# Energy Efficient Reliable Cooperative Multipath Routing in Wireless Sensor Networks

Gergely Treplan, Long Tran-Thanh and Janos Levendovszky

*Abstract*—In this paper, a reliable cooperative multipath routing algorithm is proposed for data forwarding in wireless sensor networks (WSNs). In this algorithm, data packets are forwarded towards the base station ($BS$) through a number of paths, using a set of relay nodes. In addition, the Rayleigh fading model is used to calculate the evaluation metric of links. Here, the quality of reliability is guaranteed by selecting optimal relay set with which the probability of correct packet reception at the $BS$ will exceed a predefined threshold. Therefore, the proposed scheme ensures reliable packet transmission to the $BS$. Furthermore, in the proposed algorithm, energy efficiency is achieved by energy balancing (i.e. minimizing the energy consumption of the bottleneck node of the routing path) at the same time. This work also demonstrates that the proposed algorithm outperforms existing algorithms in extending longevity of the network, with respect to the quality of reliability. Given this, the obtained results make possible reliable path selection with minimum energy consumption in real time.

*Index Terms*—wireless sensor networks, reliability, cooperative routing, Rayleigh fading model, energy balancing

## I. INTRODUCTION

Due to the recent advances in electronics and wireless communication, the development of low-cost, low-energy, multifunctional sensors have received increasing attention [4]. These sensors are compact in size and besides sensing they also have some limited signal processing and communication capabilities. However, these limitations in size and energy make the wireless sensor networks (WSNs) different from other wireless and ad-hoc networks [2]. As a result, new data packet transmission methods must be developed with special focus on energy effectiveness in order to increase the lifetime of the network which is crucial in case applications, where recharging of the nodes is out of reach (e.g. military field observations, living habitat monitoring etc., for more details see [14]).

Although a number of methods has been developed for energy aware data packet transmission in WSNs, such as destination-sequenced distance-vector (DSDV) routing [12], dynamic source routing (DSR) [10], and ad hoc on-demand distance vector (AODV) routing [13], much of the research works is based on idealized assumptions about the wireless channel characteristics. That is wireless communication can be perfect in term of packet loss within a circular radio range. However, several recent studies have convinced researchers

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that there is a need to replace this idealistic channel model with a more realistic one [16].

Against this background, using the Rayleigh fading model [6] for wireless communication, this paper addresses reliable packet transmission in WSN when packets are to be received on the base station ($BS$) with a given reliability in terms of keeping the transmission error probability under a given threshold. In realistic communication channel models, the success of every individual packet transmission depends on the distance and the power of transmission, the probability of correct reception will diminish exponentially with respect to the number hops, in the case of multi-hop packet transfers. In this paper, a cooperative multipath approach is proposed for data packet routing which achieves optimal energy balancing (i.e. it minimizes the energy consumption of the bottleneck node of the network), with respect to the constraint of guaranteeing reliable packet transfer to the $BS$. In particular, in order to maximize the probability of successful delivery (i.e. reliability), a multipath routing technique is used. That is, each sensor node multicasts data to a set of relay nodes, which then independently forward each copy of the packet to the $BS$. The advantage of multipath routing is that, the reliability of the network does not depend on single node failures, which makes the network more robust. Given this, the main concern is to derive the appropriate transmission energies and the appropriate number for relay nodes needed to achieve a given reliability and to maximize the lifespan at the same time. To achieve this, first the energy output vector is optimized, if the set of cooperative nodes is given in order to keep the optimal energy balancing subject to the required reliability parameter. Second, an algorithm is devised which chooses the optimal cooperation set in polynomial time with respect to the bottleneck node. Finally the achieved lifespan of the proposed algorithm is compared to the longevity of traditional protocols by extensive simulations.

The remainder of the paper is organized as follows. First, related work is discussed in section II. Following this, the proposed model is introduced in section III. Then section IV contains the analysis of the case of fixed relay set with fixed source transmission energy. In addition, the analysis of the case of fixed relay set with arbitrary source transmission energy is described in section V. Following this, the optimal set of relay nodes is studied in section VI. Then section VII demonstrates that the proposed method is more efficient in terms of extending the life span of the network, compared to other, existing routing algorithms. Finally, the last section concludes.

