Energy Constrained Multipath Routing in Wireless Sensor Networks

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Abstract. This paper addresses the issue of Quality of Service (QoS) Routing to improve energy consumption in wireless sensor networks (WSNs). Building upon a previously proposed QoS provisioning benchmark model, we formulate the problem of routing sensed information in a WSN network as a path-based energy minimization problem subject to QoS routing constraints expressed in terms of reliability, delay and geo-spatial energy consumption. Using probabilistic approximations, we transform the path-based model into a link-based model and apply methods borrowed from the zero-one optimization framework to solve this problem. By comparing the performance achieved by its solution to the benchmark model, simulation results reveal that our model outperforms the benchmark model in terms of energy consumption and quality of paths used to route the sensed information.

1 Introduction

Wireless Sensor Networks (WSNs) are a family of wireless networks which are currently deployed in both military and civil applications to achieve different types of sensing activities such as seismic, acoustic, chemical, and physiological sensing. They consist of a large number of tiny nodes, each node being regarded as a cheap computer deployed inside the phenomenon or very closed to it [1] to perform sensing, computation and communication. A typical WSN deployment scenario consists of a placing sensing devices in a human hostile environment to sense chemical substances and communicate the results via a satellite link or an helicopter to a center where these results are processed and appropriate decisions are taken about the controlled environment. It is predicted that by allowing allowing communication between inanimate objects, WSNs will bring a third dimension to the the first mile of the future Internet where information will not only be accessed *"anywhere and anytime"* but also represent *"anything"*.

As pointed out by Akyildiz et al. [1], wireless sensor networks present several limitations. These include

1. Sensor nodes are densely deployed and are range-limited systems, therefore efficient multi-hop routing algorithms are required.
2. Sensor nodes are unreliable and prone to failure, and the topology of sensor networks changes very frequently, hence it is desirable to set up energy constrained multi-path routing.

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3. Sensor nodes are limited in power, computational capacities and memory, thus the topology control with per-node transmission power adjustment is needed [2].

Low power consumption is an important paremeter upon which the efficiciency of the routing algorithms for wireless sensor networks depends. Single path routing algorithms are apparently simple than multi-path routing and consume lower energy in wireless sensor networks. However multi-path routing may be used in delay and reliability constrained wireless sensor network settings to (1) increase the likelihood of reliable data delivery by sending multiple copies of data along different paths [3] and (2) decrease the data delivery delays by sharing the data transmission delay among the different paths available from the source to the destination. Energy, Delay and Reliability can thus become competitive constraints in WSNs raising a tradeoff between single path and multipath routing deployment when energy and delay minimization and reliability maximization are at stake.

It was pointed in [4] that traditional node disjoint paths have attractive resilience properties, but they can be energy inefficient since they lead to longer alternate node-disjoint paths which consume more energy than the primary path. The work presented in [4] proposes the *braided multi-path* routing model where the node disjointedness constraint is relaxed by considering alternative paths which are partially disjoint from the primary path. A braided multi-path model based on constrained random walks to achieve almost stateless multi-path routing on a grid network is proposed in [5]. Recently, X. Huang and Y. Fang [6] proposed a braided multi-path routing model for WSNs referred to as Multi-Constrained Multi-Path routing (MCMP) where packet delivery from nodes to the sink is achieved based on QoS constraints expressed in terms of reliability and delay. This model addresses the issue of multi-constrained QoS in wireless sensor networks taking into account the unpredictability of network topology and trying to minimize energy consumption.

This paper models Quality of Service (QoS) routing in Wireless Sensor Networks (WSNs) to achieve energy efficiency. Building upon geo-spatial energy propagation considerations, we extend the model proposed by [6] to formulate QoS routing in WSN networks as an energy optimization problem constrained by reliability, play-back delay and geo-spatial path selection constraints. We solve this problem using optimization methods borrowed from the zero-one mathematical framework. We compare the energy consumed by our model referred to as Energy-Constrained Multi-Path routing (ECMP) to the energy consummed by the MCMP benchmark model and a Link-Disjoint Paths Routing model referred to as LDPR.

In the remainder of this paper, we present a sensor network communication model in Section 2 and examine the path delay, energy and reliability behavior in Section 3. Thereafter, we present in the same section a brief formulation of the MMCP and ECMP routing problems. Finally, Section 4 proposes the ECMP model while simulation results comparing the ECMP, MCMP and LDPR algorithms are presented in Section 5. Our conclusions are presented in Section 6.

