Combined Hop Count and Received Signal Strength Routing Protocol for Mobility-enabled WSNs

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Abstract— **In this paper, a new routing protocol is proposed for Wireless Sensor Networks (WSNs). The scenario taken is a WSN to be deployed non-intrusively in moving vehicles. WSNs are a class of wireless networks that require specific protocols, whose execution occurs in resource-constrained nodes. As a consequence, the protocol that calculates the optimal path for the packets to reach the sink must be lightweight. In this context, not only the mobility of nodes is challenging, but also the energy consumption. The innovation introduced by this protocol is its combination of the Received Signal Strength Indicator (RSSI) and number of hops to find the best path for the packets, allowing to have the benefits in terms of end-to-end delay and packet delivery ratio. Simulation results show that, when compared with approaches that only take into account the number of hops or RSSI, the protocol increases the number of delivered packets, whilst decreasing the end-to-end delay and the energy consumption. It can also deliver up to 271% more packets, while using less 71% of energy than Flooding.**

I. Introduction

Wireless Sensor Networks (WSNs) are an emerging class of small, low power, and self-organised networks. Developing protocols for these networks is a challenging task, because the energy is very limited, and the computational resources are very scarce.

In this paper, a suburban scenario with information flow WSN for a vehicle-to-road infrastructure is addressed. The data generated in the car must be sent to the road authority in real-time. Moving vehicles constitute a challenge for the routing of the packets, since to avoid deploying a large infrastructure vehicles must use each other as data relays, and their relative speed is constantly creating and destroying links among them. In the considered scenario, the information is gathered by a WSN that is independent of the vehicle, having to rely on its own power source and sensors to perform its task. This corresponds to a commercial off-the-shelf component that is purchased by the driver, and is installed in the windscreen without any cables. This allows for a simple and non-intrusive application, not requiring cables connected to the car battery and leaving the cigarette lighter receptacle free for other appliances (such as GPS navigation system or mobile phone).

The mobility-based routing protocol proposed in this paper relies on periodic information exchange between the vehicles to identify new paths and eliminate non-existent ones. It uses the number of hops, and a value associated to the probability of having transmission errors, to find the most suitable path for the packets. This combination allows for obtaining paths with low end-to-end delay and high delivery ratio. The protocol is designed to run beside the IEEE 802.15.4 standard in nonbeacon-enabled mode, so all the routing procedures are performed in the framework of the standard.

The remainder of this paper is organised as follows. Section II discusses the challenges for the routing in WSNs. Section III presents the developed protocol and discusses the scenario, along with the protocol working principles and how this suits the considered scenario. Section IV discusses the results obtained by simulating the protocol, while section V concludes the paper.

II. Routing protocols and WSNs

Routing is the process of selecting paths for sending packets from one source to a destination, over a network. In ad hoc networks there are no coordinators, hence nodes have to cooperate with each other in order to determine the best path for the packets. WSNs are one type of ad hoc networks, with special characteristics. First, they rely on low cost hardware, thus having limited memory, computational power and transmission capacities. Secondly, they have to be small in size, which limits the amount of energy that can be stored. Thirdly, their protocols are application oriented: a protocol whose performance is satisfactory in a network with low number of nodes can be ineffective if applied to larger networks; or a protocol that is reliable delivering packets in a monitoring network may fail to achieve the delay limits of a multimedia WSN.

As a consequence, the following characteristics need to be accounted for in WSNs protocol design:

1) Lightweight – the protocol must run with a minimal resource consumption. Since WSNs nodes have low RAM capacity, the size of the routing table (and the remaining elements of the protocol that reside in the nodes' memory) must be as small as possible. Besides, protocol operations must use as less processor cycles as possible;
2) Energy efficient – with the energy available limited to a small battery, the protocol must minimise its consumption. Reducing the time the radio spends in the

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transmission mode is one way of address this issue, avoiding retransmissions is another;

3) Network requirements – the protocol must be aware of the network characteristics and deliver the packets within the limits set by the application.

The characteristics above apply to protocols from any layer developed for WSNs, not just the networks layer ones.

