in the network. In our wireless network, the wireless links are characterized by two parameters: the CSI of the link and the mean energy required to transmit a bit between the two sensors of this link. Therefore, on the graph, an edge (i,j) is labeled by two costs: the energy of the edge E_{V_i,V_j} and the CSI of the link CSI_{V_i,V_j}. The links of the network are symmetric and bidirectional, so we can suppose that: CSI_{V_i,V_j} = CSI_{V_j,V_i} and E_{V_i,V_j} = E_{V_j,V_i}.

B. Channel Model

In our formulation, channels are modeled by a Rayleigh fading distribution. It supposes the existence of obstacles in the environment that scatter the transmitted signal. In addition, the sensors perform the Decode and Forward (DF) technique. They decode the received packet, and then re-encode it before forwarding it without verification. The technique that verifies the packet after decoding is called Selective-Decode-and-Forward (S-DF [14]). The packet verification itself is out of the scope of this paper. The signal can be represented by the following formula:

$$Y_{SD} = \sqrt{P_{SD}} \cdot h_{SD} \cdot X_s + n_{SD} \tag{1}$$

Where P_{SD} is the power of the signal received by the destination, X_s is the signal transmitted by the sender and h_{SD} is the Rayleigh distributed fading coefficient of the channels between the source and the destination of one hop, and n_{SD} is the additive white Gaussian noise of the channel. Besides, if we suppose that a neighbor node (we call it Relay R), has overheard the transmitted signal due to the broadcast nature of the channel, then the signal received by R can be modeled by the following formula :

$$Y_{SR} = \sqrt{P_{SR}} \cdot h_{SR} \cdot X_s + n_{SR} \tag{2}$$

Where P_{SR} is the power of the signal received by the relay, X_s is the signal transmitted by the sender and h_{SR} is the Rayleigh distributed fading coefficient of the channels between the source and the relay and n_{SR} is the additive white Gaussian noise of the channel. The two channels, from S to R and from S to D can be modeled by an equivalent channel :

$$Y_D = W_{SD} \cdot Y_{SD} + W_{RD} \cdot Y_{RD} \tag{3}$$

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 [14]. We suppose in our model that the sensors have knowledge of the CSI of their two-hop neighborhood so that they can compute the performance of equivalent cooperative channels. In fact, the neighbors exchange hello packets where they put the CSI of their neighbors. Therefore, when a node receives a Hello packet it deduces from it the CSI of the direct channel to the transmitter node and extract from it the CSI of the neighbors of the transmitter.

C. Problem Formulation

The main objective of this paper is to present a routing algorithm that computes routing path based on the energy consumption and channel qualities. In addition the channel qualities are evaluated based on the presence of relay nodes. For each hop, the relay node that proposes the best channel and consumes the least energy is selected and considered as a part of the route. In order to solve this dilemma, we represent it by the Minimum Cost Path problem With Relays [13]. In this problem, relay nodes serve as optimizer nodes that help to reduce the cost and hence optimize the quality of the links. Our routing problem can be modeled as follows:

$$E_i(p) = Min \sum_p Ei_{(V_i,V_j)} \quad V_i \text{ and } V_j \in p \quad (4)$$
$$E_r(p) = Min \sum_p Er_{(V_i,V_j)} \quad V_i \text{ and } V_j \in p \quad (5)$$
$$CSI(p) = Max\,(Min\,C\_CSI_{V_i,V_j}) \quad V_i \text{ and } V_j \in p \quad (6)$$

Where p is a path joining a source and a destination and p is a member of $P_{s,d}$ the set of possible paths from S to D. $E_i(p)$ is the sum of energy consumed by the nodes of p to transport the packet from S to D. $E_r(p)$ is the sum of energy consumed by the eventual relay nodes. CSI(p) is the minimum CSI value of the links composing the path. As described by the previous formula, our problem is a multi-objective optimization problem. Generally, the problem does not have a unique optimal solution. Several solutions exist and they are called efficient non-dominated solutions (they replace the optimal solution notion in mono-objective problems). In our case, a solution S is efficient if there is no second solution S' that respects the following conditions with at least a strict inequality :

$$E_i(S) \leq E_i(S') \quad (7)$$
$$E_r(S) \leq E_r(S') \quad (8)$$
$$CSI(S) \leq CSI(S') \quad (9)$$

This type of problem is known to be NP-Hard [12]. Our resolution algorithm, explores only the potential efficient solutions and eludes the exploration of inefficient solutions. The details of the algorithm are given in the following section.

