Finding Diverse Shortest Paths for the Routing Task in Wireless Sensor Networks

Wilton Henao-Mazo and Ángel Bravo-Santos
Departamento de Teoría de la Señal y Comunicaciones
Universidad Carlos III de Madrid
Avda. de la Universidad 30, Leganés, 28911 Madrid, Spain
$\{$*wiltonhm, abravo*$\}$*@tsc.uc3m.es*

***Abstract*—Wireless Sensor Networks are deployed with the idea of collecting field information of different variables like temperature, position, humidity, etc., from several resource-constrained sensor nodes, and then relay those data to a sink node or base station. Therefore, the path finding for routing must be carried out with strategies that make it possible to manage efficiently the network limited resources, whilst at the same time the network throughput is kept within appreciable levels. Many routing schemes search for one path, with low power dissipation that may not be convenient to increase the network lifetime and long-term connectivity. In an attempt to overcome such eventualities, we proposed a scenario for relaying that uses multiple diverse paths obtained considering the links among network nodes, that could provide reliable data transmission. When data is transmitted across various diverse paths in the network that offer low retransmission rates, the battery demand can be decreased and network lifetime is extended. We show, by using simulations, that the reliability in packets reception and the power dissipation that our scheme offers compare favourably with similar literature implementations.**

***Keywords*-WSNs; Wireless Sensor Networks; K Shortest Paths; Diverse Paths.**

I. INTRODUCTION

Wireless Sensor Networks (WSN) have been one of the trending research topics for several years due to their particular features among which are worth to highlight topologies flexibility, distributed detection capacity, low energy consumption and stand alone operation. All these WSN features allow to cope different tasks such as target tracking for mobile agents, event detection, environment information gathering and remote monitoring/controlling. At the same time this technology must perform the activities they are required to accomplish, bearing in mind that there are some limitations like the energy source that in almost all the cases is a battery, the low processing capacity, the unpredictable reliability on the information delivery due to some phenomena of wireless channel, the relative-low transmission rates and the short range in wireless communication.

In a WSN, there exists a task which consists in taking the data through the network from one node to another in a determined period of time, and it is known as the relaying or the forwarding of data packets. In this process, an important issue necessary to deal with is the transmission reliability, whilst energy efficiency is maintained in order to guarantee a considerable network lifetime. These issues have been treated in routing tasks and mechanisms implemented in the application layer related to energy saving goal [1][2][3]. One justification to pay attention in obtaining quite good reliability levels in communication is the belief that significant energy resources can be saved when the number of required retransmissions is reduced [4]. On the other side some, of the referenced works only try to obtain a single optimum route by which the data traffic mainly flows from source node to destination node, and such strategy can incur faster energy depletion of the nodes of this route. Finding multiple paths, obtained based on the Ad hoc On-Demand Distance Vector (AODV) that requires distances and hop count, can be used for the relaying task and it seems to be a good option when network survivability is required [2]. In the present paper, a different strategy is implemented. Here, the idea of finding multiple paths which have certain degree of diversity among them becomes important. In this way, it is possible to guarantee reliable successfully transmitted data rates and the power dissipation is distributed among the nodes involved in the data forwarding task.

As seen before, one important aspect in routing is finding multiple paths. Hence, it is important to know that the K shortest paths problem is a natural and widely-studied generalization of the shortest path problem in which not one, but several paths in increasing order of length are sought. The K shortest paths problem in which paths can contain loops turns out to be significantly easier. But the problem of determining the K shortest loopless paths has proved to be more challenging. The problem was first examined by Hoffman and Pavley [5]. For undirected graphs, the most efficient algorithm, proposed by Katoh et al. [6], has the complexity of $O(K(|L| + |M| \log |M|))$ ($|L|$ the number of edges and $|M|$ the number of nodes). For the most general case, the best known algorithm is that proposed by Yen in [10]. This algorithm has achieved the complexity of $O(K|M|(|L| + |M| \log |M|))$. Here, we use the Yen's algorithm as a basis for our proposal.

The organization of the paper follows with a brief outline of Yen's algorithm in Section II, jointly with some useful assumptions and graph theoretic concepts. Later, in Section III, the proposed algorithm to find diverse shortest paths (DSP) in a WSN is presented. Section IV shows simulation

ISBN: 978-1-61208-231-8

results and an analysis about the proposed scheme, and finally, some conclusion of the developed work are drawn in Section V.

