Cost-Benefit Aware Routing Protocol for Wireless Sensor Networks with Hybrid Energy Storage System

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Abstract

At the eve of a new decade, when energy concerns are at the top of the research priorities, this work presents a new cost-benefit function for wireless sensor networks (WSNs) powered by harvesting energy sources. The models rely on a Hybrid Energy Storage System (HESS) that combines a super-capacitor (SC) with a Rechargeable Battery (RB). While the SC has low energy storage capability but is capable of providing high level of energy throughput and frequent charge cycles, the RB has higher energy storage capability but limited charge cycles. Our proposal for the protocol associated with HESS assigns different weights to the residual energy in both energy storage systems whilst favouring routes with more SC energy and harvesting rates. The main innovation is the application of a new routing cost metric to prolong the network lifetime. An energy model framework has been developed in MATLAB with different application scenarios to test the proposed cost metric. The simulation results show that, by using the HESS flexible energy-aware cost-benefit function, significant extension of the network lifetime is achieved by means a balance between the energy consumption and the reliable delivery of data packets.

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Keywords: wireless sensor networks, routing protocol, hybrid energy storage system, supercapacitor, rechargeable battery.

1 Introduction

While miniaturization in Wireless Sensor Networks (WSNs) enables the introduction of the so called "Smart Dust" concept [1] into our quotidian, energy conservation issues are still one of the main concerns [2]. Usually, the power for these small sized nodes is supplied by ordinary non-rechargeable batteries, which limits the network lifetime. In these scenarios, energy plays a role of major importance. Longer network operation may be maintained by means of an optimal selection of type of power source. In order to operate self-sustainable WSNs in isolated places, the energy-aware routing protocol carefully routes data packets whilst extending the network lifetime [3].

In this work, one explores how environmental energy becomes an attractive power source for low power WSNs. However, nodes are still limited by the number of charge-discharge cycles of a Rechargeable Battery (RB) before its capacity falls below 80% of its initial rated capacity [4]. It is assumed that the network lifetime is the time period until the first node drains all its energy.

According to the radio model proposed in [5], wireless communications require much more energy consumption than sensing and computing tasks. Hence, it may be desirable to use short-range communication between nodes in opposition to long-range ones, resulting in transmission power savings. As multi-hop communications are needed, the energy awareness of the routing protocol is of key importance to prolong the network lifetime.

Another lifetime limitation is caused by the unbalanced load of the data transmission, which results in backbone formation, as shown in Figure 1. This characteristic of the WSN is more evident when several nodes want to route data to a Base Station (BS) or sink node through the same path. Some nodes may experience a total lack of energy when located in a backbone formation [6], while neighbours can still have higher levels of energy. It is therefore important to be aware of the routing queue along the data paths. The length of the queues may also cause delay and packet drops within the network. Energy-aware routing protocols play therefore an important role in selecting the next node, avoiding crowded paths and low residual energy.

To extend the lifetime in WSNs, we consider that a harvesting device powers each node in association with a Hybrid Energy Storage System (HESS). The HESS is composed by an RB and a super-capacitor (SC), as well as a power management device that controls all the operations in the energy