## II. RELATED WORK

To date, cooperative routing techniques in WSNs can be classified into two groups, namely: (i) flat routing; and (ii) hierarchical routing. In the former, each node can send information to any other nodes within its communication range. On the other hand, hierarchical routing forms a hierarchical structure, so that each node can send data to those who are in a higher position in the hierarchy. Given this, related work can be discussed as follows.

From the side of reliable flat routing in WSNs, many research works have been published recently, such as directed diffusion (DD) [9], rumor routing [3], and SPIN [8]. In these approaches, one must choose routing paths such that the occurrences of packet loss on those paths are minimized. In these methods the possible forwarding nodes are carefully evaluated and the node of a higher probability of delivery is then selected as a forwarding node. However, the applied evaluation metrics vary in different approaches. For instance, in GeRaF [17] the geographic distance and a loss-aware metric in ETX [5] was used. However, these methods use a simplified wireless communication model, which, in many cases, is not sufficient to model the probability of data loss of the network. More recently, Zamalloa *et al.* proposed a position-based routing method using metrics similar to ETX [16]. Furthermore, in [15], the authors have proposed a flat routing algorithm, called BERA, that aims to maintain energy balancing, while the quality of reliability is satisfied. Their work can be seen as the closest to this work from the topic of reliable cooperative routing, since they also used a generic lossy link model instead of idealized simplified channel models. The aforementioned algorithms, however, do not exploit the advantage of multipath routing, and thus, may fail in environments with highly lossy radio links, or node failures.

On the other hand, a number of proposed methods in the topic of hierarchical cooperative routing in WSNs has also been proposed, such as the low energy adaptive clustering hierarchy (LEACH), proposed by [7], and power efficient gathering in sensor information systems (PEGASIS), proposed by [11]. In general, these methods make good attempts to try to balance the energy consumption by electing the clusterheads ($CH$s), each of which is responsible for relaying the data from a subset of nodes back to the $BS$ in an intelligent way. These methods, however, do not take data loss into account, and thus, are not suitable for reliable routing.

## III. THE MODEL

In this model, a WSN of $N$ nodes with a single $BS$ is considered. To forward data towards the $BS$, each node uses a set of relay nodes for relaying data. Here, the focus is on the case when a single node wants to deliver its packets. Hereafter, for the sake of simplicity, that node is referred to as the source node, and is denoted it with $S$. Given this, in this model, the source node broadcasts its packets to several relay nodes (i.e. the source has to send that packet *once* to multiple relay nodes at the same time), which then forward the copies of the packet *directly* to the $BS$. This model can be regarded as an extension of the hierarchical cooperative routing protocols. In particular,

the relay nodes can be seen as nodes with higher positions in the hierarchy, and thus, the others have to forward data through them. On the other hand, in the proposed approach, the set of relay nodes are not fixed, that is, each transmitting node can use a different optimal set of relay nodes, in order to forward data to the $BS$. The main idea of this protocol is that, instead of using unicast transmission, where data sending needs large transmission power in order reach the reliability quality of service (QoS), it is more efficient for the node to multiast data with smaller power consumption, while the reliability QoS is still maintained, since there is a higher chance that at least one copy of the packet will arrive to the $BS$.

According to the Rayleigh fading model, the energy needed for transmitting the packet to distance $d$ with the probability of correct reception $P_r$ is given as

$$P^{(r)} = \exp\left\{\frac{-d^\alpha \Theta \sigma_Z^2}{g}\right\} \qquad (1)$$

where $\Theta$ is the modulation constant, $\sigma_Z^2$ denotes the energy of noise, and $\alpha$ is the propagation coefficient (its value is typically between $2$ and $4$). One must note that equation 1 connects the reliability of packet transfer $P_r$ over distance $d$ with the required energy $g$. For the sake of notational simplicity this relationship will be denoted by $P_r = \Psi(g)$. Furthermore, when need there is a transmission by a single hop packet transfer between two nodes $i$ and $j$ in the chain, then the corresponding reliability is $P_{ij}^{(r)} = \Psi(G_{i,j})$, where $G_{i,j}$ denotes the transmission energy on node $i$.