2 Sensor Network Communication Model

When deployed in sensing activities, sensor nodes communicate wirelessly using radio wave, satellite or light and are deployed in three forms : (1) Sensor node used to

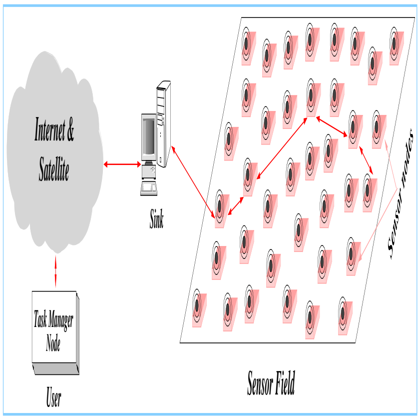


Fig. 1. Sensor Nodes Scattered in a Sensor Field

sense the information, (2) Relay node used as relay for the information sensed by other nodes and (3) Sink node acting as a base station with high energy used to transmit the sensed information to a remote processing place. A WSN operates in a multi-hop mode where sensor nodes co-operate to ensure that every information sensed and data collected are successfully relayed to the sink. This is illustrated by the the sensor network communication model depicted by Figure 1 where the sensor nodes scattered in a target observation area collect and route data to the end users via the sink or base station and the base station may communicate with the task manager node via Internet or satellite.

Sensor nodes may fall into one of the following states [7]:

1. Sensing: a sensing node monitors the source using an integrated sensor, digitizes the information, processes it, and stores the data in its on-board buffer. These data will be eventually sent to the base station.
2. Relaying: a relaying node receives data from other nodes and forwards it towards their destination.
3. Sleeping: for a sleeping node, most of the device is either shut down or works in low-power mode. A sleeping node does not participate in either sensing or relaying. However, it “wakes up” from time to time and listens to the communication channel in order to answer requests from other nodes. Upon receiving a request, a state transition to “sensing” or “relaying” may occur.
4. Dead: a dead node is no longer available to the sensor network. It has either used up its energy or has suffered vital damage. Once a node is dead, it cannot re-enter any other state.

3 A Path-Based Routing Model

Let consider a sensor network represented by a directed graph $\mathcal{G} = (\mathcal{N}, \mathcal{L})$ where $\mathcal{N}$ is the set of sensor nodes (location) and $\mathcal{L}$ the set of links. As a data source is usually far from the sink with the distance exceeding the range of communication, there is a need to deploy a certain number of sensor nodes that may act as relays used to route data over a multi-hop path. The multi-hop path between node s_1 and node s_ϵ is represented by $p = (s_1, \ldots, s_\epsilon)$ an ordered list of nodes $s_i \in \mathcal{N}$ such that the pair $(s_i, s_{i+1}) \in \mathcal{L}$, for $i = 1, \ldots, \epsilon - 1$.

3.1 Path Set Delay, Reliability and Energy

The path p is a series system of links and the path delay $i.e$ the delay between the node s_1 and s_ϵ is given by the sum of link delays

$$\mathcal{D}(p) = \sum_{i=1}^{\epsilon-1} d(s_i, s_{i+1}) \tag{1}$$

where $d(s_i, s_{i+1})$ is the delay of data over the link $(s_i, s_{i+1}) \in \mathcal{L}$.

Similarly, the energy consumption between node s_1 and node s_ϵ is given by [1].

$$\mathcal{W}(p) = \sum_{i=1}^{\epsilon-1} \omega(s_i, s_{i+1}) \tag{2}$$

where $\omega(s_i, s_{i+1})$ is the energy required to receive and transmit data between the node s_i and s_{i+1}. The necessary energy per bit for a node s_i to receive a bit and then transmits it to the node s_{i+1} is given by [7]

$$\omega_i(s_i, s_{i+1}) = \alpha_1 + \alpha_2 \|x_{s_i} - x_{s_{i+1}}\|^n \tag{3}$$

where $\alpha_1 = \alpha_{11} + \alpha_{12}$ with α_{11} the energy per bit consumed by s_i as transmitter and α_{12} the energy per bit consumed as receiver, and α_2 accounts for the energy dissipated in the transmitting operation. Typical values for α_1 and α_2 are respectively $\alpha_1 = 180nJ/bit$ and $\alpha_2 = 10pJ/bit/m^2$ for the path loss exponent experienced by a radio transmission $n = 2$ or $\alpha_2 = 0.001pJ/bit/m^4$ for the path loss exponent experienced by a radio transmission $n = 4$. x_{s_i} is the location of the sensor node s_i, and $\|x_{s_i} - x_{s_{i+1}}\|$ is the euclidean distance between the two sensor nodes s_i and s_{i+1}, $i = 1, \ldots, \epsilon - 1$. Thus, in (2), we have

$$\omega(s_i, s_{i+1}) = f_{s_i \to s_{i+1}} \cdot \omega_i(s_i, s_{i+1}) \tag{4}$$

where $f_{s_i \to s_{i+1}}$ denotes the data rate on the link $(s_i, s_{i+1}) \in \mathcal{L}$.

Assuming that the links of a path are independent, from [8], the path reliability $\mathcal{R}(p)$ is given by

$$\mathcal{R}(p) = \prod_{i=1}^{n-1} R(s_i, s_{i+1}) \tag{5}$$

where $R(s_i, s_{i+1})$ is the reliability of the link $(s_i, s_{i+1}) \in \mathcal{L}$.