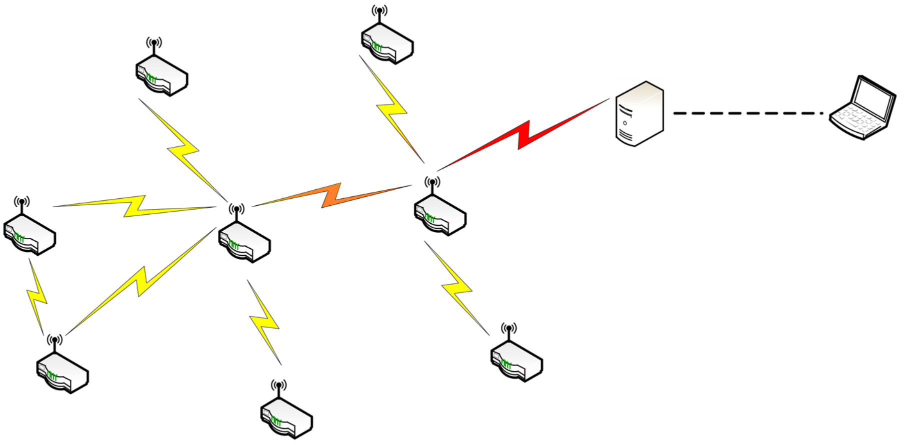

Figure 1 Diagram of a WSN when information goes towards the sink node

system. Innovative research has been carried out in the field of WSNs that considers energy harvesting from the environment to increase the network lifetime. The Energy-Opportunistic Weighted Minimum Energy (E-WME) routing protocol is presented in [7]. Its metric accounts for the nodes' RB residual energy, the harvesting rate as well as the energy requirement to route packets and optimally utilizes the available energy. The harvested energy is directly used for the battery daily recharge cycles, but it may quickly reduce the battery lifetime. In [8], several approaches to improve battery runtime in mobile applications with SC are addressed. Three different approaches enable to analyze the use of SCs to extend the mobile device runtime. An overall reduction in the internal losses is possible by connecting SCs in parallel, resulting in 4 to 12% extension of the run-time. Dougal et al. [8] also show that the use of a DC-DC converter seems to be a cost effective option, since it facilitates the use of reduced number of capacitors whilst maintaining a comparable performance. The performance of a battery/super-capacitor hybrid power source under pulsed load conditions is also analytically described in [9], where Merrett et al. show that (i) peak power can be greatly enhanced, (ii) internal losses can be considerably reduced, and (iii) discharge life of the battery is extended. However, Kailas and Ingram [10] measured a considerable energy leakage for the SC, showing that the leakage is directly proportional to the residual energy.

The goal of this work is to give contributions to the extension of network lifetime. The aim is to balance the energy consumption of the network without causing excessive delay. Since the routing protocol decisions are based on cost-benefit functions, a reliable and light metric has to be proposed. Palma et al. [7] developed a metric which treats RBs with infinite cycle life and 100% Depth of Discharge (DoD). Their metric is asymptotically optimal in terms of the competitive ratio and increases exponentially with the energy depletion, discouraging the use of nodes with low harvesting rate. The metric from Guilar et al. [11] already accounts for the lowest DoD of the RB as well as its cycle lifetime. However, both of them have complex computation requirements which influence the energy consumption.

The contribution of the paper relies on the knowledge of the element variations that contribute to the extension of the network life time in a HESS, knowing that the route paths are the same as in the Energy Aware Routing (EAR) protocol [6].

The remainder of this paper is organized as follows. Section 2 establishes the problem definition and addresses the energy models and cost function that were used to develop the HESS routing protocol. Section 3 presents the evaluation metrics and analyzes the simulations results. Finally, conclusions are presented in Section 4 along with suggestions for future work.

2 Problem Definition and HESS Model

Although the benefit from using harvesting sources in order to power WSNs has already been extremely studied [12, 13], the majority of the works assume an unlimited RB cycle lifetime which leads to inaccurate results. The gain arising from the change of a hybrid energy storage system must be precisely formulated in order to compare its advantages and disadvantages in the context of energy-aware routing protocols. This should lead to flat energy consumption for the network when using a context-aware routing protocol.

The HESS energy model is based on the research work from Guilar et al. [11], where the authors consider the battery cycle life as well as a hybrid energy harvesting system. In turn, their work is based on Palma et al.'s [7], who propose a cost metric that takes into account the nodes' RB residual energy, harvesting rate and energy requirement to route the packet.

2.1 Connection Scheme for Energy Storage System

The new nodes powered by a hybrid energy storage system require a specific management unit to control the different energy flows. Figure 2 shows a simplified scheme for the HESS.