In this model, the source node transmits the data packet with certain $G_s$ energy. According to equation 1, if the relay node $R_i$ is in the receive mode, it can receive the packet successfully with the following probability:

$$P_{S,R_i} = \exp\left\{\frac{-d_{S,R_i}^\alpha \Theta \sigma_Z^2}{G_S}\right\} \qquad (2)$$

where $d_{S,R_i}$ is the distance between the source node $S$ and the relay node $R_i$. Each relay node then forwards the received packet towards the $BS$ with $G_{R_i}$ energy. The probability that the transmission of relay node $R_i$ is successful can be calculated as the following:

$$P_{R_i,BS} = \exp\left\{\frac{-d_{R_i,BS}^\alpha \Theta \sigma_Z^2}{G_{R_i}}\right\} \qquad (3)$$

where $d_{R_i,BS}$ is the distance between the relay node $R_i$ and the $BS$. In the model $BS$ can receive messages from all of the sender nodes with a certain probability. Hence, the probability that the packet arrives successfully to the $BS$ is:

$$P_{\text{success}} = 1 - (1 - P_{S,BS}) \prod_{i=1}^{K} (1 - P_{S,R_i} P_{R_i,BS}) \qquad (4)$$

where $K$ is the number of relay nodes used in this data delivery.

First, suppose that the set of relay nodes is given a priori for source node $S$. This set is denoted with $\mathbf{R} = \{R_1, R_2, \dots, R_K\}$ The energy required by a packet transfer is described by the set of the transmission energies with $\Im_{\mathbf{R}} = \{G_S, G_{R_1}, G_{R_2}, ..., G_{R_K}\}$. In addition, let denote the

energy level of each node $v$ (both relay and source nodes) before the transfer with $c_v$. Given this, the objective is to find the energies $\Im_{\mathbf{R}}^{opt} = \{G_S^{opt}, G_{R_1}^{opt}, G_{R_2}^{opt}, \ldots, G_{R_K}^{opt}\}$, that achieve optimal energy balancing; that is, it *maximizes the residual energy of the bottleneck sensor node in the transfer of the packet toward the $BS$*. The formulation of the problem can be described as follows:

$$\Im_{\mathbf{R}}^{\mathrm{opt}} : \max_{\Im_{\mathbf{R}}} \left\{ \min_{v \in \mathbf{R} \cup \{S\}} (c_v - G_v) \right\} \qquad (5)$$

That is, it is necessary to determine the optimal energy consumption values that maximizes the residual energy level of the bottleneck node (i.e. the node that has the lowest energy level after data transmission). However, it also has to be guaranteed that the packets arrive at the $BS$ with a given reliability $(1 - \varepsilon)$; that is:

$$P_{\mathrm{success}} \geq (1 - \varepsilon) \qquad (6)$$

where $P_{\mathrm{success}}$ is defined in equation 4.

Now, since the set of relay nodes is typically not given for source node $S$, the optimal set of relay nodes has to be determined as well. Given this, the second objective is to determine the optimal set of relay nodes as well. That is, the goal can be formulated as follows:

$$\mathbf{R}^{\mathrm{opt}} : \max_{\Im_{\mathbf{R}}^{\mathrm{opt}}} \left\{ \min_{v \in \mathbf{R} \cup \{S\}} (c_v - G_v^{\mathrm{opt}}) \right\} \qquad (7)$$

In so doing, the case of fixed relay set will be studied, then an algorithm that determines the optimal relay set will be proposed in the subsequent sections. In particular, the analysis of the case of fixed relay set with fixed source transmission energy will be described. This will be followed by the analysis of the case of fixed relay set with arbitrary source transmission energy. Finally, the optimal set of relay nodes will be determined.

## IV. ROUTING WITH FIXED RELAY SET AND GIVEN SOURCE TRANSMISSION ENERGY

In this section, it is assumed that both R and $G_S$ are already given. Thus, the goal is to find the optimal energies $\Im_{\mathbf{R}}^{opt} = \{G_S, G_{R_1}^{opt}, G_{R_2}^{opt}, ..., G_{R_K}^{opt}\}$ which maximize the residual energy of the bottleneck relay sensor node subject to fulfilling the reliability criterion. Given this, one has the following:

**Theorem 1:** *Assuming that $G_S$ is already given, under the reliability parameter $(1 - \varepsilon)$, the value of the residual energy level of the bottleneck relay node reaches the maximum when all the residual energy levels are the same.*