Considering the set of parallel paths $\mathcal{P} = \{p_1, \ldots, p_M\}$, the delay experienced and the energy consumed by data source routed over the path set $\mathcal{P}$ are respectively given by

$$\mathfrak{D}(\mathcal{P}) = \max\{\mathcal{D}(p) : p \in \mathcal{P}\} \tag{6}$$

and

$$\mathfrak{W}(\mathcal{P}) = \sum_{p\in\mathcal{P}} \mathcal{W}(p) \tag{7}$$

where $\mathcal{D}(p)$ and $\mathcal{W}(p)$ are computed respectively in (1) and (2).

And finally, from [8], the reliability of the data source routed over $\mathcal{P}$ is given by

$$\mathfrak{R}(\mathcal{P}) = 1 - \prod_{p\in\mathcal{P}} \left(1 - \mathcal{R}(p)\right) \tag{8}$$

where $\mathcal{R}(p)$ is computed using the formula given in (5).

3.2 The Path-Based Routing Problem

Let $\mathcal{P} = \{p_1, \ldots, p_M\}$ denote the set of possible paths from s to the base station b assumed to be stationary. Each path $p_\jmath \in \mathcal{P}$, $\jmath = 1, \ldots, M$, is associated with the delay $d_\jmath$ and reliability $r_\jmath$. If every path $p \in \mathcal{P}$ has delay larger than the delay D required by the data source, then the data source is dropped since no path can fulfill the delivery of the packet with that constraint. In the case of the reliability constraint, multi-path routing can be used to improve the reliability. However, the use of several path increases energy consumption, which therefore affects the lifetime of the network. Thus, in order to save the energy, the path set with minimum number of paths is chosen as forwarding set.

The routing objective is then to find a minimum number of path in $\mathcal{P}$ that satisfy the QoS requirements of a given data source f with minimum energy consumption. This can be formulated as an optimization problem given below.

Problem 0**.** Given delay and reliability requirements D and R, the QoS routing problem consists of finding the smallest set of paths $\mathbf{P}[s, b]$ from a source s to the base station b which minimize the energy consumption $\mathfrak{W}\left(\mathbf{P}[s, b]\right)$ subject to delay and reliability constraints as expressed by

$$\min_{\mathbb{P}\subset\mathcal{P}} \mathfrak{W}\left(\mathbb{P}\right)$$

subject to

$$\mathfrak{D}\left(\mathbf{P}[s, b]\right) \leq D \tag{9}$$

$$\mathfrak{R}\left(\mathbf{P}[s, b]\right) \geq R \tag{10}$$

where $\mathfrak{D}\left(\mathbf{P}[s, b]\right)$, $\mathfrak{R}\left(\mathbf{P}[s, b]\right)$, and $\mathfrak{W}\left(\mathbb{P}\right)$ are respectively defined by the relations (6), (8), and (7).

3.3 Probabilistic Transformation

Problem 0 assumes global knowledge of topology and network characteristics, and requires exact information about path quality which is almost impossible to get in wireless sensor networks. Moreover, as expressed by the equations (9) and (10), the QoS constraints are hard constraints that require QoS enforcement for the entire lifetime of a session [9]. However, after the connection is setup, there exist transient periods of time when the QoS specification may not be honored due to frequent changes of the sensor network topology. This means that QoS requirement can be provided only with a certain probability referred to as soft-QoS. Thus, the problem can be reformulated as follows.

Problem $0^{'}$**.** Given delay and reliability requirements D and R, the QoS routing problem consists of finding a smallest set of paths $\mathbf{P}[s,b]$ from a source s to the base station b that minimize energy consumption subject to delay and reliability constraints as expressed by

$$\min_{\mathbb{P}\subset\mathcal{P}} \mathfrak{W}\left(\mathbb{P}\right)$$

subject to

$$Pr\big[\mathfrak{D}\left(\mathbf{P}[s,b]\right) \leq D\big] \geq \alpha \tag{11}$$

$$Pr\big[\mathfrak{R}\left(\mathbf{P}[s,b]\right) \geq R\big] \geq \beta \tag{12}$$

where $Pr\left(X\right)$ denotes the probability of event X, and α and β are respectively soft-QoS probability for delay and reliability.

3.4 Approximating Global by Local Constraints

Based on the assumptions that the path model is inappropriate for QoS routing in wireless sensor networks, different approximations were proposed in [6] to tranform the path- into link-based constraints by expressing the reliability and delay constraints into stochastic constraints which are more relevant to a wireless sensor network setting. The main objective of these transformations is to redesign the routing process in a local context where the routing decision is concerned with only a node and its direct neighbors rather than an end-to-end path. These transformations are based on the following key features:

- The links are assumed to be independent in term of delay and reliability and reliability and delay are expressed as random time dependent processes where the time t is omitted in our notation for simplicity sake.
- The delay constraint is expressed for each node $\imath$ in terms of hop requirement

  $$L_\imath^d = (D - D_\imath)/h_\imath$$

  with $D_\imath$ being the actual delay experienced by a packet at node $\imath$ and $h_\imath$ the hop count from node $\imath$ to the sink.
- The reliability requirement is expressed for each node $\imath$ in terms of hop requirement

  $$L_\imath^r = \sqrt[h_\imath]{R_\imath}$$

  with $R_\imath$ being the portion of reliability requirement assigned to the path through node $\imath$ decided by the upstream node of $\imath$.

