Improving Delivery Ratio and Power Efficiency in Unicast Geographic Routing with a Realistic Physical Layer for Wireless Sensor Networks

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Abstract

In the last few years, the amount of work in the field of routing algorithms for WSN has increased significantly. The special characteristics of WSN make a challenge for researchers to design efficient routing protocols. Nevertheles, most of the work done left out of scope an inherent aspect to WSN such as the radio tranmsission errors. The well-known unit disk graph model has been widely used as a basis for several routing protocol. However as recent experimental research has revealed, real links behave completely different to that model. In this paper we evaluate the problems that arise when considering that messages can be lost and propose a new geographic routing protocol which takes into account the probability of error transmission to achieve a high delivery ratio while reducing the energy consumed to the minimum possible. We present the results of the extensive simulation made using our protocol and compare it against a centralised version and two others previous work. Our protocol, being totally distributed and using only local information, outperforms the previous work and achieves almost the same results as the centralised version.

1. Introduction and Related Work

The usefulness of Wireless Sensor Networks (WSN) is already known not only by the research community but also by the industry. The number of areas in which this technology can be of great utility is widening. It is a long time since Finn's first introduction of geographic routing [1]. Further enhancements of this technique to prevent dead ends such as GFG [2] or GPSR [3] definitively increased the interest for this routing technique. The main advantage of geographic routing is its scalability, reduction of overhead and robustness to topological changes. For this reason, in the last years, the number of new geographic routing protocols has grown. Nevertheless most of the work done is based on the well-known unit disk model that considers that two nodes can directly comunicate if and only if the Euclidean distance between them is lower or equal to a constant called transmission radius. Although simple, this model is no longer accurate to represent a WSN. Specially after the work of Zhao and Govindan [6] and Woo et al [7] that show the huge differences between a real link and the unit disk model. Considering a realistic link layer, the previous geographic routing algorithms can no longer guarantee perfect delivery due to packet losses.

We believe that the design of routing protocols for WSN has to take into account the properties of realistic physical layers and the inherent problems of sensor nodes. One of the most important aspect to care about routing in sensor networks is the lack of resources. Specially the energy consumption aspect has to be considered very carefully. Several researches have focused its efforts on designing routing protocols which increase the lifetime of the sensor or the complete network [9] but almost none had considered a realistic MAC. Modern hardware has the possibility of adjusting the power used to transmit messages. It is possible to save energy adjusting the power to reach only the desired node and this characteristic has also been explored by some authors like Kuruvila, Nayak and Sojmenovic in [10] and [11]. In this paper, authors find an optimal transmission radii and design some routing algorithms called Expected Progress Ratio with acknowledgments (aEPR) and Ideal Hop Count Routing protocol (IHCR). These protocols try to achieve the greater possible delivery ratio.

Our work is mainly motivated by the lack of work taking in account both properties, delivery ratio and energy eficiency. In this paper, we present a new way to estimate the goodness of chosing a concrete neighbour to be used as a relay. We take into account not only the probability of transmission but also the necessity of an ARQ system that guarantees the delivery of the message. Therefore our routing metric account for the energy needed to send messages and ACK responses. We take advantage of the posibility of ajusting transmission power so that each message is sent using only the minimun necessary power to reach the desired destination. We call this estimation Estimated Transmission Energy (ETE) and we use it to design an algorithm which locally computes the best way to reach the neighbour closest to the final destination. After having this best path computed, the node sends the message to the first node in that path providing advance towards the destination. To do this we use Source Routing (SR) that is a well-known technique consisting in including information in the header of the message to be used by intermediate nodes. These nodes must not calculate its next hop, they only have to follow the instruction included in the SR header.

The rest of the paper is organized as follows: Our proposed scheme is described in Section 3. In Section 4 we show an analysis of the performance of our solution. Finally, Section 5 provides some conclusions and discusses open issues.