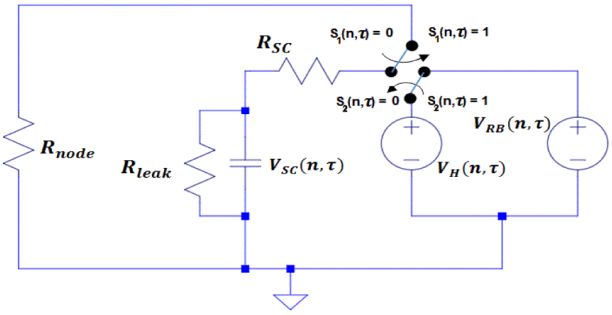

Figure 2 Connection scheme for the energy storage system

We assumed that the harvested energy $V_H(t)$ is directed to the SC ($S_2(n, \tau) = 0$) while the RB does not reach its designed DoD. Otherwise, the RB will be recharged until it gets full replenishment ($S_2(n, \tau) = 1$). This allows for a better control of the cycle life of the battery. As soon as a node is selected to relay a packet, it checks its residual energy and selects the appropriate energy storage to be used whilst routing the data. By default, the SC is the main power supplier for the node ($S_1(n, \tau) = 0$). This is due to the internal energy loss caused by a fast rate of current leakage which limits the time energy storage for the capacitor. Batteries also have an internal current leakage, but at a considerably slower rate. Merrett et al. [9] investigated the self-discharge rate of the super-capacitors applied in the context of WSN. They showed that the SC leakage is much higher than RB leakage, and highly depends on its residual energy.

2.2 Analytical Model

Palma et al. [7] considered that the energy costs for the transmission and the reception are nearly the same, as supported by Trakadas et al. [14]. However, the routing layer has a very important role on the control of the energy wasting; hence, it must not be neglected. In [15], an analysis of the energy consumption in the Mica2dot sensor platform showed that, in data transmission, the energy requirement per byte is nearly two times more than the energy requirement in data reception. Therefore, it becomes clear that the energy wasted in transmission and reception depends on the wireless platform; hence, it must be differentiated.

This work considers a discrete-time system where each node harvests energy. At the beginning of each time slot τ, node n receives the harvested energy, accumulated in the previous time slot. At the end of each time slot, the energy required to route the data packet is instantaneously removed from the energy storage system. The work presented by Palma et al. [7] considers an energy storage system composed by a RB which has been reformulated in this work, in order to use SC benefits presented in [8, 9, 10]. As so, this enables to extend the previous models to the context of HESS, one of the main contributions of this work.

The energy for the SC at node n in HESS model is presented and modelled by the following equations:

$$\begin{aligned}&\hat{E}_{\mathrm{load,SC}}(n, \tau, R(j))\\&\quad = l(j)E(n, R(j)) \cdot I(\hat{E}_{\mathrm{SC}}(n, \tau) - l(j)E(n, R(j)) > 0)\end{aligned} \tag{1}$$

$$\hat{E}_{\mathrm{SC}}(n, \tau) = \min((E_{\mathrm{SC}}(n, \tau) - \alpha(\tau - 1)) + [1 - S_2(n, \tau)]\gamma_n(\tau - 1), u_{\mathrm{SC}}) \tag{2}$$

$$E_{\mathrm{SC}}(n, \tau) = \beta(n, D, \tau)[\hat{E}_{\mathrm{SC}}(n, \tau) - \hat{E}_{\mathrm{load,SC}}(n, \tau, R(j))] \tag{3}$$

where $l(j)$ represents the length of the jth packet in bytes, $E(n, R(j))$ is the transmission and reception energy per byte consumed by the nth node at the jth packet, $I[\ ]$ is an indicator function which takes the values of one, if the route request is powered by the RB, and zero otherwise, $\alpha(\tau - 1)$ denotes the time-invariant fraction of energy leaked from the SC over a time slot, $\gamma_n(\tau - 1)$ denotes the harvested energy in the previous time slot, u_{SC} describes the maximum capacity of the SC, and the use of the min( ) function mathematically prevents the possibility of SC exceeding it, and $\beta(n, D, \tau)$ works as an indicator function for the event that the RB (on node) has not exceeded its finite cycle lifetime.

It is worthwhile to note that $\beta(n, D, \tau)$ is a non-increasing function of τ. For a fixed τ, it is a strictly decreasing function of, which represents the DoD on the RB. For example, if it is assumed to never use more than 50% of the RB energy within a single discharge cycle, then $D = 0.5$. It is assumed that the node cannot survive only powered by the SC. As a consequence, the node is considered dead (or out-of-service) as soon as the RB reaches the end of its cycle lifetime.