**Proof:** First, the solution of equation 5 under the constraint 6 must fulfill

$$(1 - P_{S,BS}(G_S)) \prod_{i=1}^{K} (1 - P_{S,Ri}(G_S) P_{R_i,BS}(G_{R_i})) = \varepsilon \qquad (8)$$

This can be proven by indirection as follows. Assume that equation 8 does not hold. Due to constraint 6, the next expression holds

$$(1 - P_{S,BS}) \prod_{i=1}^{K} (1 - P_{S,R_i} P_{R_i,BS}(G_{R_i})) < \varepsilon \qquad (9)$$

In this case there is a $\hat{\mathbf{G}}$ for which $\hat{G}_{R_i} < G_{R_i}$, $R_i = \arg\min_{R_j}(c_{R_j} - G_{R_j})$, and equation 8 is satisfied. This will yield a better solution for equation 5, which contradicts the initial assumption. Thus, equation 8 does hold.

Theorem 1 states that if $\mathbf{G}$ is a solution of equation 5, then $c_{R_i}(k + 1) = A$, for $\forall i \in [1, 2, ..., K]$. Assume that this does not hold. In this case, there is a set of $A_{R_i}$ such that:

$$A < A_{R_i}, \forall i. \qquad (10)$$

and $c_{R_i}(k + 1) = A_{R_i}$ is a better solution for equation 5. Without loss of generality, it can be assumed that

$$A_{R_1} < A_{R_2} \leq ... \leq A_{R_K} \qquad (11)$$

that is, the remaining energies are different. However, this implies the following:

$$(1 - P_{S,BS}) \prod_{i=1}^{K} (1 - P_{S,R_i} P_{R_i,BS}(G_{R_i})) > \varepsilon \qquad (12)$$

as $P_{R_i,BS}(G_{R_i})$ is monotone decreasing with respect to the remaining energy and $A$ is the solution of equation 5, which contradicts constraint 6. This indicates that $G_{R_i} = c_{R_i} - A$ for each $i = 1, 2...K$. Furthermore, the residual energies for every relay nodes is $A$. The result above yields that equation 8 can be reformulated as the following:

$$\begin{aligned} \varepsilon &= (1 - P_{S,BS}) \prod_{i=1}^{K} (1 - P_{S,R_i} P_{R_i,BS}) \qquad (13) \\ &= (1 - P_{S,BS}) \prod_{i=1}^{K} \left(1 - P_{S,R_i} \exp\left\{\frac{-d_{R_i,BS}^{\alpha} \Theta \sigma_Z^2}{G_{R_i}}\right\}\right) \\ &= (1 - P_{S,BS}) \prod_{i=1}^{K} \left(1 - P_{S,R_i} \exp\left\{\frac{-d_{R_i,BS}^{\alpha} \Theta \sigma_Z^2}{C_{R_i} - A}\right\}\right) \end{aligned}$$

which is an equation with only one unknown parameter $A$.

$\square$

Now, one can state the following:

**Lemma 1:** *Assuming that $G_S$ is already given, equation 13 has only one solution in parameter $A$.*

**Proof:** Since $G_S$ is given, $P_{S,R_i}$ is given as well. Note that $1 - P_{S,R_i} \exp\left\{\frac{-d_{R_i,BS}^{\alpha} \Theta \sigma_Z^2}{C_{R_i} - A}\right\}$ is strictly monotonously increasing as $A$ increases, for $\forall i \in [1, 2, ..., K]$. Therefore, $(1 - P_{S,BS}) \prod_{i=1}^{K} \left(1 - P_{S,R_i} \exp\left\{\frac{-d_{R_i,BS}^{\alpha} \Theta \sigma_Z^2}{C_{R_i} - A}\right\}\right)$ is also strictly monotonously increasing as well. Moreover, it asymptotically reaches 0 in $-\infty$ and 1 in $+\infty$. Hence, there is only one value $A$ that satisfies equation 13.