2. Physical Model

A WSN is made upon a set of nodes. Nodes use their radio hardware to transmit and receive messages. Although there are nodes equipped with directional antennas, we are focused on nodes with omnidirectional antennas. In general, as the coverage radio of a sensor is not enough to send messages to every other node in the network, the use of reachable nodes as relays in a multihop fashion is the best way to deliver messages to nodes placed outside the sender's maximum radio of coverage. Furthermore, radio transmission is affected by environmental properties, interference, and so on. It is also known that the distance has a fundamental influence in the probability of reception of messages. In general, the further the destination the less probability to reach it. To avoid this problem we need to use an ARQ strategy based on sending ACK messages to confirm the reception of a message. The usage of NACK is not possible because it is only useful to inform the sender of an incorrect or incomplete reception of a message but it is useless when there are no signs of any message. For example if r is unable to receive any message at the time s is sending it, (r might be in a sleep cycle or busy sending another message), the message will be lost and r will not have any mean to know that s had sent him a message. ACK messages suffer from the same problems: they might be lost. Thus the alternative for node s is to keep sending messages until the first ACK arrives. Between two consecutive messages node s needs to wait some amount of time approximately equivalent to time needed for r to receive, process and send the ACK back. WSN do not normally have a predefined topology, for that reason nodes have to dinamically determine its neighbourhood. Nodes can periodically send a broadcast including information about its identity and, if known, its position. When nodes cannot be equipped with hardware to determine their geographical position they can use virtual position as in [4]. These messages are usually called beacons and are used by a node to determine its neighbourhood. Evidentely, as beacons are also messages, they can suffer from errors of transmission and losses. Finally, notice that a node and its neighbours can be seen as a subnet in which the node knows the position of all the nodes. The reason is that it has received their beacons messages in the last beacon period. This is a litle obvious but is very important because centralized algorithms, as the whell-known Dijkstra, can be applied over that subnet to find optimal paths.

2.1. Energy Consumption

Nodes are devices equipped with two different pieces of hardware, the first one is used to sens its environment. The rest of the hardware is devoted to process, transmit and receive messages. Nodes such as the MICA2 have the possibility of adjusting the power used to transmit messages. Thus, the power can be seen as a function of the distance. There are different energy models that can be used to estimate the energy required by a node n to send a message far enough to reach another node placed at distance d. In the most commonly used model, the energy consumption for transmitting a fixed size message at distance d is:

$$E(d) = d^{\alpha} + C$$

Being α the media attenuation factor satisfying $2 \leq \alpha \leq 6$ and C a constant representing the power used to process the radio signal. Following the results of Rodoplu and Meng in [5], in our studies we have considered $\alpha = 4$ and $C = 100000$. Fig. 1 shows how the energy needed to send a message varies as distance increases. Values of the curve are normalised to the maximum, it is $E(R)$ being $R = 50$ the radio of coverage we have chosen.

2.2. Transmission Errors

The Log-Normal Shadowing Model [12] is a commonly accepted model to accurately represent the effects caused in the probability of reception of a radio transmission between two nodes by parameters such as the distance between sender and receiver, reflexions and environmental properties. On the other hand, considering the experimental results that Zhao and Govindan show in [6], we have decided to use these data in our simulations. Using Zhao's data we have built a table that model the probability of reception given the distance between sender and receiver. Instead of using the complex Log-Normal Shadowing Model we had rather used these data because the mathematical model is an ideal and continuous function that, in our opinion, is less accurate than the empirical data recollected using real sensors. The empirical data we are using do not

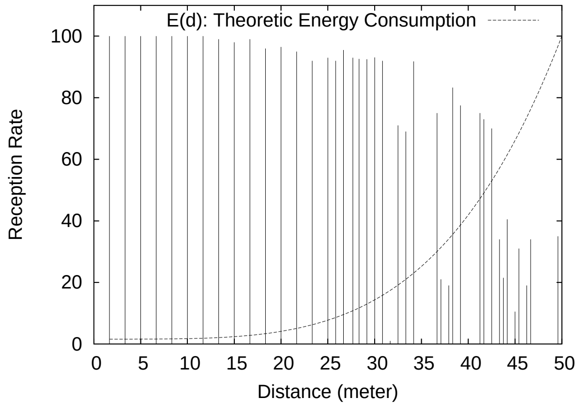


Figure 1. Packet reception rate and energy Consumption.

fit in any mathematical curve as they presents some atypical jumps in consecutive values. Zhao and Govidan [6] found that sensor placed very close could not receive the same percentage of packet even when the difference in distance from the source is very short. We define the function $prr(d)$ as the probability of reception at distance d. In our implementation, this function returns the value of the Zhao table for the distance nearer to d. Fig. 1 shows the values of the $prr(d)$ function.