The energy model for the RB follows the previous philosophy and is expressed as follows:

$$\begin{aligned}&\hat{E}_{\mathrm{load,RB}}(n, \tau, R(j))\\&\quad = l(j)E(n, R(j)) \cdot \{1 - I[\hat{E}_{\mathrm{SC}}(n, \tau) - l(j)E(n, R(j)) > 0]\}\\&\qquad \cdot I[\hat{E}_{\mathrm{RB}}(n, \tau) - l(j)E(n, R(j)) > (1 - D)u_{\mathrm{RB}}]\end{aligned} \tag{4}$$

Table 1 Parameters for the HESS cost function

Symbol	Description
E_{RB}	RB residual energy
hc	*Hopcount*
E_{SC}	SC residual energy
γ	Harvested energy in the last time slot
L_c	Cycle life for the battery
q_{oc}	Length for the transmission queue occupation

$$\hat{E}_{\mathrm{RB}}(n,\tau) = \min(E_{\mathrm{RB}}(n,\tau) + S_2(n,\tau)\gamma_n(n,\tau-1), u_{\mathrm{RB}}) \tag{5}$$

$$E_{\mathrm{RB}}(n,\tau) = \beta(n,D,\tau)[\hat{E}_{\mathrm{RB}}(n,\tau) - \hat{E}_{\mathrm{load,RB}}(n,\tau,R(j))] \tag{6}$$

where u_{RB} is the maximum capacity of the RB, and the use of the min( ) function prevents the RB from exceeding its maximum capacity, while D represents the depth of discharge for the RB.

The RB will only supply the energy for the communication if its residual energy is above the DoD.

The HESS energy model is structured into two parts:

- The availability to supply the transmission, represented by equations (1) and (4);
- The residual energy of each energy storage system at the beginning of a time slot τ, represented by equations (2) and (5), and at the end of time slot, as shown in equations (3) and (6).

2.3 Cost-Benefit Function

We propose a light cost-benefit function that evaluates the cost and revenue to route a packet through a specific node. The metric is used whenever a node wants to route a data packet to its neighbours.

The source node selects the node with the lowest cost, whose values were sent back to it. To ensure an extended lifetime for the network, the cost function must reflect the node ability to forward the packet through nodes with high SC residual energy and high harvesting energy rates. Table 1 presents the cost-benefit function parameters.

This information is gathered in the cost function, and translates the individual capability to route data packets:

- h_c (*hopcount*) represents the (minimum) path length between the queried node and the hub/sink node (this information is set up in the routing and represents how far is the next node from the hub/sink node);

- E_{SC} and E_{RB} represent the SC and RB residual energies in Joules;
- γ is the harvested energy the node scavenged in the last time slot;
- L_c represents the RB cycle lifetime;
- q_{oc} is the length for the node's transmission queue occupation.

The cost-benefit function reflects the cost/revenue to/from route data and is defined as follows:

$$\begin{aligned}\mathrm{Cost}(n,\tau) = {} & (hc(n,\tau) * w_{hc} + q_{\mathrm{oc}}(n,\tau) * w_{q_{\mathrm{oc}}}) - E_{\mathrm{SC}}(n,\tau) \\ & * w_{\mathrm{SC}} + E_{\mathrm{RB}}(n,\tau) * w_{\mathrm{RB}} + \gamma(n,\tau) * w_{\gamma} + L_c(n,\tau) * w_{L_c})\end{aligned} \tag{7}$$

This polynomial equation incorporates two kinds of information and reflects the formulation of the cost-benefit function (i.e., the complementary of a utility function) based in two separated terms:

- Benefit or positive parameters which stands for parameters that support the extension of the network (residual energy, harvested energy and RB cycle life).
- Undesirable or negative parameters (*hopcount* and transmission queue).

The first term carries the routing cost while the second gives the corresponding benefit. Each parameter may vary from 0 to 100, e.g., $E_{\mathrm{RB}} = 100$ means the RB is fully charged.

Each parameter has an associated weight. This allows for a priority scheme in the cost function calculation. The weights constraints are set as follows:

$$w_{hc} + w_{q_{\mathrm{oc}}} = 1.0 \tag{8}$$

$$w_{\mathrm{SC}} + w_{\mathrm{RB}} + w_{\gamma} + w_{L_c} = 1.0 \tag{9}$$

Several simulations have been considered as a way to find the optimum values for the weights in our scenario, as shown in Table 2. The SC residual energy weight gets the maximum weight since this energy is volatile and suffers from leakage problems. The RB characteristics (RB residual energy and cycle life) are assigned with an importance of 20% while the harvesting energy has a weight of 15%. The two "negative" (or cost) parameters share a responsibility of 50% of in the cost function result. These weights can easily be adapted to different application scenarios. WSN applications that have lower harvesting energy rates can assign higher weight to w_{γ}, in order to customize the data flow. This formulation increases the flexibility of the HESS cost function.