- The resulting local constraints are expressed by

$$x_\jmath\left(\frac{\alpha}{1-\alpha}\left(\Delta^d_{\imath\jmath}\right)^2 + 2L^d_\imath d_{\imath\jmath} - d^2_{\imath\jmath}\right) \leq \left(L^d_\imath\right)^2 \mid L^d_\imath > d_{\imath\jmath} \tag{13}$$

$$\sum_{\jmath\in\mathbf{N}[\imath]} x_\jmath \log\left(\mathcal{Q}\left(\frac{R_{\imath\jmath}-r_{\imath\jmath}}{\Delta^r_{\imath\jmath}}\right)\right) \geq \log\beta, \tag{14}$$

$$\sum_{\jmath\in\mathbf{N}[\imath]} x_\jmath \log\left(1-R_{\imath\jmath}\right) \leq \log\left(1-L^r_\imath\right) \tag{15}$$

$$0 \leq R_{\imath\jmath} \leq r_{\imath\jmath}, \text{ for all } \jmath \in \mathbf{N}[\imath] \tag{16}$$

$$x_\jmath = 0 \text{ or } 1, \text{ for all } \jmath \in \mathbf{N}[\imath] \tag{17}$$

where $x_\jmath$ is a decision variable which takes the value 1 if the path $p_j \in P[s,b]$ and 0 otherwise. $R_{\imath\jmath}$ and $D_{\imath\jmath}$ are respectively the delay and reliability of the link $\ell_{\imath\jmath}$, $\Delta^d_{\imath\jmath}$ and $\Delta^r_{\imath\jmath}$ are respectively standard deviation of $D_{\imath\jmath}$ and $R_{\imath\jmath}$. The $\mathcal{Q}-$function in (14) is defined by

$$\mathcal{Q}(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty \exp\left(-\frac{1}{2}t^2\right)dt, \tag{18}$$

Note that the equations (13), (14) are an approximation of the delay (11) constraint while (15) is an application of the reliability (12) constraint to a link model. These approximations are detailled in [6].

4 The Energy Constrained Multipath (ECMP) Model

The MCMP model was proposed in [6] to minimize the number of paths used in forwarding data source to the sink with the expectation of minimizing the total energy transmission. It is expressed by

Problem $1'$. At each node $\imath$, find the subset $\mathbf{N}_0 \subseteq \mathbf{N}[\imath]$ the set of neighbors of node $\imath$ that solves the following linear zero-one program

$$\min \sum_{\jmath\in\mathbf{N}[\imath]} x_\jmath \tag{19}$$

subject to the constraints (13),(14),(15),(16) and (17) above.

However, this model does not really take into consideration the geo-spatial energy consumption in the network as illustrated by Figure 2 since it discounts the best link selection in case where a choice must be made between two links to satisfy the QoS requirements. As the objective is to send data from source to the sink with the total energy transmission as minimum as possible, the choice between node $\jmath$ and k is an important factor upon which the performnace of the optimization model depends.

4.1 Considering a Geo-Spatial Constraint

It is relevant in energy-efficient modelling of WSNs to account for geo-spatial energy consumption constraints. To illustrate our proposal, let us consider Figure 2 where the

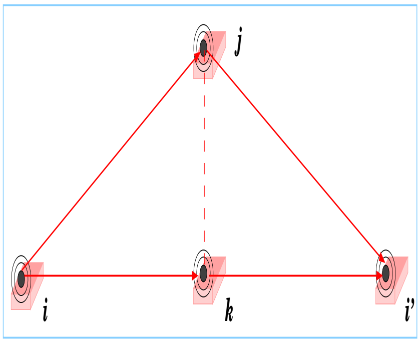


Fig. 2. MCMP model Inefficiency

choice must be made between the link $(\imath, \jmath)$ and the link $(\imath, k)$ or equivalently the node $\jmath$ and node k to be added to the subset $\mathbf{N}_0$ of $\mathbf{N}[\imath]$ the set of the neighbors of $\imath$, assuming that the two candidates $\jmath$ and k may satisfy the QoS requirement for data source.

From Pythagoras' theorem, the distance between node $\imath$ and node $\jmath$ is larger than that between $\imath$ and k. Combiningg Pythagoras' theorem with the formula in (3) for energy transmission computation, one can easily find that the energy transmission between $\imath$ and $\jmath$ is higher than energy transmission between $\imath$ and k. This means that chosing $\jmath$ as best neighbor node to forward data to leads to the higher energy consumption as compared to the selection of node k. However, the MCMP model proposes an arbitrary choice between the nodes $\jmath$ and k as neighbor node; a random choice which is not likely to select the best node in term of minimum energy consumption.