2.3. Estimated Transmission Energy

The energy estimated to make a tranmission between two nodes s and r is the energy necessary to send a message from s to r and successfully receive the ACK sent back from r to s. Let $d = dist(s,r)$ be the Euclidean distance between s and r and $E(d)$ the energy of sending a message at a distance of d, it is, the energy needed to reach r from s. Let X be the random variable meaning "number of transmission before the first ACK is received correctly". As the probability of sending a message (normal or ACK) is determined by the distance between sender and receiver following the distribucion of the function $prr(d)$, the probability of the receiver to receive correctly the message is $prr(d)$ and the probability of the sender to receive correctly the ACK will be the same, thus, the probability of the complete action is then $prr(d)^2$. It is now clear that $X \rightsquigarrow Geo(p = prr(d)^2)$, therefore, the number of messages needed for a successful transmission including its ACK is the mathematical expectation ($E[X]$) that, in this case, can be calculated as $E[X] = \frac{1}{prr(|sr|)^2}$

If a node keeps resending the message up to $E[X]$ times it is statisticaly almost sure that the ACK will be received correctly. On the other hand, energy is a scarce resource that has to be saved as much as possible. Thus, the resending process has to finish in a finite, not too high, number of attempts. Setting this number to a high value will cause the message to losse its interest for the final recipient because the delay incurred might be excessive. It is better to lower the limit but taking into account that, as the maximum number of attempts decreases, the probability of the message to reach its final destination decreases too. For that reason, the mean number previously calculated has to be limited with a constant called T. Thus, the estimated number of transmissions to send a message from s to r and correctly receive its ACK can be defined as $min(\frac{1}{prr(|sr|)^2}, T)$. Finally, as each transmission needs an energy equal to $E(d)$, the estimated transmission energy $ETE(s,r)$ can be defined as

$$ETE(s,r) = E(|sr|)min(\frac{1}{prr(|sr|)^2}, T)$$

.

3. The new Routing Protocol

Routing has two important phases: first one is to choose the relay and second one is to pass the message to that relay. Algorithms such as GPSR [3] are made upon the assumption that the link layer is perfect so they focus only on the selection of the best relay neighbour. Taking into account a realistic physical layer means that, in the election of the relay we must to consider the probability of errors and the energy needed to reach it. Furthermore, if nodes can adjust its transmission power, reaching a neighbour can be done in several ways. First it can be reached directly as it is a neighbour but when there are others neighbours it might be possible to use them as relays to send it a message. The question that arises is, which is the best way to send a message to a neighbour?. The answer depends on the criteria to minimise. In our case we want to minimise the energy needed to reach the neighbour.

Let s be the node currently holding the message and r the neighbour selected to be its next relay. Sending the message directly has an energy cost given by $ETE(s,r)$, but, if the distance $d = |sr|$ is enough, it can be better sending the message through an intermediate neighbour (when it exists). Doing two shorter hops can be less energy consuming than doing only one. That is, for some values of d, $ETE(s,r) > ETE(s,a) + ETE(a,r)$ for a certain node a that must be neighbour of s and r at the same time. As the number of possible chains of nodes grows with the number of neighbours, one way to find out the best chain is applying Dijkstra algorithm to the subnet consisting of s and its neighbours. In this subnet two nodes a and b can comunicate directly if and only if the distance between them is less or equal than the maximum radio of coverage and that communication is characterised by an energy cost given by the function $ETE(a,b)$. The obtained chain is the less energy consuming path between s and r using as intermediate relays neighbours of both nodes and taken into account possible retransmissions due to errors. Moreover, this algorithm can be run locally by each node of the network because it only needs the information about the neighbours of the node.