$\square$

## V. ROUTING WITH FIXED RELAY SET

This section extends the aforementioned optimization problem as follows. Here, the source node $S$ is allowed to modify its transmission energy. Thus, beside finding the optimal value for each $G_{R_i}$, the optimal value of $G_S$ has to be determined as well. According to theorem 1, the maximal residual energy

level of the bottleneck relay node is achieved when the residual energies are equal at the relay nodes. This energy level depends on the value of $G_S$. Thus, hereafter this energy level is referred to as $\Phi(G_S)$. Given this, one can state the following:

**Lemma** 2**:** *The function $\Phi(G_S)$ is strictly monotonously increasing.*

**Proof:** Note that $\Phi(0) = 0$. Now, according to equation 2, as $G_S$ increases, each $P_{S,R_i}$ increases as well. Therefore, if $G_S$ is increased, in order to fulfill equation 9, each $P_{R_i,BS}$ has to be decreased. That is, the residual energy level of each relay node (i.e. $\Phi(G_S)$) increases.

$\square$

In the general case, the source node is also taken into account. Thus, the residual energy at the source node is $c_S - G_S$. Since $\Phi(G_S)$ is increasing, and $c_S - G_S$ is strictly decreasing, as $G_S$ is increased, it can be proven that the maximum value of the general bottleneck node's residual energy (including the source and all the relay nodes) is achieved only if $c_S - G_S = \Phi(G_S)$. As the result, one can state the following:

**Theorem 2:** *Under the reliability parameter $(1 - \varepsilon)$, the maximal value of the residual energy level of the general bottleneck node is achieved when all the residual energy levels at the source node and the relay nodes are equal to each other.*

According to Theorem 2, equation 13 can be reformulated as follows:

$$
\begin{aligned}
\varepsilon &= (1 - P_{S,BS}) \prod_{i=1}^{K} (1 - P_{S,R_i} P_{R_i,BS}) \\
&= \left(1 - \exp\{\frac{-d_{S,BS}^{\alpha} \Theta \sigma_Z^2}{G_S}\}\right) \cdot \\
&\quad \cdot \prod_{i=1}^{K} \left(1 - \exp\{\frac{-d_{S,R_i}^{\alpha} \Theta \sigma_Z^2}{G_S}\} \exp\left\{\frac{-d_{R_i,BS}^{\alpha} \Theta \sigma_Z^2}{G_{R_i}}\right\}\right) \\
&= \left(1 - \exp\{\frac{-d_{S,BS}^{\alpha} \Theta \sigma_Z^2}{c_S - A}\}\right) \cdot \\
&\quad \cdot \prod_{i=1}^{K} (1 - \exp\{\frac{-d_{S,R_i}^{\alpha} \Theta \sigma_Z^2}{c_S - A} + \frac{-d_{R_i,BS}^{\alpha} \Theta \sigma_Z^2}{c_{R_i} - A}\})
\end{aligned} \quad (14)
$$

Since equation 14 is a monotonous function, fast and computationally efficient algorithms can be used, such as the well known Newton-Raphson method, to determine the optimal value of $A$. Note that since $A$ must be non-negative, otherwise there is no solution for the reliability routing problem.

## VI. SELECTING THE OPTIMAL RELAY SET

So far in this paper it was assumed that the set of relay nodes is already given. In this section, the selection of the optimal set of relay nodes participating in the cooperation is investigated in more detail. Let $\mathbf{R}^{\text{opt}}$ denote the optimal set of relay nodes, as defined in equation 7.

Using theorem 1, one can assume that for each node $v$ of the optimal set, including the source node as well, the optimal residual energy level is $c_v - G_v = A$. Given this, for each

given value of $A$, $G_S$ and $G_{R_i}$ can be calculated by using eqation 14.

Against this background, an algorithm is proposed which determines the optimal set of relay nodes. In so doing, first a number of notation is introduced as follows. Given a set of relay nodes $\mathbf{R}$, let $A_{\mathbf{R}}$ denote the optimal residual energy level of nodes within $\mathbf{R}$, including source node $S$. That is, $A_{\mathbf{R}} = c_v - G_v^{\text{opt}}$ for $\forall v \in \mathbf{R} \cup \{S\}$. This value can be calculated by solving equation 14. Now, consider the following algorithm:

