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Research Article

Modelling and Implementation of QoS in Wireless Sensor Networks: A Multiconstrained Traffic Engineering Model

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This paper revisits the problem of Quality of Service (QoS) provisioning to assess the relevance of using multipath routing to improve the reliability and packet delivery in wireless sensor networks while maintaining lower power consumption levels. Building upon a previous benchmark, we propose a traffic engineering model that relies on delay, reliability, and energy-constrained paths to achieve faster, reliable, and energy-efficient transmission of the information routed by a wireless sensor network. As a step forward into the implementation of the proposed QoS model, we describe the initial steps of its packet forwarding protocol and highlight the tradeoff between the complexity of the model and the ease of implementation. Using simulation, we demonstrate the relative efficiency of our proposed model compared to single path routing, disjoint path routing, and the previously proposed benchmarks. The results reveal that by achieving a good tradeoff between delay minimization, reliability maximization, and path set selection, our model outperforms the other models in terms of energy consumption and quality of paths used to route the information.

1. Introduction

Sensor Networks (SNs) are a family of networks which are currently deployed in our daily living environment to achieve different sensing activities with the objective of delivering services to both civil and military applications. These activities include seismic, acoustic, chemical, and physiological sensing to enable different applications such as battlefield surveillance and enemy tracking, habitat monitoring and environment observation and forecast systems, health monitoring and medical surveillance, home security, machine failure diagnosis, chemical/biological detection, animal tracking, plant monitoring, and precision agriculture. Sensor networks can be deployed using a fixed infrastructure called fixed sensor network (FSN) where the packets of information collected from sources are routed to the destination by having the sensor nodes connected to endpoints of a fixed network such as an ADSL or Ethnernet network. When connected to a wireless infrastructure, the nodes of the SN referred to as wireless sensor network (WSN) communicate wirelessly using radio wave, satellite or light. While FSNs are usually energy-rich networks that rely on a stable and constant power supply, WSNs are energy-poor networks operating unattended sometimes in harsh environmental conditions with intermittent power supply. As depicted by Figure 1 illustrating the architecture proposed by Akyildiz et al. in [1], a WSN is a network communicating using a many-to-one model with a number of sensor nodes scattered into a target observation area with objective of collecting and routing data to the end users via a single sink node also called base station. Wireless sensor nodes are usually low energy, low-range devices requiring multihop deployment to extend their reach. To ensure that the data collected from the environment is successfully relayed to the sink, wireless sensor network implements a co-operative multi-hop routing scheme where each sensor may play one of the three different roles: (1) sensing node used to sense the environment, (2) relay node used as transit for the information sensed by other nodes, and (3) sink node acting as a base station attached to a high energy device also referred to as gateway used to transmit the information to a remote processing place. Using this scheme, the data captured in

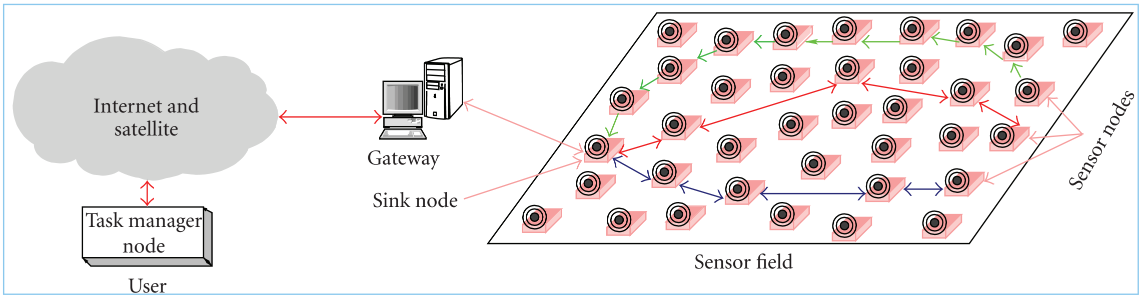


Figure 1: Sensor nodes scattered in a sensor field.

the target environment is forwarded to the end users by a multi-hop infrastructureless network via the sink node which passes this information to a gateway communicating with the task manager node using the Internet, wireless communication such as WiFI, WiMax, or a satellite link as illustrated by Figure 1.

When deployed in a sensor field to perform sensing operations, a sensor node may fall into one of the following states [2].

(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. This information 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.