We now know how to reach each neighbour using the less energy possible and at the same time achieving the best delivery ratio possible as both parameters build the function ETE. It then remains to select an adequate neighbour. As the routing task is in charge of delivering a message from one node to another one, the neighbour being closer to the final destination is the best possible option. Furthermore, as we are sure that we can reach every neighbour with the best chain of intermediate neighbours, that combination must be the most effective (as our simulation confirmed). After several experiments we have noticed that when routing in a greedy way using only local information is better not to advance too much at every step. It is necessary to advance to avoid entering cycles but taking longer steps may lead to a worse global path than taking shorter ones. We then decided not to follow completely the chain computed using Dijkstra because this chain takes to the neighbour closest to the final destination, it is, is a long hop (made upon shorter ones). Instead we follow the chain only up to the first intermediate neighbour providing advance towards the destination. This decision will increase the number of hops but as these hops are computed using Dijkstra and the ETE function, we are sure that this will not increase the total amount of energy needed. Moreover, this decision allows the routing protocol to correct possible trajectory errors as the message is getting closer to the final destination.

Finally, when a node has decided the next relay (the first node in the chain that provides advance) it uses Source Routing (SR) to guarantee that the message is delivered following the calculated path. This well-known technique applied in IP routing consist in insert the list of hops in an special header of the message. Intermediate neighbours receiving a message whith a SR header in which their IDs appear as next hops, they just remove themselves from the list and pass the message to the next hop indicated. Notice that the number of intermediate nodes is likely to be low thus the overhead is not a problem.

4. Experimental Results

We have developed an event-driven simulator to evaluate the performance of our new routing protocol. The most important parameters evaluated are delivery ratio, energy consumption and number of transmissions. The basic scenario is a square of 100x100 metres with the source node placed at (0,0) and (100,100) coordinates respectively. We consider that all the nodes have the same maximum coverage radio and we set it to be 50 meters. As we have already commented, to model the probability of error in transmissions we use a static table having that probability for a variety of distances. In all the generated scenarios two nodes are neighbours if the distance between them is less or equal to 50 meters and the probability of reception for that distance is higher than a 1%. Considering density of a WSN as the mean number of neighbours we wanted to evaluate the impact of density in the behaviour of our protocol. For that reason we have generated 20 different graphs for each of the following mean densities: 6,8,10,13,15,17,19,22,33,44,55. During simulations, when a node needs to send a message to another one, the simulator generates a random value between 0 and 100 and if that value is less or equal to the probability of transmission for the distance between sender and receiver, the receiver receives the message and then sends back the ACK. That sending is managed in the same way. Thus it can also be lost. If the ACK is correctly received by the sender, the process ends but if not the process is repeated at most T times. We have chosen four different values of T (5,10,15 and 20) to test our routing protocol in order to show the impact of this parameter. The algorithms simulated are Dijkstra, Expected Progress Routing (aEPR), Ideal Hop Count Rouging (IHCR) and our algorithm labelled as NEW. By Dijkstra we refer to the centralised computation of the shortest path between source and destination having as links weights the Estimated Transmission Energy. We then simulate the routing of a message through that precomputed path. Evidently, errors are possible to occur during that simulation so Dijkstra will not have a perfect result but it should have the best performance of the four tested algorithms because, unlike the other three protocols, it has all the information about the complete topology. aEPR and IHCR are two localised routing protocols described by Kuruvila, Nayak and Stojmenovic in [8]. Finally in order to achieve an acceptable level of confidence in the results showed we have run each algorithm in each scenario 100 times having a confidence interval for the 95% reduced enough.

4.1. Impact of the mean density

Fig. 2(a) shows the total energy consumed by each algorithm at varying the mean density and having the maximumn number of retransmissions fixed in $T = 10$. It is clear that our new algorithm outperforms aEPR and IHCR for all the tested densities. Notice that as density grows our new algorithm takes advantage of the increasing in the number of possible path to reach a neighbour using other neighbours. The figure shows that the energy consumption of our protocol approaches significantly to Dijkstra centralised values. At each step, our algorithm computes the best path using only the neighbours of the current node, thus, as the