II. PRELIMINARIES

In order to define in a clear way what is wanted to do in a WSN, we are using classical statements from graph theory by which our wireless network of sensors can be represented as a pair $G = (M, L)$. Here, G represents an undirected graph where M is the set of m sensor nodes, each of them identified by a unique mote number inside the net, and L is the set of possible wireless links between nodes $i \in M$ and $j \in M$. For simplicity, it is necessary to consider a cost communication matrix $A^{m \times m}$, in which each consigned entry $a_{ij} \in \{\mathbb{R}^{+} \cup +\infty\}$ holds for the cost or weight that is required to establish the links of the previously described set L.

A. Some network assumptions

- Node's mobility in the network is not allowed, hence every node has a fixed position.
- Ordinary sensor nodes have the same capabilities, the same radio-transmitter devices and constrained power resources.
- The sink node is assumed to have unconstrained resources.
- Symmetric cost model is assumed. This means link cost of transmit data from sensor i to sensor j is the same than in the opposite direction.
- The received signal strength (RSS) can be measured in each of the nodes, without significant cost in power consumption.
- Without loss of generality, a log-normal path loss radio propagation model is assumed as a well-suited approximation for the link layer modelling of a wireless sensor network. Such a model is deeply described in [7] [8].
- In order to guarantee a good performance of the network with respect to communication reliability, an ACK mechanism is used in each hop of the transmission rather than an end-to-end error recovery strategy.

B. An algorithm that finds shortest paths

One of the most important algorithms developed for finding certain amount of paths between a pair of source-destination nodes in a graph is the Yen's algorithm (1971) [10]. This is based on a deviation principle. First, let us denote the source node by $s \in M$ from which it is desired to get the sink node $t \in M$, through K shortest loop-less paths. These paths form a set of K components, $P = \{P_1, P_2, \cdots, P_K\}$. At the same time, each path of the latter set is defined by the sequence $P_K = \langle s = v_1^K, v_2^K, \cdots, v_i^K = t\rangle$, where v_i^K is the i-*th* node of the K-*th* shortest path. In the next algorithm, there is a brief outline of this procedure.

Algorithm 1 Yen's algorithm

```
Require: $A, s, t, K$.
 1: $P^1 \leftarrow$ Dijkstra($s, t$)
 2: $D \leftarrow \{P^1\}$ %Set of candidates
 3: $P \leftarrow \{\}$ %Set of the $K$ shortest paths
 4: for $k$ from 2 to $K$ do
 5:   $SP \leftarrow$ the shortest path in $D$
 6:   $v \leftarrow$ the deviation node $(SP, P)$
 7:   $P \leftarrow P + SP$
 8:   while $v \neq t$ do
 9:     discard all nodes of $SP$ from $s$ to $v$
10:     discard each output link of $v$ which belongs to $P$
11:     $SP' \leftarrow$ Dijkstra($v, t$)
12:     join $SP'$ and $SP$ from $s$ to $t$
13:     $D \leftarrow D + \{SP'\}$
14:     restore all discarded nodes and links
15:     $v \leftarrow$ successor($v, SP$)
16:   end while
17: end for
```

As it can be figured out from Algorithm 1, given an adjacency matrix and a source-sink pair of nodes, the algorithm is initiated by calculating the shortest path P^1 (line 1) and initializing some variables. Then the algorithm will perform K iterations. At the *k-th* iteration, the algorithm extracts the shortest path stored in candidates set D. This path is the K-*th* resulting path from s to t. Then, the deviation node is calculated from all the $K - 1$ paths in SP. To avoid recalculation of the already computed paths, the algorithm discards certain nodes and links as it is shown in lines 9 and 10. The shortest path SP' between deviation and source node is calculated with the remaining graph. Then, SP' joins the sub-path of the K-*th* shortest path from source to deviation node and saves this new produced path in the candidate set D. Finally, all the links and nodes previously discarded are restored and the algorithm moves to the successor of the deviation node (line 15) in the K-*th* shortest path.