IV. Relay selection Based and Cooperative Routing (RBCR)

In the current section we present our routing protocol. The optimal paths are found by solving the multi-objective optimization problem presented in section III. . These types of problems require important computational capabilities when solved by a unique entity. In our case, we use a distributed algorithm to solve it. An optimal path is computed by propagating a label from the source towards the destination.

A label in a given intermediate node is a pointer to the previous node in the reverse path to the source. The structure of such a label is given by Figure .1. It contains seven fields. The first field is used to identify the label in the current node. The second field is a pointer to the label that generated the current label. The Energy I and Energy R fields contain the mean of the consumed energy respectively by the intermediate nodes and the relay nodes. The *CSI* field describes the qualities of the links from the source to the current node. The *PP ID*, *Relay ID* and *Previous ID* fields define the identities of the previous nodes in the two-hop path. The *Previous ID* field contains the identity of the node preceding the current one in the path. The *Relay ID* field identifies the relay between the current node and the previous one. Finally, the *PP ID* field contains the identity of the node preceding the previous one.

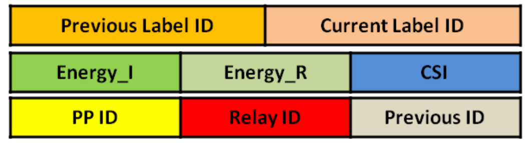

Fig. 1. The label's structure

In order to trigger a route search, the source broadcasts a Route Request packet containing a label. It fills the Previous ID field by its address as well as the Previous Label ID field. Next, it puts on the *Energy_I* field the quantity of energy required to send the packet. Finally, it affects zero to all the other fields. The RReq packet is then relayed over the network from a node to its neighbors until reaching the destination.

When a node V_i receives a RReq it extracts the label. The following actions taken by V_i depend on the value of the field *Relay ID* field. If its value is -1 (the previous node on the path is not a relay), so, the current node can be an intermediate node or a relay node. Otherwise, the current node can only be an intermediate node.

CSI	Energy_R	Energy_I
$CSI_c \geq CSI_i$	$E_{I_c} \geq E_{I_i}$	$E_{R_c} \geq E_{R_i}$

TABLE I
Optimality Conditions (one strict inequality at least)

At first, V_i starts by considering itself as an intermediate node on the path. It checks if it already has a routing entry corresponding to this destination. If no entry was found it creates a new one and appends it with the label. Otherwise, the coming label is compared to the existent ones to verify its optimality. Suppose that $L_c = (E_{I_c}, E_{R_c}, CSI_c)$is the coming label and $L_i = (E_{I_i}, E_{R_i}, CSI_i)$ is a label of the routing entry. The subpath represented by L_c is more efficient than the one represented by L_i if one of the conditions of Table .I is true. In this case L_c is added to the Routing entry and L_i is deleted (It is a dominated solution as explained in Section .III-C).

CSI	Energy_R	Energy_I
$CSI_c \geq CSI_i$	$E_{I_c} \geq E_{I_i}$	$E_{R_c} \leq E_{R_i}$
$CSI_c \geq CSI_i$	$E_{I_c} \leq E_{I_i}$	$E_{R_c} \geq E_{R_i}$
$CSI_c \leq CSI_i$	$E_{I_c} \geq E_{I_i}$	$E_{R_c} \geq E_{R_i}$
$CSI_c \geq CSI_i$	$E_{I_c} \leq E_{I_i}$	$E_{R_c} \leq E_{R_i}$
$CSI_c \leq CSI_i$	$E_{I_c} \geq E_{I_i}$	$E_{R_c} \leq E_{R_i}$
$CSI_c \leq CSI_i$	$E_{I_c} \leq E_{I_i}$	$E_{R_c} \geq E_{R_i}$

TABLE II
Equivalence Conditions (one strict inequality at least)

Moreover, if one of the conditions of Table .II is true, therefore both labels are equivalents and L_c is added without deleting L_i. In both cases, a new label is created, the fields are updated using Algorithm .1included in the RReq, and broadcast.