A typical WSN deployment scenario consists of placing sensor devices into a given environment to sense what is happening in that environment and report the results wirelessly to a processing place where appropriate decisions are taken about the environment being controlled. This can be applied, for example, in Precision agriculture by using sensors to measure the humidity and temperature levels at different points of the ground and take appropriate irrigation decisions. In a region-wide emergency situation, a sensor network could also be deployed in a gas contaminated urban area by air-dropping chemical sensors from Unmanned Aerial Vehicles (UAVs) to achieve real-time situation assessment, report the extent and movement of gas back to nearby UAVs and take appropriate decisions concerning an evacuation plan. Embedding sensors in roadbeds, alongside highways, or bridge structures and placing cameras at street intersections to measure traffic flow and detect traffic violations have become common practice in many modern cities. These devices are networked to build a smart road network infrastructure used to make roads safer, reduce congestion, help people find the nearest available parking space in an unfamiliar city, achieve routing assistance, or provide early warnings on weather-related road conditions. The efficiency of such deployments may be measured by (1) the lifetime of the WSN often expressed by the time spanning from the outset of the WSN and the time when the first sensor is battery depleted, (2) the throughput expressed by the proportion of the information sensed in the environment which has successfully reached the gateway, and (3) the delay and time taken by the information collected by the WSN to travel from the sensing area to the gateway where the information is processed.

Life Time. Energy conservation is a key parameter upon which the lifetime of WSNs depends since the sensor nodes often operate unattended in unrecoverable locations where the labor and costs associated with the batteries use and replacement may outweigh the ROI (Return on Investment) that the sensor network could deliver.

Throughput. WSNs are by nature broadcasting networks which require tight control to avoid duplication of the same information on the network which might waste bandwidth and reduce the throughput of the network. Furthermore, the uncontrolled deployment of a WSN may lead to the unwanted behavior where high packet drop may arise from competition on the mac layer between sensor nodes trying to send information on a shared medium (channel) using the CSMA protocol.

Delay. Many of the emerging WSN deployments involve delay sensitive applications with real-time delay constraints. Meeting such delay constraints may require both hardware efficiency at the level of the clock of the WSN and software efficiency by deploying efficient routing techniques that can improve delay and on-time packet delivery.

Traffic engineering (TE) is a network management technique which, once the preserve of fixed networks, will be reinvented to address the issues associated with the performance parameters described above. Traffic engineering moves the traffic (information collected in the WSN) to where the network resources are available to achieve QoS agreements between the offered traffic and the available resources.

1.1. Related Work. Single path (SP) routing approaches using different schemes have been proposed as TE approaches for energy efficient communication in wireless networks. Some are based on data-centric routing schemes such as directed diffusion [3] using the flooding of interest by sinks to allow gradients to be set up within the wireless network. Other approaches rely on routing metrics (costs) such as the distance to the destination or the node residual energy level [4] to reduce energy consumption in WSNs. These follow the work of Stojmenovic and Lin [5] where routing algorithms for wireless networks are discussed with the goal of increasing the network lifetime by defining a new power-cost metric based on the combination of both node's lifetime and distance-based power metric, thus proposing power aware routing algorithm that attempts to minimize the total power needed to route a message between a source and a destination. In [6], a protocol is proposed which, given a communication network, computes a sub-network such that, for every pair (u, v) of nodes connected in the original network, there is a minimum-energy path u and v in the subnetwork where a minimum-energy path is the one that allows messages to be transmitted with a minimum use of energy. Liu and Li [7] considered the problem of topology control in a network of heterogeneous wireless devices with different maximum transmission ranges, where asymmetric wireless links are not uncommon. P. X. Liu and Y. Liu [8] developed a novel energy-efficient routing called the THEEM (Two Hop-Energy-Efficient Mesh) protocol for wireless sensor network. However, though appearing simple, flexible, and scalable, SP routing might result in the faster depletion of the nodes energy supply and subsequent shorter lifetime, higher transmission delays and are unreliable.