Building upon this finding, we propose a routing model referred to as Energy-constrained Multipath (ECMP) that overcomes this drawback by ensuring that data is transmitted towards the least energy consuming links. The ECMP model finds the subset $\mathbf{N}_0$ of the set $\mathbf{N}[\imath]$ with the lowest expected energy transmission while satisfying the QoS requirements when delivering data from source to sink. The goal of ECMP model is then to find the subset $\mathbf{N}_0 \subseteq \mathbf{N}[\imath]$ satisfying the QoS requirements of the data source and minimizing the total energy transmission. Indeed, denoting $\omega(\imath, \jmath)$ the energy required from a node $\imath$ to receive data and then transmits it to the node $\jmath$ given by the formula (4), the ECMP model assumes a neigbhor selection scheme based on the geo-spatial constraint expressed by

$$\omega(\imath, \jmath) \leq \omega(\imath, \tilde{\jmath}) \mid \chi(\imath, \jmath) \leq \chi(\imath, \tilde{\jmath})$$

where $\chi(\imath, \jmath)$ is the euclidean distance between i and j.

4.2 The Routing Model

Let us consider a wireless sensor network represented by a directed graph $\mathcal{G} = (\mathcal{N}, \mathcal{L})$, where $\mathcal{N}$ is the set of sensor nodes and $\mathcal{L}$ is the set of wireless links between nodes. Suppose there exists a data source f at a given location x_s sensed by the node s. This data must be routed to the base station. The data possesses a QoS requirement expressed in term of delay D and reliability R.

Problem 1. At each node $\imath$, find the subset $\mathbf{N}_0 \subseteq \mathbf{N}[\imath]$ the set of neighbors of node $\imath$ that solves the following zero-one linear program

$$\min \sum_{\jmath \in \mathbf{N}[\imath]} x_\jmath \tag{20}$$

subject to the constraints (13),(14),(15),(16) and (17) and

$$\omega(\imath, \jmath) \leq \omega(\imath, \tilde{\jmath}) \mid \chi(\imath, \jmath) \leq \chi(\imath, \tilde{\jmath}) \tag{21}$$

Algorithmic solution. The ECMP problem as well as the MCMP problem are deterministic linear zero-one problems. Several methods have been proposed by the literature to address such kind of problems [11, 12]. In both problems, the number of constraints is $2\,|\mathbf{N}[\imath]| + 2$, and the number of the decision variables is $|\mathbf{N}[\imath]|$ which is the size of $\mathbf{N}[\imath]$. Thus, the problem size is relatively small and might be proportional to the node density. Building upon the zero-one framework proposed in [11], we considered an implementation where the two local routing problems MCMP and ECMP are solved using the Bala's Algorithm but using different path selection strategies: (1) a random selection for the MCMP algorithm where at each node the next hop to the sink is selected arbitrarily among the neigbhors of the node and (2) energy-efficient selection where the closest neighbor in term of euclidean distance is selected by the node as next hop to the sink.

An illustration. The main idea behind this path selection is illustrated by figures 3 and 4. Figure 3 depicts a WSN where each link ℓ is associated with two positive QoS measures expressing the reliability and delay in ms. This figure depicts a WSN where data from the source node 0 to the base station (sink node) 10 is routed under two QoS constraints: (1) delay $\leq$ 80 ms and (2) reliability $\geq$ 0.9. The tree of eventual paths generated by the MCMP and ECMP algorithms is depicted by Figure 4. To each node $\imath$ of that tree is associated the node state $\mathcal{S}_\imath = (x_0, x_1, x_2, x_3, x_4)$ describing the QoS of the eventual path segment followed by data from the source node 0. The components of the node state are described as follows:

- x_0 is set to the value 1 if when a node satisfies the requirement to be used as relay node or the node is the source or the sink node. It is set to the value 0 otherwise.
- x_1 is the minimum hop count from the given node to the sink.
- x_2 is set to 0 where the routing process stops and 1 otherwise.
- x_3 is an indication on the delay achieved by the data entering at the given node.
- x_4 is set to the value 1 if the node satisfies reliability and delay requirements and 0 otherwise.

The tree of eventual paths followed by the data from the source 0 to the sink 10 shows that three link disjoint paths can be found, namely $0 \rightarrow 1 \rightarrow 4 \rightarrow 9 \rightarrow 10$, $0 \rightarrow 2 \rightarrow 4 \rightarrow 7 \rightarrow 10$ and $0 \rightarrow 3 \rightarrow 4 \rightarrow 8 \rightarrow 10$, with reliability of 0.5814, 0.4277 and 0.618 respectively. While all the three paths meet the delay requirement, none of them satisfy the reliability constraint (reliability $\geq$ 0.9). However, when taken together as a set of three node-disjoint paths, the three paths achieve a reliability value 0.902 allowing data to reach the sink with the required reliability 0.9.