Table 2 Weight distribution for the cost function

Positive Parameters	Negative Parameters
$w_{\mathrm{SC}} = 0.45$	$w_{hc} = 0.5$
$w_{\mathrm{RB}} = 0.2$	$w_{q_{\mathrm{oc}}} = 0.5$
$w_{\gamma} = 0.15$	–
$w_{L_c} = 0.2$	–

Whenever a node wants to route a data packet, it sends a Cost Function Request (CFR) to its neighbours. The neighbours, in turn, will retrieve a Cost Function Packet (CFP) with the cost associated with the packet transmission.

2.4 EAR Description

In order to route the packets through the network, it is essential to use a routing protocol that is energy-aware, and ZigBee compliant. The Energy Aware Routing (EAR) protocol presented in [15] proposes a network where nodes generate messages containing information that is of interest to the network. These messages are forwarded to the hubs in the network through multi-hop routing. A hub (or sink node) is a special node equipped with an additional communication technology to route the sensing packets to the Base Station (BS). The sensing nodes will send all messages to the hub for processing before further disseminating them to the network users located at the base station.

In all sensor network applications, reliable and fast delivery of messages can be a major requirement. Based on this, the EAR protocol present an efficient and reliable routing protocol that routes packets to the sink node reliably and quickly using lightweight mechanisms that require little maintenance and control messages to handle a rapidly changing of topology and route maintenance.

2.4.1 Setup Phase

The setup phase of the EAR protocol handles the routing table replenishment of each node. It is filled with at least a route to the sink node in order to route the sensing packets. This is carried on with the broadcast of control packets that carries route information concerning the sink node.

The setup phase starts with a hub broadcast of an Advertisement (ADV) packet indicating that it wants to receive Report (RPT) packets generated by nodes. When neighbouring nodes around the hub receive this ADV packet, they will store this route in their routing table.

The nodes will then wait a random time before starting the initialization process. As a consequence, a portion of nodes will receive route information before they have begun their initialization process. This enables fast propagation of route information and reduces the amount of control packets generated in the setup phase, reducing the setup phase time as well as the control packets energy consumption. Hence, the nodes randomly start their initialization process by broadcasting a Route Request (RREQ) packet asking for a route to any hub. If a hub receives a RREQ packet, it will broadcast a Route Reply (RREP) packet. Similarly, when a node receives a RREQ packet, it will broadcast a RREP packet if it has a route to a hub. Otherwise, it will ignore the RREQ packet. Nodes do not need to propagate RREQ packet. This would delay the setup phase and the energy consumption. The route information is taken into account by the random waiting time.

Each node will store more than one route to the hub. The route in the routing table is indexed by the next node's ID (the node's neighbour) and by the path length or hop count, through the relay(s), until the packet reaches the hub. This information is available in each routing table since the control packets broadcast is started by the hub and is extended to the external zones of the network, always carrying the path length.

2.4.2 Route Management

The main EAR metric used by Keong et al. [15] is the *RouteScore*:

$$RouteScore = P_E \cdot W_E + P_L \cdot W_L \tag{10}$$

where P_E is the energy level of the next hope node, W_E is the assigned weight for P_E, P_L is the link quality to the next hope node, and W_L is the assigned weight for P_L.

The *RouteScore* takes values from 0 to 100. Higher values indicate a better route.

The packets are usually routed through nodes with higher *RouteScore*. All the routes stored in the routing table must be refreshed in order to choose the higher *RouteScore*. In order to accomplish this task, a feedback packet is transmitted from the neighbours with a packet length of one byte each time and for every neighbour.