Multipath routing is a TE strategy which provides the potential to increase the likelihood of reliable data delivery of information from source to destination by sending multiple copies of the same data along different paths [9]. It can also increase the throughput of a network by sending different pieces of the information in parallel over different paths and restoring the entire information at the destination. This might result in better playback delay (the maximum delay taken by all the pieces of information to arrive to the destination) and minimized on-time packet delivery. Multipath routing algorithms minimizing the energy consumption to extend the lifetime of a network while satisfying the QoS traffic requirements such as delay and reliability are important parameters upon which the wide deployment of WSNs depend. The routing protocols proposed in [10, 11] use multiple path routing with network reliability as design priority. They are implemented by having data transmission relying mostly on an optimal primary path and an alternative path reserved as an emergency path used only when the nodes on the primary route fail. The energy-aware routing proposed in [10] uses localized request messages flooding to find all possible routes between the sources and sinks, as well as the energy costs associated to these paths. By using a sensor node routing table where every neighbor is associated with a given transmission probability computed based on the cost of the path passing through it, the scheme maintains multiple paths but uses only one of them at a time, in order to avoid stressing a particular path and extend the network lifetime. Pointed out by Ganesan et al. [11], the traditional disjoint paths (node disjoint paths) have the same attractive resilience properties, but they can be energy inefficient. Alternate node-disjoint path can be longer and therefore expends significantly more energy than that expended on the primary path. Since this energy can adversely impact the lifetime and the performance of a sensor network, they have considered a slightly different kind of multipath, namely, a braided multi-path, which relaxes the requirement for node disjointedness. Alternate paths in a braid are partially disjoint from the primary path, not completely node-disjoint. The multipath routing approach proposed in [11] expands on directed diffusion [3] to improve the resilience to node failures by exploring the possibility of finding alternate paths connecting the source and sink nodes when node failures occur. Sue and Chiou [12] explored the possibility of extending the braided multi-path routing method proposed by Servetto and Barrenechea [13] to the case of more general random geometric graphs. The Barrenechea et al. scheme is based on constrained random walks and achieves almost stateless multi-path routing on a grid network. The works presented in [14, 15] revisit multipath routing to extend the Dynamic Source Routing (DSR) and Ad hoc On-demand Distance Vector (AODV) routing protocols to improve the energy efficiency of ad hoc networks using frequency of route discovery reduction. Using a retransmission probability function to reduce redundant copies of the same event data, Directed transmission [16] is proposed as one of the probabilistic routing techniques built around the flooding mechanism. This mechanism uses the hop distance to the destination and the number of steps that the data packets have traveled as routing parameters. It is also based on a retransmission control mechanism to avoid intensive usage of the shortest path. Assuming sources transmitting data packets at a constant rate, [17] proposes a multipath routing scheme formulated as a linear programming problem with the objective of maximizing the time until the first sensor node runs out of energy. The work presented in [18] uses a multipath routing algorithm where the routing process is formulated as a constrained optimization problem using deterministic network calculus. Reference [19] highlights the issue of sensor coverage as a major challenge in wireless sensor network through the investigation of two algorithms that address the energy efficient communication in wireless sensor network using multipath routing while preserving coverage. They also propose a metric referred to as Standard Deviation of Source Partition times to measure coverage and show that their proposals outperform previously proposed algorithms proposed in [20] in terms of network coverage and first-source partition time without compromising on other performance metrics.

1.2. Contributions and Outline. Taking into account the unpredictability of network topology, Huang and Fang [21] proposed a braided multi-path routing scheme that delivers packets to the sink on time and at desired reliability with the objective of trying to minimize energy consumption. This scheme referred to as Multi-Constrained Multi-Path routing (MCMP) addresses the issue of multi-constrained QoS in wireless sensor networks by mapping a path-based model into a probabilistic routing scheme. Using the work done in [21] as benchmark, we proposed in [22] the Energy Constrained Multipath (ECMP) Routing scheme which fine-tunes the MCMP model to achieve better energy performance.

This paper revisits the problem of Quality of Service (QoS) provisioning to (1) assess the relevance of using multipath routing to improve the reliability and packet delivery in wireless sensor networks while maintaining lower power consumption levels and (2) proposing an implementation model supporting QoS in WSNs. The main contributions of this work are twofold.

WSN QoS Modelling. Firstly, building upon the works done in [21, 22], we formulate the problem of QoS routing in WSNs as an energy-aware traffic engineering model relying on delay, reliability and energy constraints to route the information collected from sources to the sink of a WSN. We also propose its algorithmic solution under the ECMP umbrella. Our work reveals through an illustrative example the relevance of integrating energy-awareness in the routing process and adds to the MCMP model a new constraint which translates into an efficient path set selection. Using extensive simulation, we demonstrate the robustness of our model and expand the initial work done in [22] on several performance parameters. These include the assessment of the tradeoff between delay and reliability constraints and the impact of the sensing intensity on the network performance.