Algorithm 1 Label Update

$E_{I_{NewLabel}} \leftarrow E_I + required\_energy\_to\_transmit()$
$E_{R_{NewLabel}} \leftarrow E_R$
$CSI_{NewLabel} \leftarrow Min\ (CSI_c\ ,\ CSI_{LastHop})$
$Previous\ ID_{NewLabel} \leftarrow my\_address$
$PP\ ID_{NewLabel} \leftarrow Previous\ ID_{L_C}$
$Relay\ ID_{NewLabel} \leftarrow -1$
$Previous\ LabelID \leftarrow Current\ Label\ ID_{L_C}$
$Current\ LabelID \leftarrow New\_Id()$

When the Relay ID field of the received Label does not contain any address (field assigned to -1), the receiving node decides if the previous node can be a relay node. Therefore, it checks if it is a neighbor to the node in the PP ID field. Provided that it is the case, the node verifies the optimality of this solution. It proceeds the same way to check the conditions of Table II and I. . Once the optimality of the solution is verified the node creates a new labels using the algorithm .2.

Algorithm 2 Label Update

$E_{I_{NewLabel}} \leftarrow E_I$
$E_{R_{NewLabel}} \leftarrow E_R + required\_energy\_to\_transmit()$
$CSI_{NewLabel} \leftarrow Min\ (CSI_c\ ,\ CSI_{LastCooperativeHop})$
$Previous\ ID_{NewLabel} \leftarrow my\_address$
$PP\ ID_{NewLabel} \leftarrow -1$
$Relay\ ID_{NewLabel} \leftarrow Previous\ ID_{L_C}$
$Previous\ LabelID \leftarrow Current\ Label\ ID_{L_C}$
$Current\ LabelID \leftarrow New\_Id()$

When the destination receives a RReq, it checks the routing entry. If no routing entry is found, the label is automatically added to a new routing entry. Afterwards, it sends a route reply containing the information from the received label. Otherwise (i.e. while a routing entry exist), the destination verifies the efficiency of the label. At the destination, the labels are added to the routing entry only if they verify the conditions of Table I. It means, only if the currently used label represent a dominated solution. Thereafter, the destination sends a Route Update (RUpd) packet to inform the intermediate nodes about the new path.

When an intermediate node receives a Route Reply or Route Update, It searches for the label whose Id correspond to the one received in the RRep or RUpd. It extracts from this label the address of the next node and the Id of the next label. It creates a new Route Reply (respectively Route Update) packet then sends it to the corresponding node. When the packet reaches the source node then the path is established.

a) MAC Layer Adaptation:: The previously defined routing protocol, assigns to each hop one potential relay when this is needed. However, it does not ensure the cooperative communication. The execution of the cooperative relaying is the role of the MAC layer. As current legacy MAC protocols do not support cooperative communication, we adapt the IEEE 802.15.4 Mac layer [15] to support it.

We add to the MAC layer, a data structure that we call the *Relay Table (RT)*. RT stores the couple of nodes (V_i and V_j)that the node will help and relay their packets in case of outage. RT is filled in coordination with the Network Layer. Indeed, when the network layer receives a RRep packet, it looks it looks whether it is part of the path (i.e. an intermediate node), or it is a relay node. If the latter is true, the network layer informs the MAC layer about the couple of nodes to help. Therefore, the MAC layer appends its RT with this new couple.

For further future communications and for each overheard data packet, the MAC layer verifies if the addresses in the packet correspond to a couple within its RT. If it is the case, it preserves the packet and starts a timer T_R. T_R corresponds to the same duration after which the source performs a retransmission in IEEE 802.15.4. When the $T_R$ends without hearing the acknowledgment (Ack) for this link, it acts on behalf the link-source and retransmits the packet. This simple modification in IEEE 802.15.4 enables cooperative communications in sensor networks.