2.4.3 Data Dissemination

After the EAR initialization phase, each node will have at least one route to the hub. At this time, the nodes will start sensing the environment and generating RTP packets. When a RTP packet is generated at the source, it is set with two fields in its header by the EAR: *ExPathLen* and *NumHopTraversed*. As explained by Keong et al. [15], the first field defines the expected number of hops that the packet needs to traverse before it reaches the hub. This is possible since each node routing table stores the next node's ID and the respective path length or hop count until the hub. The packet is then queued into the output buffer of the node before being forwarded to the next node in the route. As soon as the packet is forwarded to the next node, the second field of the header (*NumHopTraversed*), which has been initialized to 0, is increased by one. This enables to provide historical information about the packet which can be used to control the delay. With this mechanism, the packet is constantly analysed in order to check if the *ExpPathLen* has been overcome, i.e., if the *NumHopTraversed* is larger than the *ExpPathLen*. If this condition is true, the packet will be routed through the shortest path by selecting the nodes with lower *hopcount* to the hub. Otherwise, the packet is routed through the route with higher *RouteScore*.

3 Simulation Results

3.1 Evaluation Metrics

It is expected that the HESS cost function enables WSNs to extend their lifetime without compromising data delivery to the sink node. In the context of MATLAB simulations for HESS and EAR, the following metrics have been compared:

- *Total Packets Received* is the total number of data packets successfully routed to the sink node;
- *Packet Latency in Hopcount* is the average time and *hopcount* a packet takes to be routed to the sink node;
- *Network Residual Energy*, where the sum of every nodes' residual energy is presented;
- *The Normalized Residual Energy* of the nodes are represented and shown; its distribution should be as regular as possible along the network;
- *Differential Energy Distribution* represents the difference between the HESS and the Energy Aware Routing Protocol (EAR) protocols; this shows the ability of the nodes with higher energy levels or harvesting rates (in the network) to provide routing capability to their neighbours, resulting in flat or balanced energy consumption.

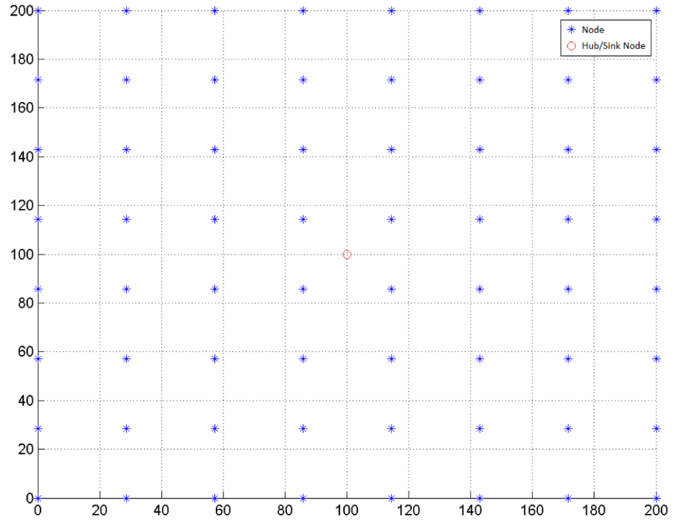

Figure 3 Grid deployment with 64 nodes

3.2 Analysis

The results obtained with the HESS cost function are compared with the EAR protocol developed by Basagni et al. [5]. Both routing protocols share the routing path establishment described in the EAR. The transmission range is fixed and includes an omnidirectional antenna with a coverage range of 56 m for each node. This value for the range is based on the work in [15], which grants a reasonably fair analysis. Since the energy storage system from the original EAR does not take into account a dual energy storage system (which is the case of HESS), a SC with the same capacity has been added to EAR energy storage system. A full use of the SC residual energy is applied in EAR simulations. The RB recharging only occurs when the RB is fully discharged. This change relies on a fair comparison between the two routing protocols, achieved by adding HESS to the EAR simulation.