WSN QoS Implementation. Multipath routing has been widely studied for wireless ad hoc networks. However, it is widely known that multipath routing solutions proposed for ad hoc network do not apply to sensor networks since while the former can be implemented with global identity (ID), wireless sensor networks lack global ID. Furthermore, the complexity of QoS models proposed for wireless sensor networks may become a limiting factor for the implementation of these solutions in real-world sensor network platforms. Building upon the breadth-first routing nature of the ECMP solution, we propose a simple and easy to implement packet forwarding protocol solution and discuss its implementation in modern WSN platforms. The proposed traffic engineering model is, to the best of our knowledge, a first step towards QoS routing implementation in real world testbed platforms.

2. The Proposed Traffic Engineering Model

In a wireless sensor network, a path p is a series system of links while a path set $\mathcal{P}$ is represented by a parallel system of paths which can split the traffic offered to a source and carry the information concurrently to the destination in order to achieve load balancing and rapid delivery of the information. In a wireless sensor network, both single paths and path sets are associated with performance parameters such as delay, energy consumption, and reliability which define the quality of service (QoS) received by the information carried by a path or a path set.

2.1. Path Delay, Energy, and Reliability

Path Delay. The path delay, that is, the delay between the node s_1 and s_ϵ is given by the sum of link delays:

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

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

Path Energy. 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}. It is defined by

$$\omega(s_i, s_{i+1}) = f_{s_i \to s_{i+1}} \cdot \omega_i(s_i, s_{i+1}), \tag{3}$$

where $f_{s_i \to s_{i+1}}$ denotes the data rate on the link $(s_i, s_{i+1}) \in \mathcal{L}$ and $\omega_i(s_i, s_{i+1})$ is the power required for a node s_i to receive a bit and then transmit it to the node s_{i+1} as proposed in [2]. It is expressed by

$$\omega_i(s_i, s_{i+1}) = \alpha_1 + \alpha_2 ||x_{s_i} - x_{s_{i+1}}||^n, \tag{4}$$

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, $\alpha_1 = 180\, nJ/\text{bit}$ and $\alpha_2 = 10\, pJ/\text{bit/m}^2$ for the path loss exponent experienced by a radio transmission $n = 2$ or $\alpha_2 = 0.001 pJ/\text{bit/m}^4$ 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 $s_{i+1}, i = 1, \ldots, \epsilon - 1$.

Path Reliability. Under the assumption that the links of a path are independent, the path reliability $\mathcal{R}(p)$ is defined 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 $(s_i, s_{i+1}) \in \mathcal{L}$.

2.2. Path Set Delay, Energy, and Reliability

Path Set Delay. The delay experienced by a data source f routed over the path set $\mathcal{P} = \{p_1, \dots, p_M\}$ is given by

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

where $\mathcal{D}(p)$ is given by (1). Note that as expressed above, the delay expresses the play-back delay, defining the delay before all the packets of the data source carried over parallel paths reach the destination.

Path Set Energy. The energy consumed by a data source f routed over the path set $\mathcal{P} = \{p_1, \dots, p_M\}$ is given by

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

where $\mathcal{W}(p)$ is expressed by (2).

Path Set Reliability. From [23], the reliability of the data source routed over $\mathcal{P}$ is given by

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

where $\mathcal{R}(p)$ is the path reliability defined by (5).

2.3. Multi-Path Routing Advantage

Multipath Reliability Advantage. As defined by (8), the reliability expression reveals the advantage related to multipath routing by showing the following.

(i) As $0 < 1 - \mathcal{R}(p) < 1$, the product $\prod_{i=1}^{n-1} R(s_i, s_{i+1})$ is reduced with the increase of the path set multiplicity (the number of paths carrying the information). It thus increases the path set reliability.

(ii) On the other hand, the expression of the path reliability reveals that the reliability of the links can increase the path reliability when high or reduce the path reliability when low.

(iii) Therefore, the reliability of a path set carrying information on a source-destination pair increases with the reliability of the links composing the associated paths and the path set multiplicity.