Routing protocols can be divided into categories [1], according to the main challenge they address. For example, the hierarchical protocols, in which the Low-Energy Adaptive Clustering Hierarchy (LEACH) [2] is included in, are designed aiming at the scalability of the network. In turn, SPEED [3] is a QoS-based protocol, and aims at delivering the packets within the limits established by real-time applications. The protocol presented in this paper fits in the category of mobility-based protocols, which are designed to address the problem of node and/or sink mobility [4]. Most of the state-of-the art protocols do not support it, or perform badly under mobile nodes conditions. If sensor nodes are mobile, links are always being created and “destroyed”, as the neighbour nodes are getting closer to each other or the opposite. This dynamic change of network topology must be addressed by the routing protocol being used [5]. The Scalable Energy-efficient Asynchronous Dissemination (SEAD) [6] protocol uses dissemination tree construction, data dissemination and link maintenance to send data from nodes to mobile sinks. It aims for a trade-off between energy consumption and delay minimisation, but introduces a lot of overhead. The authors from [7] present a protocol for secure communications, but at the cost of the complexity. The protocol presented in this paper, which is detailed in section III, is designed to be easily implemented, maintaining a very low overhead for maximum network performance.

III. Mixed Hop and signal Received routing for mobile WSN

The Mixed Hop and signal Received routing for mobile Wireless Sensor Networks (MHRWSN) is a network layer protocol conceived for WSN that have multiple mobile nodes generating data for a single sink. The main requirements for this scenario are the following ones:

- Mobility handling - protocol must be able to maintain dynamically the network connected, adjusting itself to the frequent topology changes caused by mobility;
- Energy efficiency - nodes operate autonomously, and rely only on their own power source to communicate, so the protocol must minimise energy consumption;
- Low latency - real-time data has strict delay tolerances, so the protocol must deliver the data as soon as possible.

The MHRWSN is designed to have all the features described above. To address the mobility, it is fundamental to constantly update the routes information. This is typically performed by exchanging beacons among nodes. In MHRWSN, as beacons are not available, the sink periodically broadcasts its presence to the wireless medium by using the proposed protocol packet format. This information is then rebroadcast by the other nodes of the network. Energy efficiency is achieved by minimising the number of bits transmitted by the nodes, since this is the most energy hungry task. The overhead introduced by the protocol (i.e., the information that is transmitted just to operate the protocol, and is not actual data) is addressed by minimising the size of the packets that transport the routing information, and by limiting the amount of routing packets that are broadcast. The latter is achieved by making the nodes only to broadcast the information on a path if its cost has changed, or if a new path with a lower cost is found. The MHRWSN assigns a cost to every available path. The path cost is proportional to the probability of transmission errors, which is calculated based on the Received Signal Strength Indicator (RSSI), and on the number of hops of the path. The protocol chooses the path with lower cost, i.e., with low bit error rate (high RSSI) and less number of hops. This reduces both the retransmissions (thus, saving energy), and the end-to-end delay (latency). Moreover, by assigning high costs to links that have low RSSI, the use of links in which nodes are moving away from each other is restrained, anticipating an alternative path to links that will be broken.

A. Functional diagram

The flowchart for the routing protocol is presented in Fig. 1.

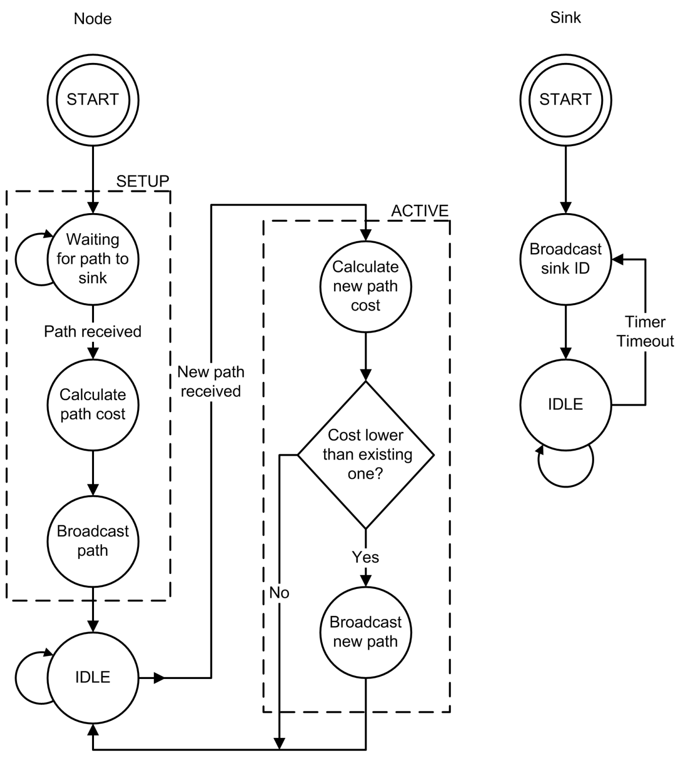

Fig. 1. Flowchart for MHRWSN.