When selecting the smallest set of neigbhors of 2 satisfying the reliability constraint, its can be observed that at node 2 both the ECMP and MCMP models will have to

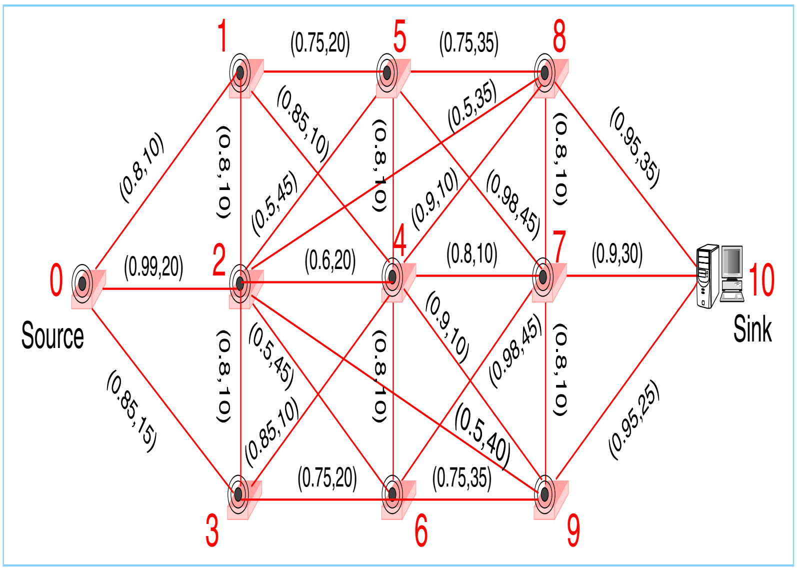


Fig. 3. Illustration

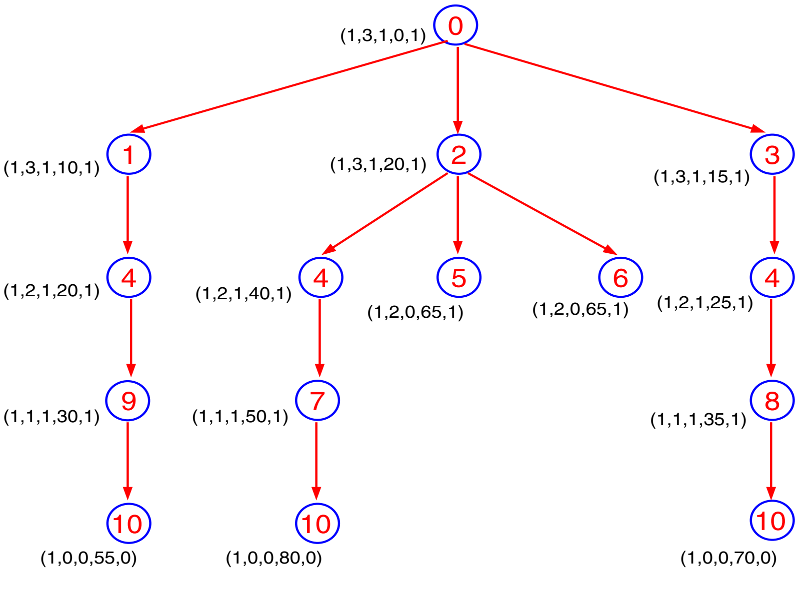


Fig. 4. Tree of eventual paths

choose the node 4 and select two nodes among nodes 5, 6, 8 and 9 to be added to the smallest set of neighbors of 2 to meet the QoS constraints. While our ECMP model will pick up the nodes 5 and 6 which lead to minimum energy consumption since their distances to the node 2 are small compared to the node 8 and 9, the MCMP model will implement an arbitrary choice which will not necessary lead to selecting the least energy consuming neigbhor nodes 5 and 6. By selecting nodes 8 and/or 9 for example, the MCMP model will increase energy consumption.

It should also be observed that though providing the potential of findind similar paths under loose reliability constraints, the ECMP and MCMP models will perform differently under stringent reliability constraints. This is the case for example when the reliability threshold is reduced from 0.9 to 0.75. This will lead the ECMP model to select the paths $0 \rightarrow 3 \rightarrow 4 \rightarrow 8 \rightarrow 10$ and $0 \rightarrow 2 \rightarrow 4 \rightarrow 7 \rightarrow 10$ while the MCMP model selects $0 \rightarrow 3 \rightarrow 4 \rightarrow 8 \rightarrow 10$ and makes an arbitrary choice between paths $0 \rightarrow 1 \rightarrow 4 \rightarrow 9 \rightarrow 10$ and $0 \rightarrow 2 \rightarrow 4 \rightarrow 7 \rightarrow 10$ in order to satisfy the reliability requirement. Such an arbitrary choice is not likely to choose the path $0 \rightarrow 2 \rightarrow 4 \rightarrow 7 \rightarrow 10$ which is less energy consuming compared to the path $0 \rightarrow 1 \rightarrow 4 \rightarrow 9 \rightarrow 10$.

5 Performance Evaluation

In this section, we evaluate through experimentation the efficiency of the ECMP model with those of baseline single path (SP) routing, MCMP and Link-Disjoint Paths Routing (LDPR) models in terms of several performance parameters.These include the average energy consumption, delivery ratio and average data delivery delay. The LDPR is a link-disjoint algorithm where the number of paths used is function of reliability requirements: the higher the reliability required, the higher the number of paths used. The LDPR model is an ideal routing model similar to the *"GOD routing"* model in [6] which assumes that each sensor node is aware of the instantaneous link delay and reliability and has complete knowledge of the network topology.