We define the relative reliability gain resulting from using multipath routing by

$$\mathfrak{R}_{\text{gain}} = \frac{\mathfrak{R}(\mathcal{P})}{\mathcal{R}(p)} = \frac{1 - \prod_{p \in \mathcal{P}} (1 - \mathcal{R}(p))}{\mathcal{R}(p)}. \tag{9}$$

Multipath Delay Advantage. Routing traffic over parallel paths presents the advantage of moving the information faster than when routed using a single path. We define the relative playback delay gain resulting from multipath routing by

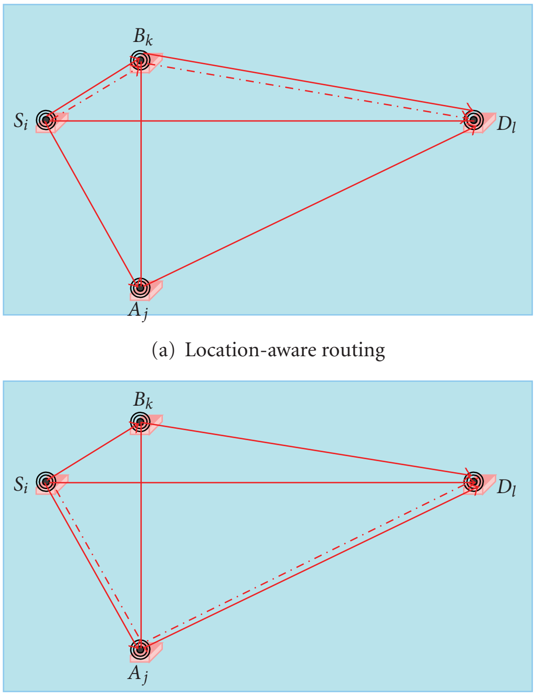
$$\mathfrak{D}_{\text{gain}} = \frac{\sum_{p \in \mathcal{P}} \mathcal{D}(p) - \max_{p \in \mathcal{P}} \mathcal{D}(p)}{\max_{p \in \mathcal{P}} \mathcal{D}(p)}. \tag{10}$$

As $(\sum_{p \in \mathcal{P}} \mathcal{D}(p) > \max_{p \in \mathcal{P}} \mathcal{D}(p))$, (10) reveals a gain which increases with the reduction of the play-back delay. Note however that while multipath routing may result in playback delay gain, increasing the path multiplicity can increase the average delay of the network as expressed by

$$\mathfrak{D}_{\text{avgr}} = \frac{\sum_{p \in \mathcal{P}} \mathcal{D}(p)}{\left| \sum_{p \in \mathcal{P}} \mathcal{D}(p) \right|}. \tag{11}$$

Multipath Power Consumption. While resulting in reliability and delay gains, multipath routing may increase power consumption by allowing many receptions and transmissions on many several paths. As expressed by (7), the energy consumed in a multipath setting is the sum of the energy consumed by the paths. It thus increases with the path multiplicity and the energy consumed on the paths. When deployed, multipath routing should therefore be carefully controlled to avoid high path multiplicity resulting in higher consumption. While sleeping and wake-up mechanisms are widely recognized as powerful mechanisms allowing high energy savings in wireless sensor networks, their deployment in multi-path settings is irrelevant in order to avoid the routing instability which might result from some packets of the same flow arriving later than the others because the path used by these packets was in sleeping mode while the other packets were routed by paths which were awake.

2.4. The Energy Constrained Routing Paradigm. Current generation WSN technology allows energy-aware routing by allowing sensor nodes to exchange reachability information such as the geospatial information related to the position of the neighbors using GPS. Building upon this finding, we proposed in [22] a location-aware multipath scheme referred to as **ECMP** that accounts for geospatial energy consumption by minimizing the distance between neighbors when selecting a forwarding link. As illustratated by the four nodes WSN of Figure 2(a), when choosing 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 the set $\mathbf{N}[\imath]$ of the neighbors of $\imath$, the ECMP would prefer the closest neighbor k assuming that the two candidates $\jmath$ and k satisfy the QoS requirement for data source. This result form a combination of (1) Pythagoras' theorem which reveals that the distance between node $\imath$ and node $\jmath$ is longer than that between $\imath$ and k, and (2) the formula in (4) showing that as a function of the euclidean distance, the energy transmission between $\imath$ and $\jmath$ is higher than the energy transmission between $\imath$ and k. The link $(\imath,k)$ is thus preferred by the ECMP algorithm since it leads to the lower energy consumption. In contrast to the ECMP model, the MMCP algorithm might select the link $(\imath,\jmath)$ leading to the situation depicted by Figure 2(b) as it implements random path set selection at node $\imath$.