For the sink, this protocol is very simple: it will periodically broadcast a packet with its sink ID to the medium. This serves two purposes: first, it allows the nodes to initiate their paths;

second, it periodically refreshes the available paths allowing for identifying new paths and paths that cease to exist. The period for these broadcasts is defined by the sink, and can be selected according to the mobility experienced by the network. In highly mobile networks the period should be low, so that path changes are rapidly identified. However, in networks with more static nodes, in which the topology changes very slowly, the period can be increased to save energy.

For the regular nodes, the protocol initiates with the SETUP state. The node initiates and starts scanning the medium for a packet with a path to the sink. Any packet received from the higher layers will be queued (to avoid the loss of that data packet) until it identifies a path to the sink, and any data packet received from a neighbour will be discarded. In principle it will not receive any packet addressed to it during this phase, since it has not broadcast a path yet, hence will not show on other nodes routing table. Once a packet is received, it extracts the path cost, calculates the cost of the path including it as an hop, and broadcasts this path. Since it has no other paths, the node will accept any path, even if its cost is high. After this step, the node enters into the IDLE state. In the IDLE state, the protocol limits itself to mark the next hop in any packet that arrives from the application layer, or from a neighbour in the route to the sink. The ACTIVE state initiates when a packet with routing information arrives from the lower layers. The protocol opens the packet, calculates the (new) path cost using the received path, and compares this cost with the existing one. If the next hop in the new path is the same than the current one, it refreshes the existing path cost with the new updated information (but only if the cost changed), and broadcasts the new path cost. Otherwise, it checks if the path cost is lower than the current one. If true, it updates the path cost and next hop, and advertises to the medium. If the next hop is not the same and the cost is higher, it resumes to the IDLE state without changing the routing information.

B. Packet format

The format for the packet used by the protocol to exchange routing information is shown in Fig. 2.

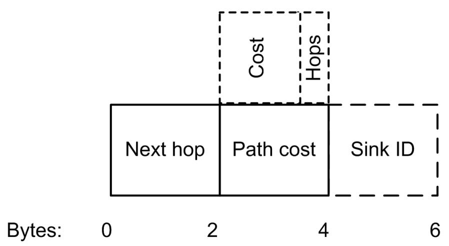

Fig. 2. The MHRWSN packet format.

To minimise the overhead introduced by the protocol, the packet contains only the least possible routing information: the path cost and the next hop. To allow the protocol to distinguish between sinks, it can use an optional field identifying the sink to which the path refers to. All the nodes use this format to broadcast their least-cost path to the sink, including the sink that fills the path cost field with zero.

C. Link cost and path cost

The MHRWSN combines the information on the number of hops and the probability of bit transmission errors to determine the best path for the packets. The MHRWSN is designed to be implemented in networks that use the IEEE 802.15.4 [8] standard, since this is the standard most used for low power and low data rate WSNs. Hence, the starting point to calculate the path cost is the Bit Error Rate (BER) defined by the standard, (1).

$$\mathrm{BER} = \frac{8}{15}\frac{1}{16}\sum_{k=2}^{16}(-1)^k\binom{16}{k}e^{\left(20\times\mathrm{SNIR}\left(\frac{1}{k}-1\right)\right)} \qquad (1)$$

Calculating the value of the BER is computationally heavy since it has combinations and summations, which are operations whose complexity is prohibited in the limited processors that are used in WSNs nodes. A simplification was needed, but this formula does not seem to allow any simplification. Thus, the values of the BER for 100 different values of the signal-to-noise interference ratio (SNIR) have been calculated. Then, the curve fitting tool of NCSS 2007 [9] was used to try to find a more simple formula to approximate this one. This proved to be unsuccessful, since the values of the BER suffer an huge variation with the SNIR value (for example, BER=1.49×10^{-43} for SNIR=10 dB, and BER=1.62×10^{-4} for SNIR=1 dB). Due to this fact, an approximation has been made, and a logarithm was applied to the obtained BER values to linearise these ones. The result cannot be called BER, but since the logarithm is applied to all values, the relative difference among them is maintained. Then, the software NCSS 2007 was able to find a function to address the modified results for the BER (which we designate as L_q), (2).

$$L_q = \begin{cases} 0 & \text{if } a \\ 299.566 - 4.341 \times \mathrm{SNIR} & \text{if } \bar{a} \end{cases} \qquad (2)$$

The condition a is valid for values of SNIR<69 dB, since for these values the modified BER is zero. The link quality is a cost function that varies between zero and around 299. $L_q = 0$ means the maximum quality, while $L_q = 299$ corresponds to a link with bad quality (the probability of the packet transmitted through the link to contain at least one error is very high).