1) Step 1: Let $\mathbf{R}_1 = \{\}$. Given this, let $A_{\mathbf{R}_1}$ denote the optimal residual energy of source node $S$, when none of the relay nodes is used for data forwarding. Let $k = 1$. GOTO step 2.
2) Step 2: For each value of $k$, if $\exists c_v > A_{\mathbf{R}_k}$, then GOTO step 3, otherwise GOTO step 4.
3) Step 3: Let $i$ denote the node that statisfies the following: $i = \arg\max_v \{c_v | c_v > A_{\mathbf{R}_k}\}$; that is, i has the highest energy level among nodes which have more energy than $A_{\mathbf{R}_k}$. Thus, $\mathbf{R}_{k+1} = \mathbf{R}_k \cup \{i\}$, and $k = k + 1$. GOTO step 2.
4) Step 4: If $A_{\mathbf{R}} > 0$ then it is the optimal solution, otherwise there is no solution for the problem.

**Theorem 3:** *The aforementioned algorithm converges to the optimal set of relay nodes, which is the optimal in terms of maximizing equation 7, with respect to the constraint given in equation 6.*

**Proof:** First, it will be shown that using the proposed algorithm, $A_{\mathbf{R}_k}$ is always monotonously increasing. In particular, if $i = \arg\max_v \{c_v | c_v > A_{\mathbf{R}_k}\}$, then

$$A_{\mathbf{R}_{k+1}} = A_{\mathbf{R}_k} \cup \{i\} \quad (15)$$

This means that if a given set of relay nodes can satisfy equation 14 then a node with greater energy level than that of $A_{\mathbf{R}_k}$ should become a relay node as well. Given this, if relay node $i$ forwards the packet with $c_i - A_{\mathbf{R}_k}$, then the probability of successful delivery is increased. Thus, by equally decreasing the transmission energy at each node, one can still satisfy equation 14, but the energy consumption is decreased. This indicates that $A_{\mathbf{R}_k}$ is monotonously increasing.

Now, it will be shown that when the algorithm terminates, the resulting set of relay nodes cannot be a local optimum. In so doing, an indirection technique is used as follows. Let assume that the result is a locally optimal set $\mathbf{R}$, which is not globally optimal. This indicates that

$$A_{\mathbf{R}^{\text{opt}}} > A_{\mathbf{R}} \quad (16)$$

It is easy to prove that

$$\nexists i : i \in \mathbf{R}^{\text{opt}}, i \notin \mathbf{R}, \quad (17)$$

since if ther is such a node $i$, then $c_i > A_{\mathbf{R}^{\text{opt}}}$, which also indicates that $c_i > A_{\mathbf{R}}$. In that case, the proposed algorithm would not have been stopped, but continued with choosing $i$ as a relay node as well. Similarly, one can have:

$$\nexists j : j \in \mathbf{R}, j \notin \mathbf{R}^{\text{opt}}, \quad (18)$$

since if it occur, then $\mathbf{R}^{\text{opt}} \subset \mathbf{R}$, which means that $A_{\mathbf{R}^{\text{opt}}} < A_{\mathbf{R}}$. Given this, $\mathbf{R}^{\text{opt}} = \mathbf{R}$. Thus, by using the proposed algorithm, one can achieve the optimal set of relay nodes.

## VII. Performance Evaluation

Within the previous sections, it has been proved that the proposed algorithm is optimal in the sense of balancing the energy consumption in the network. However, it is not clear that this approach is whether efficient, compared to other existing algorithms, such as LEACH, or BERA. Given this, this section demonstrates that by using multipath cooperative routing, one can achieve a better longevity of the network, compared to that of networks using LEACH for data forwarding.

In so doing, first the parameter settings of the simulation environment will be described. Following this, since LEACH is originally not suitable for reliable routing, it will be discussed how to modify it such that reliability can be still maintained, in order to make the comparison between LEACH and the proposed approach fair. On the other hand, since BERA also takes Rayleigh fading into account, it is suitable for reliable data forwarding. Thus, there is no need to modify BERA in order to compare it with the proposed approach. Then the analysis the numerical results will be taken place as well.

In the simulations, values are assigned to the parameters based on the widely used RF module of the CC2420 (these values can be found in [1]). Here, $\alpha = 2$, and the sensor nodes are deployed in a $100m \times 100m$ field and placed randomly with uniform distribution. In the simulations, the number of nodes are varied from 10 to 100.