(a) Location-aware routing

(b) Myopic multipath routing

Figure 2: Energy-aware paradigm.

As proposed in [22], the ECMP model builds its forwarding links preferentially on the least energy consuming paths by ensuring that data is transmitted by a node to its closest neighbor. For each node $\imath$, the ECMP scheme was designed to find the subset $\mathbf{N}_0 \subseteq \mathbf{N}[\imath]$ of neighbors of $\imath$ satisfying QoS requirement of data source and minimizing the total energy transmission by including in its set of constraints a geo-spatial constraint expressed by

$$\mathcal{F}(\imath,\jmath) \leq \mathcal{F}(\imath,\tilde{\jmath}) \mid \mathcal{E}_\imath(\jmath) \leq \mathcal{E}_\imath(\tilde{\jmath}), \tag{12}$$

where $\mathcal{F}(\imath,\jmath)$ is the forwarding preference between $\imath$ and $\jmath$ when routing the traffic coming from $\imath$ and $\mathcal{E}_\imath(\jmath)$ is the transmitting power from $\imath$ to $\jmath$. Note that for ease of implementation, the geo-spatial constraint (12) can be translated into a path set selection model defined by a forwarding queue $\mathcal{F}_q[\imath]$ defined by

$$\mathcal{F}_q[\imath] = \left\{ l_{\imath\jmath} : \forall \jmath \in \mathbf{N}[\imath];\ \left| \mathcal{E}_\imath(\jmath+1) - \mathcal{E}_\imath(\jmath) \right| < \delta \right\}, \tag{13}$$

where $\mathcal{F}_q[\imath]$ is implemented as a priority queue of neighbors of the links of the neighbor $\imath$ sorted in ascending order of their distances to $\imath$. We observe the following.

(i) These neigbhors belong to the set

$$\tilde{\mathbf{N}}[\imath] = \left\{ \jmath \mid l_{\imath\jmath} \in \mathcal{F}_q[\imath] \right\} \tag{14}$$

(ii) As expressed by (13), the forwarding queue $\mathcal{F}_q[\imath]$ discards higher energy consuming links by having successive links differ by a predefined energy threshold δ.

2.5. The Traffic Engineering Problem. 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. Huang and Fang [21] proposed a distributed link-based QoS routing model where a data source f located at a given location x_s sensed by the node s is routed with some QoS requirements expressed in term of delay D and reliability R.

The ECMP Problem. At each node $\imath$, find the subset $\mathbf{N}_0 \subseteq \mathbf{N}[\imath]$ of neighbors of node $\imath$ that solves the following problem:

$$\min \sum_{\jmath \in \tilde{\mathbf{N}}[\imath]} x_\jmath \tag{15}$$

subject to

$$\jmath \in \tilde{\mathbf{N}}[\imath] \mid l_{\imath\jmath} \in \mathcal{F}_q[\imath], \tag{16}$$

$$x_\jmath \left(\frac{\alpha}{1-\alpha} \left(\Delta^d_{\imath\jmath} \right)^2 + 2L^d_\imath d_{\mathrm{ij}} - d^2_{\imath\jmath} \right) \leq \left(L^d_\imath \right)^2, \quad \text{for } L^d_\imath > d_{\imath\jmath}, \tag{17}$$

$$\sum_{\jmath \in \mathbf{N}[\imath]} x_\jmath \log \left(\mathcal{Q} \left(\frac{R_{\imath\jmath} - r_{\imath\jmath}}{\Delta^r_{\imath\jmath}} \right) \right) \geq \log \beta, \tag{18}$$

$$\sum_{\jmath \in \mathbf{N}[\imath]} x_\jmath \log \left(1 - R_{\imath\jmath} \right) \leq \log(1 - L^r_\imath), \tag{19}$$

$$0 \leq R_{\imath\jmath} \leq r_{\imath\jmath}, \quad \forall \jmath \in \mathbf{N}[\imath], \tag{20}$$

$$x_\jmath = 0 \text{ or } 1, \quad \forall \jmath \in \mathbf{N}[\imath], \tag{21}$$