- Average energy consumption indicates the average energy consumption in transmission and reception of all packets in the network. This metric reveals the efficiency of an approach with respect to the energy consumption.
- Delivery ratio is one of the most important metrics in real-time applications which indicates the number of packets that meet a specified QoS level. It is the ratio of successful packet receptions referred to as received packets to attempted packet transmissions referred to as sent packets.
- Average data delivery delay is the end-to-end delay experienced by successfully received packets.

In addition, we compare the quality of paths used by the MCMP and ECMP models in terms of (1) path length (number of hops of paths used) (2) path multiplicity (average number of paths used to send data to the base station) and (3) path usage showing how often a model uses its preferred paths: a measure of the stability of the model. While the path length gives an indication on QoS since using longer paths lead to higher delays, the path multiplicity reveals energy consumption since an algorithm which shares data over a lower number of paths will consume less energy.

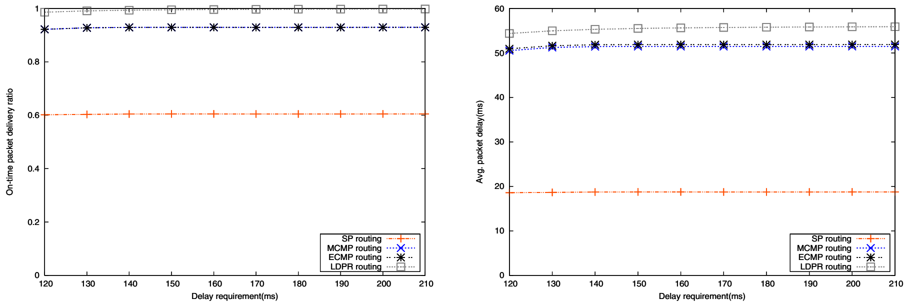
5.1 Experimental Setup

We consider a wireless sensor network where 50 sensor nodes are randomly deployed in a sensing field of $100m \times 100m$ square area and the transmission range is $25m$. 10 among the 50 sensor nodes are selected randomly to generate data.

We adopt a scenario where link reliability and delay are randomly chosen to assess the worst case where link delay and reliability change suddenly at any transmission instant. The reliability values are uniformly distributed in the range $[0.9, 1]$ and the delay in the range $[1, 50]$ ms. Note that the delay includes queueing time, transmission time, retransmission time and propagation time. The delay constraints are taken in the range of $[120, 210]$ ms with an interval of 10 ms, which produces 10 delay requirement levels and the threshold of reliability is set to 0.5. Both parameters α and β are set to 95%. The size of a data packet is 150 bytes and a packet is assumed to have an energy field that is updated during the packet transmission to calculate the total energy consumption in the network. To achieve 10 trials for each experiment, we applied different random seeds to generate different network configurations. Each simulation lasted 900 sec.

5.2 Experimental Results

The experimental results are presented in figures 5(a)-5(b) respectively for the delivery ratio and data delivery delay while figures 6(a)-6(d) depict the network energy consumption. Figures 7(a)-7(c) reveal the quality of paths in terms of path length, multiplicity and usage.

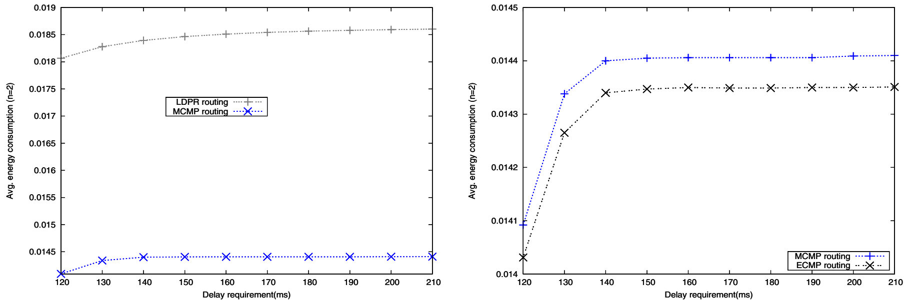


(a) On-time Packet Delivery Ratio (b) Avg. End-to-End Packet Delay

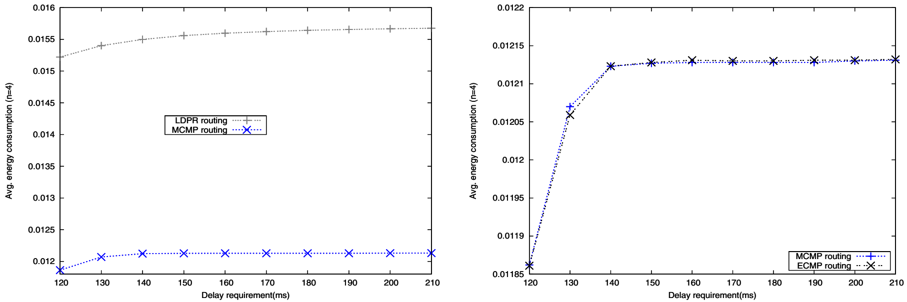
Fig. 5. Delivery Ratio and Data Delay Comparison

In term of delivery ratio, ECMP and MCMP models perform equally, and both models outperform single path routing as shown by Figure 5(a). As expected, the LDPR model achieves the best performance since it assumes that each sensor node has complete knowledge of the network topology. The slight difference of average end-to-end delay between ECMP and MCMP models is due to the fact that the paths used by the two models are different in term of number of hops as depicted by the route lengths in Figure 7(a).