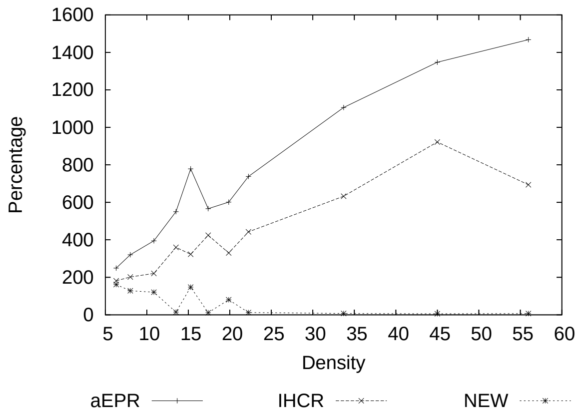


Figure 3. Energy reduction.

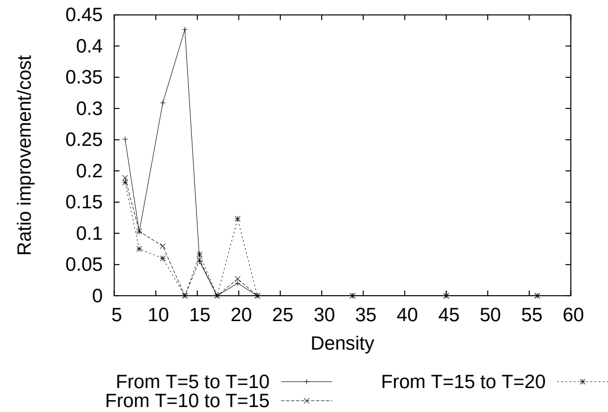


Figure 5. Best option for T.

number of neighbours increases, the computed path gets closer to the perfect one. That is, the one computed by the centralised approach. The reason for our new algorithm to be so superior to the other two localzed protocols is that the metric we are using includes the energy due to retranmissions and therefore, the probability of error that causes those retransmissions. Thus we chieve a good tradeoff between delivery ratio and energy consumption.

Fig. 2(b) shows percentage of messages arriving to the destination. Each algorithm is executed 100 times over each of the 20 different graphs generated for each density. That makes a total amount of 2000 messages sent for each density. The figures shows the percentage of those 2000 messages that correctly arrived to the destination. Our algorithm obtain better results than aEPR and IHCR and for densities under 22 and almost perfect delivery over that density. Thus, the tradeoff we have achieved is really good. Finally Fig. 3 shows the difference between the best energy consumption achieved by Dijkstra algorithm and the other three algorithms tested. This difference is showed in percentage. Our protocol keeps under 170% of the energy consumed by Dijkstra and as the density increases that difference falls up to the 4% and remains almost constant at that value. The other protocols present greater differences for all the tested densities and get worse as density increases.

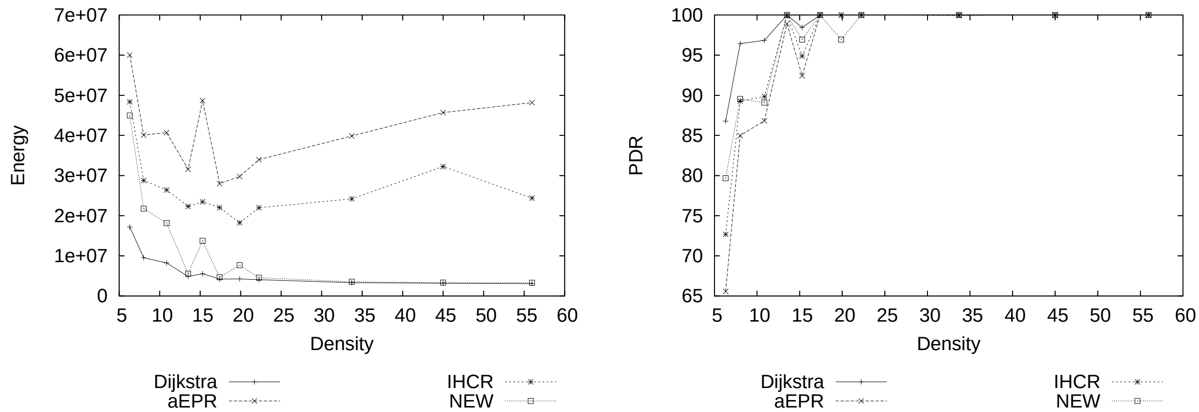
4.2. Impact of the maximun number of retransmissions