III. PROPOSED ALGORITHM

As previously noted, algorithms that find shortest paths need metric information. This metric information can be considered as the cost of possible inter-node links, and according to this the algorithms try to minimize the total cost of paths. As mentioned before, the packet reception rate (PRR) will be useful for finding reliable paths by which data is relayed from source to destination nodes. Trying to avoid significant delays in the process of path discovery, the PRR can be computed easily at each node by the following procedure: since each sensor node is able to obtain the

RSS when an incoming message is correctly received, based on this measure, the wanted metric can be estimated. In order to illustrate how to estimate the PRR when there exists a BPSK modulation, with a measurement of RSS and a good estimated characterization of noise, the SNR can be computed as $\gamma[dB] = RSS - P_n$. Then, a bit error probability is calculated for the current case as [7]

$$P_e = \mathcal{Q}(\sqrt{2\gamma \frac{B_n}{R}}), \tag{1}$$

where B_n is the noise bandwidth and R is the bit data rate. Furthermore, provided that all bits are received without errors, there exists a correct reception. Then, we can derive the probability of successfully packet reception for a frame of f-bytes length at certain distance as[7]

$$p = (1 - P_e)^{8f}. \tag{2}$$

Finally, the PRR can be calculated regarding a NRZ encoding mechanism with preamble length L [7] with the expression[7]

$$PRR = (1 - Pe)^{8L}(1 - Pe)^{8(f-L)}. \tag{3}$$

So far, the computation of the PRR has been described, but the useful metric for our algorithm is missing. If we pretend to use an algorithm that yields shortest paths, the raw obtained PRR is non meaningful for our desired goals of power efficiency through reliable data relaying. Thus, each possible communication link is going to have the inverse of the PRR as metric, or cost, between nodes i and j for finding the shortest paths,

$$LC(i, j) = 1/PRR_{ij}. \tag{4}$$

These link costs are consigned in the previously defined network cost communication matrix. A total link cost (TLC) of such paths are computed within the Yen's algorithm as

$$TLC_{P_{st}} = \sum_{(i,j)\ links\ \in\ P_{st}} LC(i, j). \tag{5}$$

Diverse paths from K shortest path

Given the Yen's algorithm as the basis for what is wanted to achieve, when this algorithm returns K paths, they usually have many links in common. But we do not really need too much redundancy in the routes avoiding this way the faster energy depletion of the nodes involved. This kind of ”trouble” can be explained by the principle of deviation nodes. However, in the present work a filtering or selection applied over the set of K shortest paths is introduced. With this selection certain degree of diversity can be achieved. It is suspected that transmitting data packets in a WSN over diverse paths lead us to trustful communication levels by avoiding the amount of retransmissions that might appear in a single path case. Algorithm 2, shown below, outlines how to proceed to obtain paths as diverse as possible starting from the K shortest paths,

Algorithm 2 Diverse paths selection

```
Require: $A, s, t, K, \alpha$.
 1: $IncludedLinks \leftarrow \{\}$ % Set of appearing links
 2: $w_{P_K} \leftarrow 0$ % Array of $K$ weights of paths
 3: Get $P_1, P_2, \cdots P_K$ the $K$ shortest paths by Yen's algorithm between $s$ and $t$.
 4: $IncludedLinks \leftarrow$ All $(i, j) \in P_1$
 5: $w_{P_1} \leftarrow 1$
 6: for $k$ from 2 to $K$ do
 7:     $w_{P_k} \leftarrow \sum_{(i,j)\in P_k} \frac{LC(i,j)}{TLC(i,j)} G(i, j)$
 8:     for each link $(i, j) \in P_k$ do
 9:         if $(i, j) \notin IncludedLinks$ then
10:             $IncludedLinks \leftarrow IncludedLinks + (i, j)$
11:         end if
12:     end for
13: end for
14: $DSP \leftarrow P_k$ whose $w_{P_K} \geq \alpha$
```

The procedure showed in Algorithm 2 is conceived on the idea of selecting diverse paths. After coming up with K shortest paths by using Yen's algorithm, we proceed to fill in the set $IncludedLinks$. This set contains links from the K shortest paths such that if we analysed these paths in ascendant order, the links that appear for the first time (hence, they have not been in this set before) in the search would be in the $IncludedLinks$ set. In the Algorithm 2 can be noted how all the links of the shortest path 1 are in the $IncludedLinks$ set.