Current radio transceivers (such as CC2420 and CC2520) usually only measure the value of the received signal, including the noise and interference from nearby nodes/networks, the RSSI. The relation between the RSSI and SNIR can be calculated according to (3), where N is the noise, I is the interference, and n is the number of interferers.

$$\mathrm{SNIR} = \frac{\mathrm{RSSI}}{N + \sum_{i=1}^{n} I_i} \qquad (3)$$

Two simplifications are assumed: there is no interference, and the noise is calculated by using (4), considering $k_B = 1.3803 \times 10^{-23}$ J/K, $T = 290$ K and $B_w = 2 \times 10^6$ Hz.

$$N = k_B \times T \times B_w \tag{4}$$

This allows to obtain (5), in which L_c is the link cost, and b stands for the condition $RSSI_{[mW]} > 5.524 \times 10^{-10}$.

$$L_c = \begin{cases} 1 & \text{if } b, \\ 300.566 - 5.422 \times 10^{11} \times \text{RSSI} & \text{if } \bar{b}. \end{cases} \tag{5}$$

For every link, the cost is an integer value between 1 and 300 (an approximation is performed after the cost calculation). A link with a unitary cost is the best link, while a link with a cost of 300 is the worst one, and should be avoided. The path cost is the sum of all link cost that compose the path; hence, for a path with m links/hops, (6) provides its cost, as follows:

$$P_c = \sum_{j=1}^{m} L_q(j) \tag{6}$$

D. Best path selection

From (6), one can see that the path cost already accounts for the RSSI and the number of hops. However, MHRWSN goes further on and explicitly uses the number of hops to calculate the best path. The procedure adopted by the routing protocol when it receives a new packet is the following:

```
Read packet
Extract number of hops
Extract path cost
Add one to the number of hops (current link hop count)
Read RSSI value from the radio
Calculate link cost according to (5)
if RSSI < Threshold then
    Increase number of hops by one
    Add 300 to the value of the link cost
end if
Compare number of hops with current "best path"
if number of hops is higher then
    Return to Idle
else
    Add link cost to the received path cost
    Compare path cost with current "best path"
    if new path cost is higher then
        Return to Idle
    else
        Replace "best path" with the new value
        Broadcast the new cost
        Return to Idle
    end if
end if
```

After receiving a routing packet, the protocol first checks the RSSI of the received packet. This is used to calculate the link cost according to (5), which is added to the received path cost. The protocol checks the number of hops of the path. Again, it checks the RSSI. If this is lower than a certain threshold, it increases the number of hops for the received path by one unit, and the value of the path cost by 300. This mechanism avoids the use of links in which the nodes are moving away form each other.

Next, the protocol begins the path comparison. First, it checks if the next hop in the path is the same as the current one (for simplicity this step is not shown in the algorithm presented above). If it is the same, the protocol updates the current path cost with the new value, and broadcasts it only if it has changed. If the path cost remained the same, no broadcast is performed, to save energy. If it is a new next hop, the new path number of hops is compared with the current path. If it proves to be higher, it discards the new path. If the number of hops is the same, the protocol compares the path cost of the new with the existing one. If the cost is lower, the next hop and cost is updated, and this information is broadcast. Any packets arrived after this event will follow the new path.

E. Sink broadcast timing selection

When the sink broadcasts a packet to the medium, nodes that listen the packet will calculate new paths and broadcast them, reaching the 2-hop away (from the sink) nodes that will calculate their own paths and broadcast them, and so on, until this information reaches all nodes in the network. Thus, it is the periodic sink announcement that dictates how often the routing information is refreshed on the nodes. If the vehicles are moving at top speed, the period of sink transmission should be lower, because the links between vehicles change more often. However, if there is a traffic jam and cars are almost stopped, there is no need to change the routing tables since the links will remain active for longer periods of time. Taken this into account, and since the sink is independent of the remaining nodes, one can dynamically change its broadcast period to best fit the current vehicle traffic conditions, without making any change in the vehicle's nodes.