V. Simulation Results

A. Simulation Environment

In this section we evaluate RBCR performances using simulations. Our protocol is implemented on the Opnet [16] simulator with the Zigbee module. RBCR performances are compared to those of: (i) AODV with a classical MAC layer (i.e. without cooperation) and (ii) AODV with COSMIC [16]. This later is a cooperative MAC layer [17], in which the relay node is selected for each data packet. When the destination receives a corrupted packet it sends a Request-For-Relay packet for the neighbors. Afterwards, the best neighbor defined as the one having the best channel and residual energy gain the access to the medium and relay the data packet. We run simulations with each of these protocols using different network configurations. All configurations contain a source, a destination and a number of intermediate nodes. We start by a network containing 10 nodes and we increase the network size by ten nodes at each step until reaching 70 nodes. The nodes are uniformly distributed in a square with a side length of 500m. The CSI of the channels is represented by the Signal-To-Noise-Ratio (SNR). The channels are Rayleigh faded with quasi-static fading: each packet is faded randomly and independently. Furthermore, we consider that the channels of the network are fully symmetric. The power consumption of the node is 17.4mA for transmission, 19.7mA for reception and 10^{-3}mA in Idle mode. For each data value we present in the results, we also give its 90% confidence interval.

B. Simulation Results

Delivery Ratio: Figure .2 depicts the delivery ratio. It defines the ratio of the successfully delivered packets to the destination. AODV has the lowest delivery ratio since it does not consider link qualities. Combined with COSMIC, the performances of AODV are obviously improved. Indeed, COSMIC enhances the use of the links of the route and saves more packets. This helps in partially solving the channel-quality issue in AODV since COSMIC tries to enhance the performance of each link. However, this does not overcome the fact that AODV does not necessarily choose the best paths in term of channel qualities. Alternatively, RBCR does by including the CSI as a parameter in route computations. By doing so, RBCR demonstrates the best delivery ratio. Since the path links used by RBCR are better and the number of lost packets is reduced.

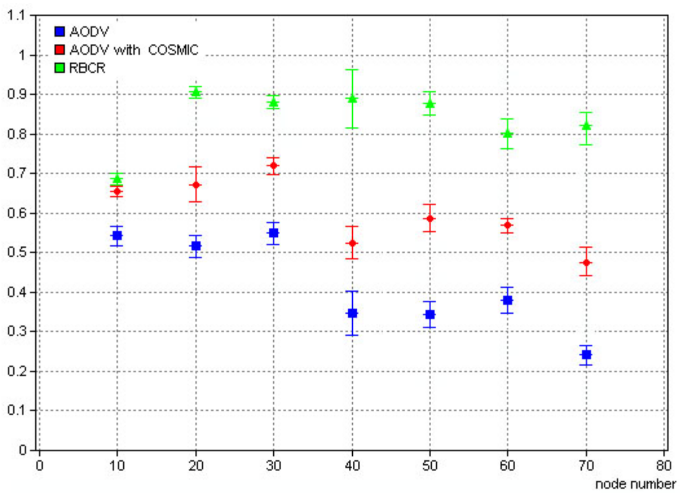

Fig. 2. Delivery Ratio Vs Number of nodes

Traffic Overhead: Figure .3 presents the traffic overhead defined as the total size of control packets divided by the total size of the transported traffic. AODV combined with COSMIC has the highest overhead ratio. It uses additional traffic to select the relay nodes. In RBCR, the relay nodes are already known and there is no additional traffic used to select them. Therefore, the overhead ratio is minimized. In that case, we see that using RBCR, we trigger as much control overhead as with the legacy AODV (i.e. AODV without cooperative relaying).