The weight of each one of the K paths is computed in the present work as,

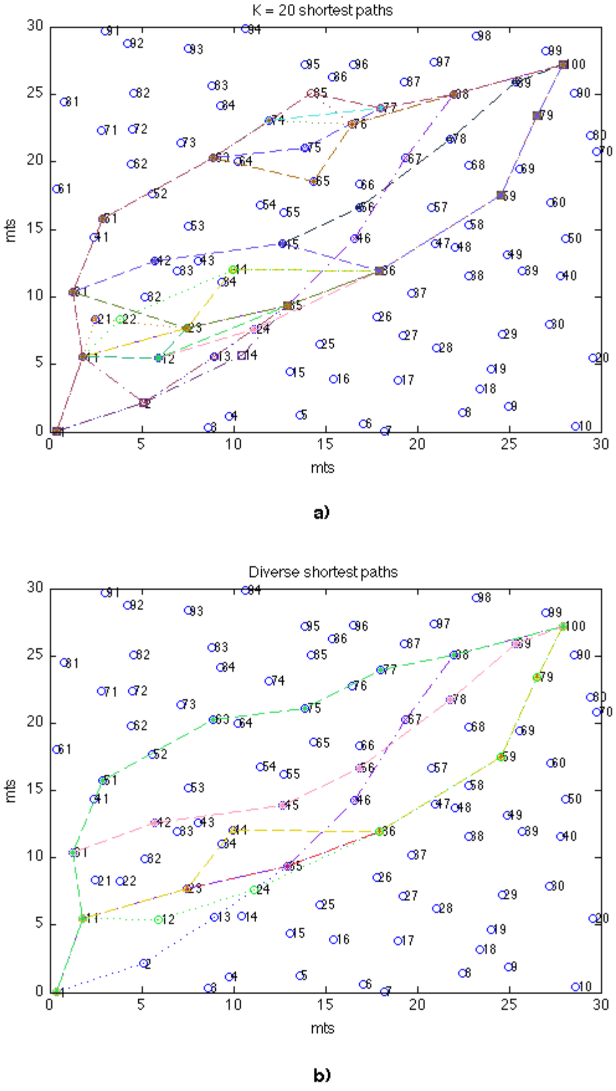
$$w_{P_k} = \sum_{(i,j)\in P_k} \frac{LC(i,j)}{TLC_{P_k}} G(i, j), \tag{6}$$

which, at the same time, is depending on $G(i, j)$, a general function which indicates the previous inclusion of the link into a previous path and defined as,

$$G(i, j) = \left\{ \begin{array}{l} 1 \text{ if } (i, j) \notin IncludedLinks \\ 0 \text{ if } (i, j) \in IncludedLinks. \end{array} \right. \tag{7}$$

The computation carried out in line 1 of Algorithm 2 is laying out how dissimilar the paths are, in the sense of the amount of links they differ, and is giving a weight or importance to the path depending on individual link costs, as well. Finally, another important aspect to review in the latter algorithm is the threshold α. From the different K paths we are selecting a reduced number of them if and only if their weights fulfil the condition $w_{P_K} \geq \alpha$. Such threshold is an arbitrary fixed value within the range $0 \leq \alpha \leq 1$, so the greater the threshold the fewer number of links the selected routes share.

In the example shown in Figure 1, where is depicted in first place (sub-figure (a) above) the resulting $K = 20$



a)

b)

Figure 1. Obtained shortest paths example in a WSN.

shortest paths in a WSN, and in other (sub-figure (b) below) the shortest paths selected from the previous ones by the Algorithm 2 with $\alpha = 0.35$. As can be verified here, whilst Yen's algorithm returns certain routes that seem to be copies from a previous one except by couple of links. With the diverse paths selection carried out over that set, we keep paths with relative few redundant links.

IV. SIMULATIONS AND PERFORMANCE ANALYSIS

We wrote the code of a customized discrete time, event-driven wireless sensor network simulator in MATLAB in order to evaluate the efficiency of the algorithm in a packet level environment. For simplicity on simulating the net, a simple CSMA/CA mechanism is used in MAC layer to avoid signal conflicts. Also the physical link layer model values reported in [7][8][9] are used. Detailed fixed simulation parameters are shown briefly in Table I.