The authors from [10] propose a method to determine the period of the sink messages according to the network mobility. This method can be applied to our case, although in the simulations performed here the period has been chosen based on the feedback from previous simulations.

IV. Simulations and Results

To evaluate the behaviour of MHRWSN, a simulation approach was followed, since it facilitates to study the performance of the protocol in different conditions. The MiXiM 2.1 framework [11], which already includes a model for IEEE 802.15.4 networks operating in nonbeacon-enabled mode, and the OMNeT++ 4.2 simulator [12], have been the selected tools to perform the simulation tests. The tests are organized as follows:

1) Flooding, and three versions of MHRWSN are implemented in the simulator: one uses only hop count to determinate the path cost (labelled "Hop count"), another uses only (5) to compare path costs (labelled "RSSI"), and the other uses the procedure described in Section III-D (labelled "MHRWSN"). This allows to compare the performance of the protocol with another,

and also show if the combined approach can achieve better performance or not;

2) The simulator loads a network with 50 nodes, places the sink statically in a predefined position and chooses random positions and moving direction for the remaining nodes;
3) The simulator selects four nodes to generate data to the sink (at a fix rate);
4) The simulator loads one of the protocols and starts the simulation, the sink generates routing information packets at a fix rate (except for the Flooding that does not require these packets) and nodes forward the data packets generated in the sources;
5) Once the predefined simulation time is reached the simulator stops, gathers the data obtained (packets delivered, end-to-end delay, etc.) and stores it for further analysis;
6) The simulator repeats the simulation for the remaining protocols, maintaining the same parameters so that direct comparison can be made;
7) The procedure is repeated for other network topologies, in order to allow the generalisation of the results;
8) The results are compared, and conclusions are extracted.

Table I presents the parameters considered in these tests.

TABLE I
SIMULATION PARAMETERS

Parameter name	Value
Number of topologies simulated	50
Simulation time	400 s
Packet inter-arrival time	0.1 s
Data packet size (at application layer)	944 bit
Protocol packet size (before MAC layer)	32 bit
Sink broadcast period	1 s
Channel model	Free-space path loss
Channel bit rate	250 kb/s
Operating frequency	2.4 GHz
Bandwidth	2 MHz
Modulation	OQPSK
Transmission power	0 dBm (1 mW)
Radio model	CC 2520 [13]
Transmission current consumption	25.8 mA
Receiving current consumption	18.5 mA
Node speed	14 m/s

According to the main requirements presented in Section III, we present the results showing that MHRWSN succeeds in reaching its goal. Figure 3 presents the total number of packets that arrived to the sink node. Flooding loses a lot of packets due to the high number of collisions experienced (since several nodes receive a packet at the same time, and will compete to gain access to the medium to transmit it). MHRWSN is the protocol that delivers more packets (between 204% and 270% more packets than Flooding). The “Hop count” fails to deliver the packets because it fails to timely identify broken links, while “RSSI” generates paths with a large number of hops, creating collisions and packet losses.

Figure 4 presents the average end-to-end delay experienced by the packets for each source. The end-to-end delay is the

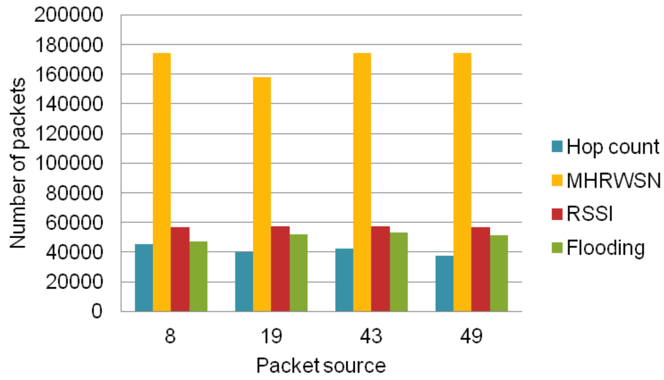

Fig. 3. Total number of packets delivered by the protocols.

time it takes for a packet that left the application layer of the source to arrive at the application layer of the sink. By using the hop count as primary decision, MHRWSN and “Hop count” deliver the packets faster than the “RSSI” and Flooding, with a maximum delay of 50 ms.