The simulation scenario considers 100% source nodes (all the nodes generating traffic). Each node is generating data packets that need to be routed through the network towards the sink node. The assumptions for the simulation parameters are presented in Table 3. In order to analyze and compare the advantages and disadvantages of the HESS protocol, a grid deployment scenario was chosen in order to interconnect the different network sizes, as shown in Figure 3. A field of nodes with 200 × 200 m^2 has been defined,

Table 3 Grid deployment setup for simulation A

Parameters	Values
Time Slot	100 ms
Source Nodes	100%
Packet Generation	1 packet/s
Simulation Duration	3600 s
Harvested Energy	1 mJ/time slot
Harvesting Rate	50%

Table 4 Simulation results

Parameters		**36 Nodes**		**64 Nodes**		**100 Nodes**	
		EAR	***HESS***	***EAR***	***HESS***	***EAR***	***HESS***
Total Packets Received at the Sink Node		$1.01 \cdot 10^5$	$1.13 \cdot 10^5$	$2.3 \cdot 10^5$	$2.26 \cdot 10^5$	$3.50 \cdot 10^5$	$3.60 \cdot 10^5$
Packet Latency	Delay [*hopcount*]	3.65	3.02	3.32	2.79	3.59	2.65
	Delay [s]	1.58	1.50	0.42	0.74	0.77	0.42
Network Residual Energy [J]		$2.55 \cdot 10^3$	$2.57 \cdot 10^3$	$4.57 \cdot 10^3$	$4.78 \cdot 10^3$	$6.74 \cdot 10^3$	$7.41 \cdot 10^3$
Differential Residual Energy, HESS-EAR [J]		$2.00 \cdot 10^1$		$2.1 \cdot 10^2$		$6.70 \cdot 10^2$	
Residual Energy per Node [J]		70.83	71.39	71.40	74.69	67.40	74.10

where a hub/sink node is placed at the centre of the field, at (100, 100) m, with three different network sizes: 36, 64 and 100 nodes. Since the variation of the SC voltage cannot be measured during the simulation, an invariant leakage is assumed. It represents an energy leakage per time slot of 0.1 mJ/τ. Low-capacity RB storage is considered to allow for quicker results during the simulation. An RB with a maximum energy of 75 J has been considered.

It relies on a small battery size. The RB cycle lifetime, L_c, starts with a value of 1150 s and decreases 0.5 s after each discharge. This scenario simulates a battery with a DoD of 50% [4]. The energy spent in transmitting 1 byte is set to 59.2 μJ/byte while the energy spent in receiving a bit is set to 28.6 μJ/byte, based on the study of the Mica2dot platform from Basagni et al. [5].

The grid deployment scenario represents a careful and controlled scenario where nodes are placed individually. The data rate of 1 packet per second is only considered for simulation purposes. It will enable to test the sustainability of the network powered by a harvesting source of 1 mJ/τ, which corresponds to an outdoor photovoltaic cell. Simulation results are as presented in Table 4.

The HESS cost-benefit functions allows for routing more successful data packets to the sink node. Even in a high density deployment, it overcomes the EAR protocol by delivering up to 10,000 more packets. The packet latency is also granted when compared with the EAR protocol. As shown in Table 4, the packet delay in *hopcounts* results in a reduction of the number of hops. However, it is a worth noting that this reduction does not literally mean that the packet is received sooner by the sink node. This is also why the energy consumption per packet decreases and is even reduced in networks with higher density of nodes (e.g., 100 nodes): with HESS the number of hops to reach the sink node is lower in denser node topologies. In turn, routing data packets through high energy node paths results in higher latency. It is worthwhile to note that small network sizes are suffering of low neighbour density, which results in a delay more than 1 s. This can cause unreliable data delivery, depending on the WSN monitoring application. The low number of routes to the sink node does not facilitate the backbone formation, since data packets are routed through nodes that have large transmission queues. From the results one also concludes that the reduction of the latency is only possible with HESS protocol compared with the EAR protocol) when a larger node density is considered.

Energy consumption is one of the most interesting parameters for the extension of the network lifetime. The spatial variation of the differential energy between EAR protocol and HESS (based on the initial energy percentage) was gathered from 60 minutes network simulations. An example with 64 nodes is presented in Figure 4.

It is shown that, with HESS, the majority of the network nodes finish the 60 minutes simulation with higher levels of energy. Only some nodes in the EAR protocol end up with a higher residual energy (dark zone near the centre of the topology). However, a higher residual energy level is achieved with energy-awareness at the network level, i.e., with HESS. By analyzing the residual energy per node, from Table 4, one concludes that this residual energy level increases for larger network sizes.

In a 50% harvesting scenario (i.e., only 50 % of nodes are harvesting energy at each time slot), the transmission load of HESS proves to be more balanced than the one from the EAR protocol which enables careful consumption abilities even in high density network, as presented in Figure 5 (where a case with 100 nodes is addressed).