where α and β are, respectively, the probabilities of meeting the delay and reliability constraints; $R_{\imath\jmath}$ and $D_{\imath\jmath}$ are, respectively, the reliability and delay of the link $\ell_{\imath\jmath}$ while $r_{\imath\jmath}$ and $d_{\imath\jmath}$ are their related time averages. In this model. the reliability and delay are assumed to be random variable depending on time t omitted for simplicity sake and the links of the network are assumed to be independent of the delay and reliability. We have $L^d_\imath = (D - D_\imath)/h_\imath$ as the hop requirement at node $\imath$ with $D_\imath$ the actual delay experienced by a packet at node $\imath, h_\imath$ the hop count from node $\imath$ to the sink, and $L^r_\imath = \sqrt[h_\imath]{R_\imath}$ hop requirement for reliability at node $\imath$, and $R_\imath$ is the portion of reliability requirement assigned to the path through node $\imath$ decided by the upstream node of $\imath$. The $\mathcal{Q}$-function in (18) is defined by

$$\mathcal{Q}(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp\left(-\frac{1}{2} t^2 \right) dt, \tag{22}$$

and $\Delta^d_{\imath\jmath}$ and $\Delta^r_{\imath\jmath}$ are, respectively, standard deviation of $D_{\imath\jmath}$ and $R_{\imath\jmath}$ computed adaptively using RTT estimation for timer management in TCP, that is, the current $\Delta^d_{\imath\jmath}(t)$ and $\Delta^r_{\imath\jmath}(t)$ are found based on the previous values of $d_{\imath\jmath}(t-1), r_{\imath\jmath}(t-1), \Delta^d_{\imath\jmath}(t-1)$, and $\Delta^r_{\imath\jmath}(t-1)$, and the current mean $d_{\imath\jmath}$ of $D_{\imath\jmath}$ and $r_{\imath\jmath}$ of $R_{\imath\jmath}$ as follows [24]:

$$\begin{aligned} \Delta^d_{\imath\jmath}(t) &= (1-\rho)\Delta^d_{\imath\jmath}(t-1) + \rho \left| d_{\mathrm{ij}}(t) - d_{\imath\jmath}(t-1) \right|, \\ \Delta^r_{\imath\jmath}(t) &= (1-\gamma)\Delta^r_{\imath\jmath}(t-1) + \gamma \left| r_{\imath\jmath}(t) - r_{\imath\jmath}(t-1) \right|, \end{aligned} \tag{23}$$

with tunable forgetting parameters ρ and γ for smoothing the variations of $d_{ıȷ}$ and $r_{ıȷ}$ in time. Note the following.

(i) While (16) expresses the energy-awareness constraint, (17) is the delay constraint and (18), (19) and (20) express the reliability constraints. Equation (21) is an expression of the zero-one optimization.

(ii) As formulated in this section, the QoS routing model borrows from [21] the delay and reliability constraints but adds the energy-awareness requirement to the set of constraints.

As proposed in [21], at each node $ı$ of a network, the *MCMP problem* aims to find the subset $\mathbf{N}_0 \subseteq \mathbf{N}[ı]$ of neighbors of node $ı$ that solves the following zero-one linear program:

$$\min \sum_{ȷ \in \mathbf{N}[ı]} x_ȷ, \tag{24}$$

subject to the constraints (17), (18), (19), (20), and (21).

3. The Algorithmic and Protocol Solution

Routing consists of moving information across an internetwork from a source to a destination using a multi-hop process where at least one intermediate node is used as transit along the way to the destination. The topic of routing has been covered in computer science literature for more than two decades, but for WSN, routing is just emerging as a main concern because of the need for the deployment of relatively large-scale wireless sensor networks. There are two basic activities involved in the routing process: optimal routing paths determination using routing algorithms and packets transportation using the optimal routing paths found through the paths determination process. Routing protocols are used to implement these two processes by having the paths determination using routing algorithms and packets transportation implemented using a packet forwarding algorithm. In both fixed and wireless networks, the paths determination lead to the creation of routing tables and the packet forwarding to the creation of forwarding tables, both used to determine the next hop that packets coming from a given source to a destination will follow. While [21] proposed only an algorithmic solution to the paths selection process, our work takes the QoS problem some steps ahead by both looking at the algorithmic path finding solution and proposing an implementation model revealing how to build the sensor nodes forwarding tables.