Table I
PARAMETER VALUES USED IN SIMULATION

Parameter	Value
Network topology	randomly uniform
Network area	$30 \times 30\ m^2$
Data rate	19.2 Kbps
Tx Power	-7 dBm
Carrier frequency	900 MHz
Path loss exponent, n	4.7
Shadowing standard deviation, σ_n	3.2
Modulation	BPSK
Noise bandwidth, B_n	30 KHz
Noise floor	-105 dBm
Encoding	NRZ
Frame size, f	50 bytes
Preamble length, L	2 bytes

We compare our proposed diverse shortest paths (denoted by DSP) algorithm with a rough implementation of the algorithm EDA proposed in [11], that finds multiple disjoint paths based on minimum spanning trees rooted at both source node and destination node, coming up with multiple paths for packet forwarding. Such EDA implementation is rough, due to it is made simulating its distributed nature by using a heap, where events with a time stamp are managed through this data structures. A second comparison is carried out with a Naive algorithm that finds disjoint paths by the following procedure: find the shortest path between source and sink nodes, then remove the nodes in the first obtained shortest path from the network; find another shortest source to sink path in the remaining network and delete them once obtained. Iterate this way until a previously defined number of paths has been found. Both algorithms used for comparison, made use of the metric LC presented in Section III , as well as our DSP proposed algorithm.

The performance of our algorithm is demonstrated by simulating a data packet forwarding environment between a source node and a sink node. Then, we measure the rate of successfully delivered packets when a source node generates 10000 information packets. Such rate is taken as the ratio of packets that reached the destination nodes between the total number of packets generated in the source. Every packet has a number of packet which helps to know whether packet loss given a period of time occur. For all the algorithms, we vary the network nodes density (# of nodes/m^2) by increasing the number of nodes from 50 to 300 and keeping the area where the net is deployed as specified in Table I.

Simulations results are contained in Figure 2. Taking

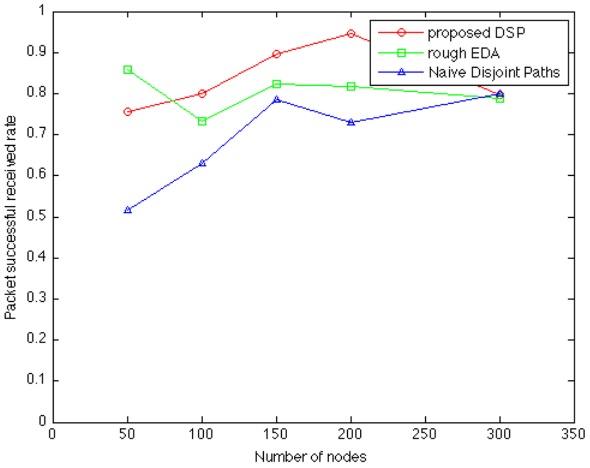


Figure 2. Reliability in packet reception varying nodes in the WSN.

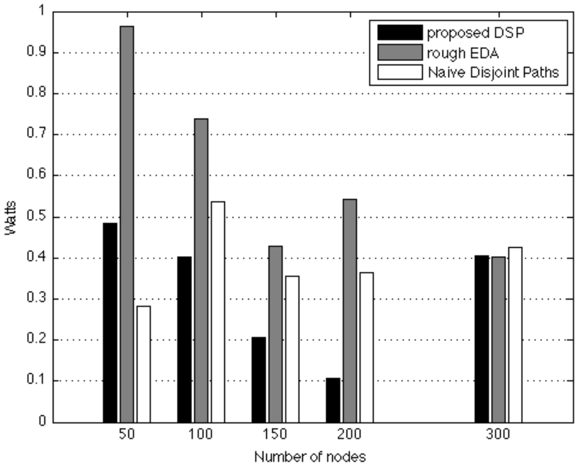


Figure 3. Average power dissipated in retransmissions.

into account that the number of nodes in the network has been varied and the transmission of the packets has been simulated for the 3 algorithms previously commented; it is remarkable how in almost all the cases our DSP proposed algorithm has the best performance among these 3 algorithms. The Naive disjoint paths algorithm has generally the weakest successful reception rate because it attempts to look for paths in a greedy way and ignoring the possibility of finding multiple paths at each iteration. All the three algorithms seem to converge to a slightly good reliability level of about 0.80 when the WSN node density is increased.