Looking at the total energy consumed in the network, we found that the ECMP model, as expected, performed better compared to MCMP model as illustrated by figures 6(b) and 6(d). On the other hand, figures 6(a) and 6(c) reveal that MCMP highly

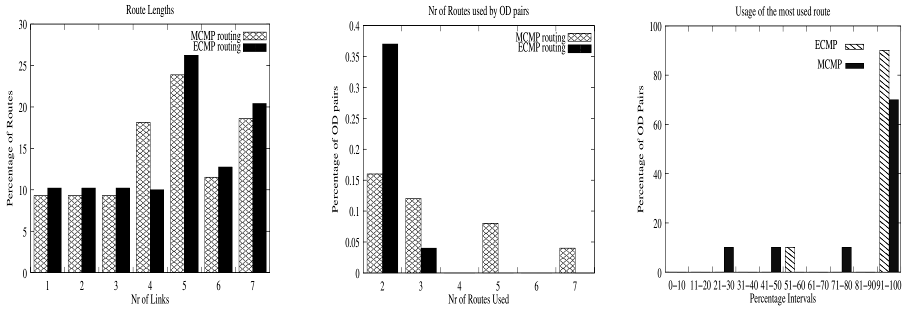


(a) Enerergy for LDPR and MCMP $(n = 2)$ (b) Energy for MCMP and ECMP $(n = 2)$



(c) Energy for LDPR and MCMP $(n = 4)$ (d) Energy for MCMP and ECMP $(n = 4)$

Fig. 6. Energy Efficiency Comparison



(a) Path Lengths (b) Path Multiplicity (c) Path Usage

Fig. 7. Quality of paths

ouperforms the LDPR model in terms of energy consumption. These results are in agreement with Table 1 which reveals the percentage of paths which are identical to both algorithms (Strong correspondence), the number of paths where both algorithms differ by one hop (weak corresponadence), and the percentage of paths used by ECMP only and those used by MCMP only. This table reveals that the MCMP algorithm shares its traffic on more paths than the ECMP algorithm: while there is no route used by

Table 1. Path correspondance

Strong Correspondence	58.86%
Weak Correspondence	25.69%
Routes used only by ECMP	0.00%
Routes used only by MCMP	15.45%

the ECMP algorithm only, the MCMP algorithm has 15.45% more routes than ECMP. Consequently, by using smaller path sets, the ECMP algorithm can achieve more energy savings compared to the MCMP model. This relative efficiency applies also to the ECMP model when compared to the LDPR model.

The results in Figure 7(a) reveal that in general the ECMP model uses longer paths (in terms of number of hops) compared to the MCMP model. Thus, the paths used by ECMP model are more likely to lead to higher end-to-end delays. However this is balanced by the impact of path multiplicity revealing that the ECMP model uses smaller path sets resulting in lower energy consumption. This justifies the results depicted by the Figure 5(b) on average end-to-end packet delay where ECMP and MCMP achieve similar performance. Finally, the two models use approximatively 99.6% single paths, and when these algorithms start using more than one path, the results depicted by Figure 7(b) reveal that the ECMP model uses smaller path sets compared to the MCMP model. Thus the MCMP model tends to consume more energy than the ECMP model. This is in agreement with the design of each of these models and justifies the results in Figures 6(b) and 6(d) concerning the network energy consumption. The results depicted by Figure 7(c) on the route usage reveal that the ECMP model uses its preferred paths more often than the MCMP model. This reveals the stability of the ECMP model compared to the MCMP model.

6 Conclusion

In this paper we analyzed the issue of using multi-path routing in wireless sensor networks and proposed the Energy-constrained Multi-Path routing (ECMP), an improvement to the MCMP model proposed by [6]. The main idea driving the ECMP model is that in the context of wireless sensor networks, efficient resource usage should reflect not only efficient bandwidth utilization but also a minimal usage of energy in its strict term. While, the MCMP model routes the information over a minimum number of hops, the strength of the ECMP model lies in the fact that it trades between minimum number of hops and minimum energy by selecting a path with minimum number of hops only when it is the path with minimum energy or a longer path with minimum energy satisfying the constraints. Using the ECMP algorithm, we show that QoS support in wireless sensor networks should be based on well defined constraints to avoid unnecessary energy consumption when delivering data. The efficiency of the proposed model is evaluated through simulation results revealing that ECMP outperforms MCMP.

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