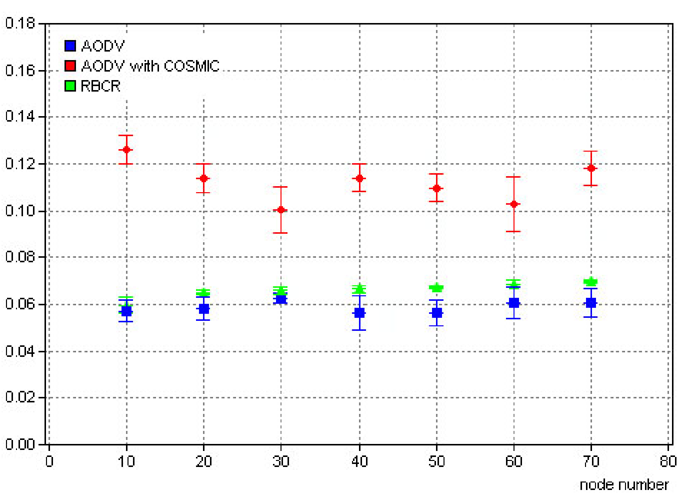

Fig. 3. Traffic overhead Vs number of nodes

End-to-End Delay : Figure .4 shows the end-to-end delay defined as the time required to deliver the packet to the destination. RBCR does not have better end-to-end delay compared to AODV and AODV with COSMIC. The routes computed by RBCR are in general longer with one or two hops, but consumes less energy and have better links. Consequently, the end-to-end delays are higher than those of AODV.

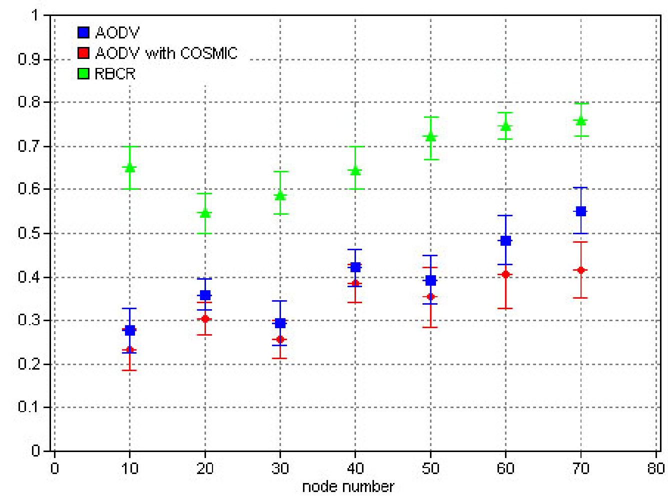

Fig. 4. End to End Delay (s) Vs Number of nodes

Energy Consumption : Figure .5 represents the average consumed energy by the nodes composing the path to deliver the packets to the destination. AODV consumes more energy because it eventually includes bad links in its routing path. Therefore, the packets are retransmitted several times. AODV with COSMIC reduces the number of packet re-transmissions and so the energy consumption. However, this only reduces the effect of bad links but does not solve the problem. With RBCR the power consumption is divided by a factor of five to ten. This is directly due to the selection of links having good qualities during the route computation.

VI. Conclusion

Wireless Sensors Networks requires new routing approaches. The classical routing methods are no more convenient since the constraints are different. In addition to energy consideration, cooperative communications and relay selection procedure should be included in the route search process. In this work we proposed a routing protocol, RBCR that copes with WSN constraints. Route computation considers the existence of relay nodes, able to enhance the channel use, in addition to the consideration of energy consumption. Simulation results show that RBCR provides routing path with better links. Energy consumption and traffic overhead are reduced in addition to the enhancement of the delivery ratio. These important enhancements are obtained with a certain cost in terms of end-to-end delays. Cost that we estimate acceptable

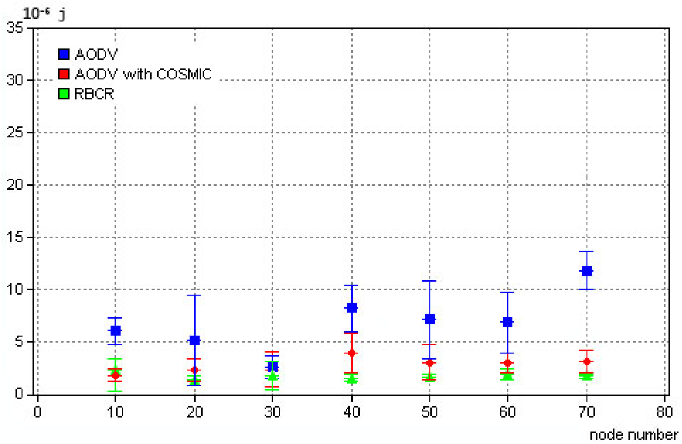

Fig. 5. Per Packet Power Consumption Vs number of nodes

in comparison to the obtained gains (energy, overhead, and delivery ratio). For Future works, we think that we can use the multitude of path discovered by our routing algorithm for further enhancement of sensor networks.

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