The highest energy routes efficiency is exploited based on the use of cost-benefit functions, causing a flat and balanced energy distribution, without compromising delay in crowded networks.

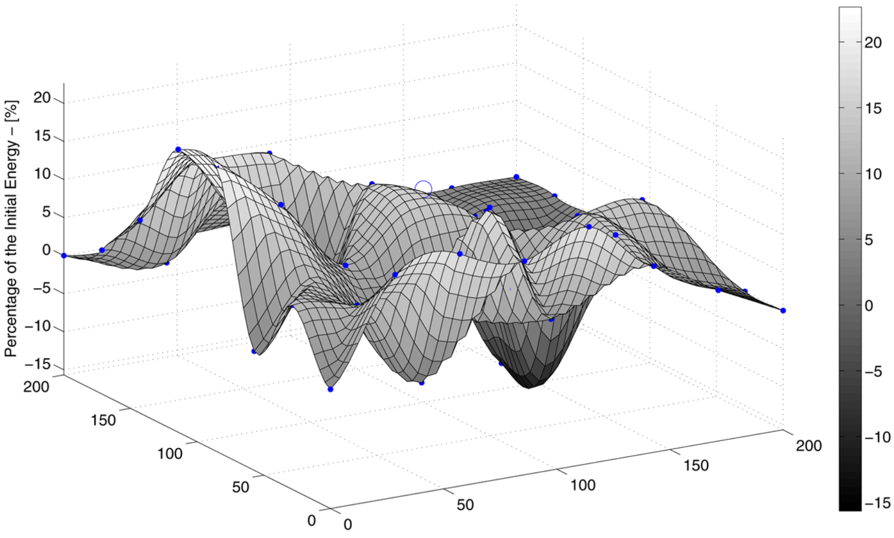

Figure 4 Variation of the differential residual energy with 64 nodes

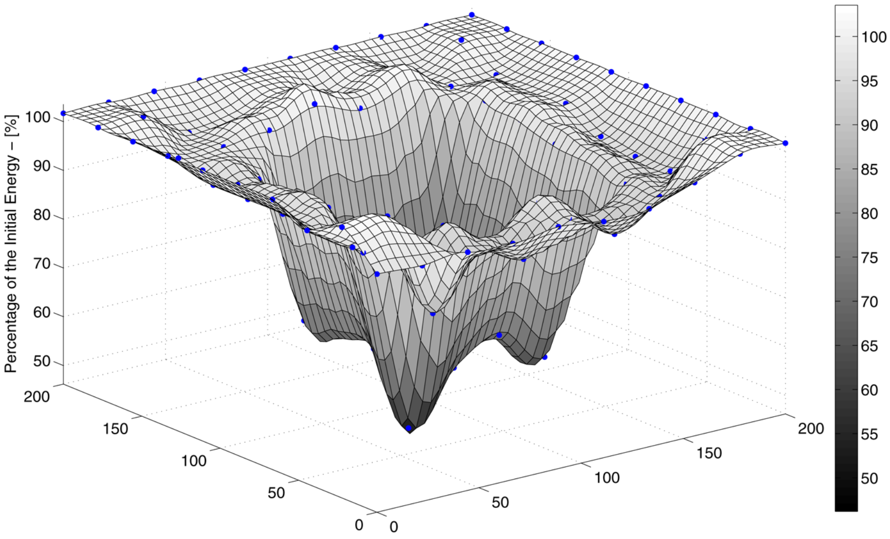

Figure 5 HESS residual energy with 100 nodes

4 Conclusions and Future Work

In this work, we have proposed a light and flexible routing metric that can be adapted to different requirement scenarios. The HESS protocol bases its decisions in a context aware on WSNs using the energy storage duality of an RB and a SC to extend the network lifetime. The SC suits the primary buffer of the storage system by preventing the quick exhaustion of the RB cycle lifetime. By using a cost-benefit aware routing protocol at the network level, HESS protocol may provide an average increase of 10% in the network residual energy without compromising the data packet delivery.

Future research directions include to study the cost function weights that adapt to the topology of the application scenario whilst extending the network lifetime as well. Longer term simulation will enable to analyze the cycle lifetime of rechargeable batteries in detail.

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