Now, since LEACH is not designed for reliable routing, it does not take into account the lossy radio links. In order to overcome this shortcomings, and make it comparable with the proposed algorithm, LEACH has to be modified as follows. First, it must be guaranteed that each packet is delivered to the $BS$ with at least $(1 - \epsilon)$ success probability. Since LEACH uses cluster heads ($CH$) to relay data from nodes to the $BS$, similarly to the proposed algorithm, to deliver a packet, two hops are needed. Thus, one must to maintain a $\sqrt{1-\epsilon}$ delivery success probability for each hop (i.e. then the total delivery success probability is $(1 - \epsilon)$). In so doing, the transmission energy of each node has to be set, including the $CH$s, by using equation 1.

Given all this, the numerical result of the simulations is depicted in Figure 1. From this figure, one can see that the proposed cooperative multipath routing algorithm outperforms the other two methods. In particular, it shows an improvement of $200\%$, compared to the BERA. Furthermore, networks using the algorithm for data forwarding can extend their longevity 14 times, compared to the life span of networks using LEACH.

## VIII. Conclusion

This paper has focused on the problem of reliable data forwarding in the wireless sensor networks. More precisely, the challenge here was to provide a routing algorithm that maintains each packet's probability of successful delivery above a certain threshold $(1 - \epsilon)$. In addition, it has also been aimed to maintain energy balancing in the network, that is, the focus was on maximizing the residual energy level of the bottleneck node. Given this, a cooperative multipath routing algorithm has been proposed, that fulfills both objectives. In particular, it has been proved that the proposed algorithm is optimal, in both energy balancing, and determining the optimal relay set. Finally, it has been demonstrated that the proposed algorithm outperforms other existing methods.

This work, however, does not consider the energy consumption of each node at data receiving. Given this, one of the possible future work is to take the receiving energy consumption into account. Another direction for extending the work is to allow multipath data forwarding on paths with lengths higher than 2. This, as it is believed, would significantly improve the performance of the network.

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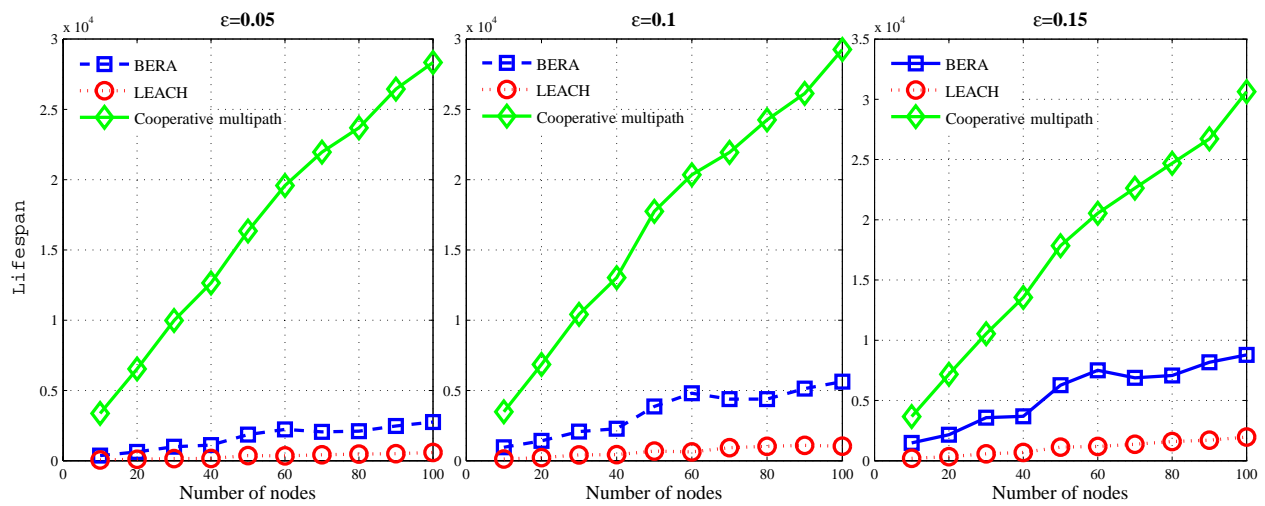
Fig. 1.   Performance evaluation of BERA, LEACH, and the cooperative multipath routing algorithm. The simulations were run with $\epsilon = 0.05$, 0.10, and 0.15, respectively.