In previous Section we have kept the maximum number of retransmissions (T) fixed at a value of 10. In this Section we evaluate four different values of T: 5,10,15,20. To see the effect of this parameter in our algorithm we have run our protocol in the same scenerios than before but changing the value of T. Thus, in Fig. 4(a) we presents the results obtained varying the density. It can be seen that the total amount of energy needed grows as the maximum number of retransmissions allowed increases. Thus, to save energy the best value fot T would be the lower one, but on the other hand, Fig. 4(b) shows that that lower values of T make the delivery ratio to decrease.

Fig. 5 shows the ratio improvement/cost for different changes in T. It shows that when density is higher than 22 there is no impact of the value of T because for these densities there are enough neighbours with high packet reception rate, thus, there is almost no need to make more than 5 retransmissions. For densities under 22, to change from T=5 to T=10 represents a better option than any other. In general we believe that the maximun number of transmissions must never be more than 10 as with this value the overal performance is good enough.

5. Conclusions and Future Work

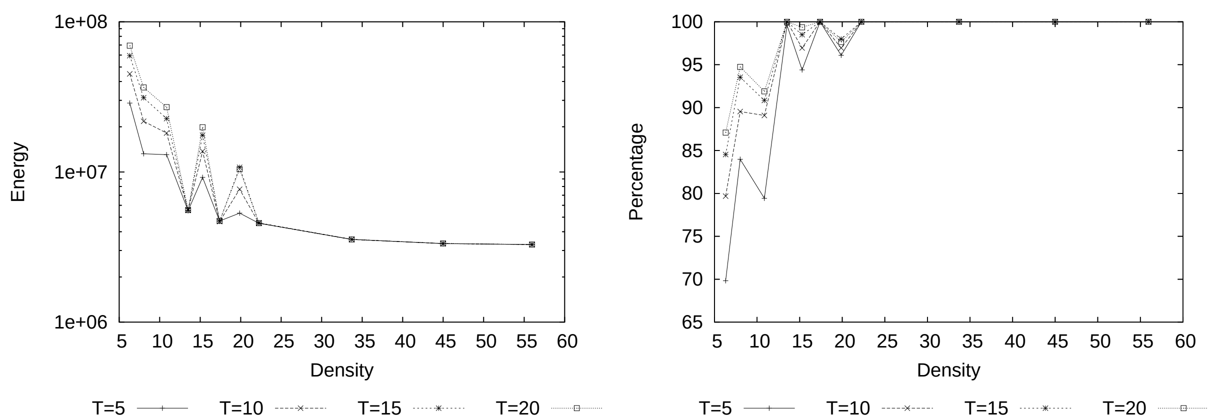
WSN are already considered to be very valuable in several scenarios as disaster relief, data gathering and monitoring of wild life, control and detection of intruders in wide open areas, etc. Several works have been done in the field of routing in WSN but, almost none of them consider realistic physical layer. Already developed routing protocols usually work with the simple but inaccurate unit disk model or take into account in an isolated way one of the two more important characteristics of WSN: errors in transmission and energy problems. Motivated by the need of a routing protocol which works well in a realistic environment we have designed a new metric to characterise how promissing is a neighbour to be used as a relay, we call it ETE. We make use of ARQ to guarantee the correct transmission of messages and based in ETE we have developed a new routing protocol that achieves almost perfect results in terms of delivery rate and energy consumption. Several experiments have been



(a) Total energy.

(b) Delivery ratio.

Figure 2. Results for a fixed value of T=10.



(a) Total energy

(b) Delivery ratio

Figure 4. New algorithm results for different values of T

done and the results show that our work outperform previous works in both parameters even when the other protocol tested were developed to achieve great performance only in one of the two parameters. For future work we are working in testing our protocol in a real environment to confirm that it is robust enough and to investigate the possibility of developping and extension for multicast routing.

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