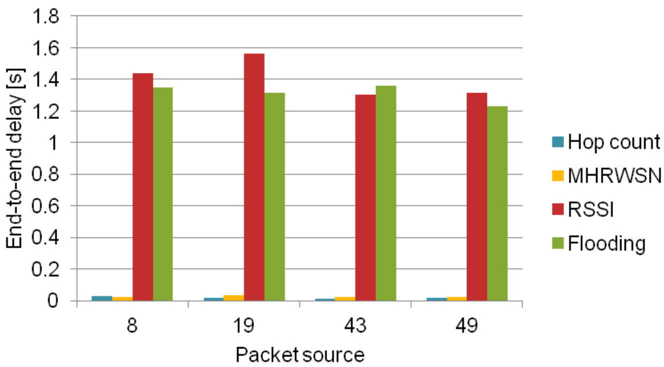

Fig. 4. Total average end-to-end delay experienced by the packets.

With the decrease of the number of hops and the use of links with higher probability delivery, MHRWSN design aims at saving energy by decreasing the number of transmissions. Figure 5 presents the total energy consumed by the nodes. The overhead from the protocol packets and its corresponding increase of energy consumption is compensated by the more efficient paths generated by it. As expected, MHRWSN saves more energy than the other protocols, since it reduces the number of transmissions by generating paths with less hops.

Frequently, protocol developers use the metric energy per bit to prove the energy efficiency of their protocols. Figure 6 presents the results for this metric, which is calculated as the ratio between the energy consumed and the bits delivered to the sink. Compared to Flooding, the energy per bit from the MHRWSN and the “RSSI” is less 71% and 12%, respectively. Compared with “Hop count”, which had a similar energy consumption behaviour according to Fig. 5, MHRWSN uses less 76% of energy to deliver packets, due to avoiding using paths that have low quality.

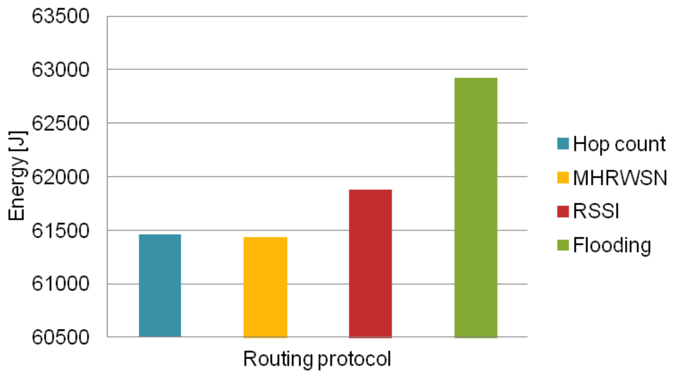

Fig. 5. Total energy consumed by the 50 nodes in all simulations.

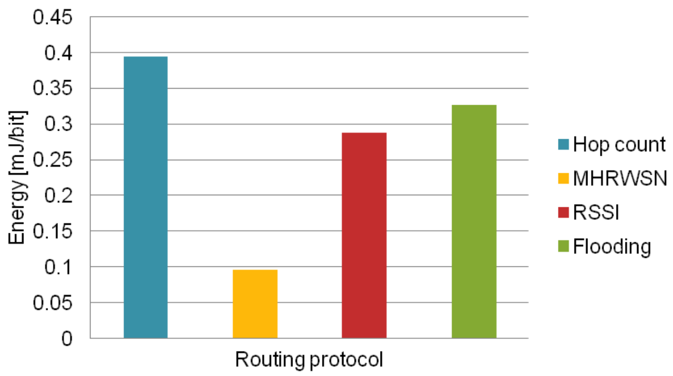

Fig. 6. Energy per bit for each protocol.

V. Conclusion

In this paper, a new routing algorithm is proposed for WSNs with mobile nodes. The reference scenario is a network where the WSN is deployed non-intrusively in vehicles, and sends data to a fixed infrastructure on the road. By using an approach that accounts for the number of hops and bit error probability of individual links, the MHRWSN facilitates to increase the number of packets delivered, when compared with the traditional Flooding approach. Simulation results have shown that it can deliver up to 271% more packets than Flooding. Besides, MHRWSN decreases the end-to-end delay of the packets whilst decreasing the energy per bit by 71%.

The need for energy efficient protocols is one of the major challenges in WSNs, since the nodes have limited power available. By computing the probability of transmission errors using the RSSI of the packets, MHRWSN can identify links in which the nodes are moving away from each other and find an alternative path. This avoids the use of paths that will cease to exist, maintaining the network connectivity and avoiding packet losses. Compared with regular routing approaches that only use the hop count or RSSI as the base for the routing, the combined feature of MHRWSN proved to outperforms them.

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