An additional important aspect that can be obtained from simulation results is the average power required in retransmitting when packet loss occurs. In Figure 3, we present the power dissipated in retransmission of the three commented strategies. Our proposal has neat advantage when the number of nodes is 200. The DSP algorithm is wasting only about 19% and 29% from the power required by the Naive algorithm and the rough version of EDA, respectively.

V. CONCLUSION AND FUTURE WORK

To obtain diverse paths for the routing task in the WSN, we proposed an algorithm that has as a main core Yen's algorithm, an efficient algorithm for computing the K shortest path problem. Here we compare our proposed algorithm with one that finds multiple disjoint paths based on a spanning tree construction [11] trying to look for some advantage, and with a Naive procedure that finds multiple node-disjoint paths. Our proposal presents some advantages over the other two algorithm used for comparison. Simulations show that relaying through the routes our proposed algorithm finds, reliable communication levels are obtained, while considerable energy saving takes place in the network. This is because of the reduction on retransmission events by selecting reliable paths. Another reason is that the network lifetime is increased due to a distributed usage of the network. A distributed usage can be seen when different nodes which compose the diverse shortest paths are used each time.

Another observation obtained from the results is the unpredictable behaviour that all the finding paths algorithms present with the variation of the number of nodes or network density. In this work for example, the throughput curves of the three algorithms do not follow similar patterns. Hence, this might be a possible improvement aspect which needs to be worked on further. Besides, a very interesting future line work is an implementation of Yen's algorithm that could take advantage of the distributed processing power present in WSNs.

ACKNOWLEDGMENT

This work has been partially supported by the Spanish government (Ministerio de Educación y Ciencia 2009-14504-C02-01, Consolider-Ingenio 2010 CSD2008-00010).

REFERENCES

[1] M.J. Baek, K.I. Kim and S.H. Cho , "*A revised Mint-Route protocol in wireless sensor networks*". Information and Communication Technology Convergence (ICTC), 2010 International Conference on , no., pp. 258-259, 17-19 Nov. 2010

[2] P. Hurni and T. Braun, "*Energy-Efficient Multi-Path Routing in Wireless Sensor Networks*". In Proceedings of the 7th International Conference on Ad-Hoc, Mobile and Wireless Networks (ADHOC-NOW 08), Sophia Antipolis, France, 1013 September 2008, pp. 7285.

[3] R. Vidhyapriya and P.T. Vanathi,"*Energy Aware Routing for Wireless Sensor Networks*". Signal Processing, Communications and Networking, 2007. ICSCN '07. International Conference on, pp. 545-550, 22-24 Feb. 2007.

[4] J. Zuo, C. Dong, S. Ng, Y. Lie-Liang and L. Hanzo, "*Energy-Efficient Routing in Ad Hoc Networks Relying on Channel State Information and Limited MAC Retransmissions*". In VTC2011-Fall, San Francisco, United States, 05 - 08 Sep 2011.

[5] W. Hoffman and R. Pavley,"*A method for the solution of the Nth best path problem*". Journal of the ACM, 6: pp. 506-514, 1959.

[6] N. Katoh, T. Ibaraki and H. Mine,"*An efficient algorithm for k simple paths*". Networks, 12: pp. 411-427, 1982.

[7] M. Zuniga and B. Krishnamachari,"*Analyzing the transitional region in low power wireless links*". IEEE SECON, Santa Clara, CA, October 2004.

[8] M. Zuniga and B. Krishnamachari,"*Link layer models for wireless sensor networks*". USC, Dec. 2005, unpublised.

[9] K. Sohrabi, B. Manriquez and G. Pottie,"*Near ground wide-band channel measurement in 800-1000 MHz*". Proceeding of IEEE VTC, Sep. 1999.

[10] J. Y. Yen,"*Finding the K shortest loopless paths in a network*". Management Science, Vol. 17, pp. 712-716, 1971.

[11] K. Zhang and H. Gao,"*Finding multiple length-bounded disjoint paths in wireless sensor networks*". Wireless sensor networks, Vol. 3, pp. 384-390, 2011.