3.1. The Algorithmic Solution. The ECMP and MCMP problems are deterministic linear zero-one problems which can be solved using several methods proposed by the literature such as in [25, 26]. In both problems, the number of constraints is $2|\mathbf{N}[ı]| + 2$, and the number of the decision variables is $|\mathbf{N}[ı]|$ which is the size of $\mathbf{N}[ı]$. Thus, the problem size is relatively small and might be proportional to the node density. Building upon the zero-one framework proposed in [25], an implementation of the two local routing problems MCMP and ECMP may be solved using the Bala's Algorithm but with different path set selection strategies: (1) a random selection for the MCMP algorithm where the next hop to the sink is selected arbitrarily among the neigbhors of a node and (2) energy-efficient selection where a set of well-chosen closest neighbors in terms of euclidean distance is used by a node as next hops to the sink. This path selection algorithm has been presented in Section 2.4, and the efficiency of the two algorithms is evaluated in Section 4.

Table 1: The ECMP key features.

(1)	Use of a simple ad hoc routing protocol which creates a breadth-first spanning tree rooted at the sink through recursive broadcasting of routing update beacon messages and recording of parents.
(2)	The beacon messages are (1) broadcasted at periodic intervals called epochs, (2) propagated progressively to neighbors, and (3) received by a few nodes which are in the vicinity of the source of the beacon message.
(3)	The transmission of the beacon is build around a source marking, progressive propagation to neighbors and rebroadcasting progress which sets up a breadth-first spanning tree rooted at the sink.
(4)	The energy-aware routing is integrated into the process by selecting a subset of neigbhors which is sorted by distance and includes only a minimum number of close neighbors. This subset excludes neighbors that largely increase the path set power consumption.

3.2. The Implementation Model. The ECMP algorithm uses a breadth-first model which can be implemented using a simplified table-driven approach based on a many-to-one data-centric routing paradigm. The implementation model is based on the key features described in Table 1.

The ECM forwarding protocol follows the main steps described in Algorithm 1.

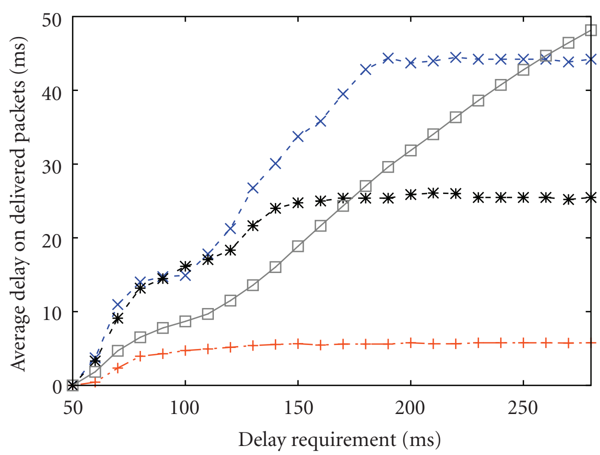
Note that current generation sensor nodes may be broadly classified into two types: some being endowed with a high hardware processing capabilities and a rich set of software instructions allowing them to compute complex functions such as those involved in the constraints used in this paper while other have poor hardware processing capabilities with only a set of software instructions allowing to compute only an elementary set of functions. While our implementation model fits well for the former, the set of steps proposed above may be used in a more elementary processing context assuming some approximations to the functions used in the constraints.

4. Performance Evaluation

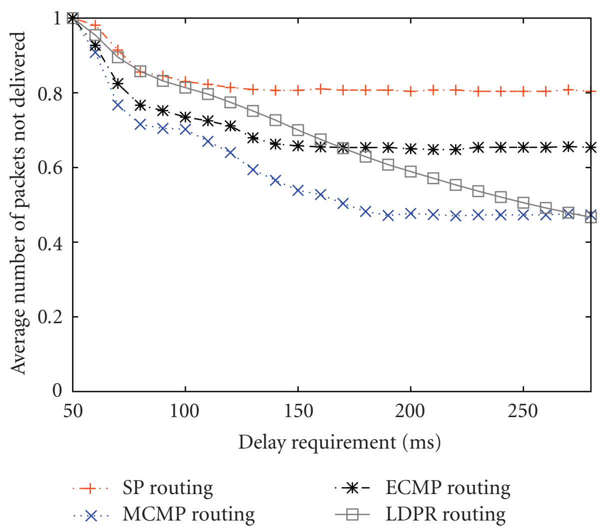
In this section, we evaluate the efficiency of the ECMP scheme by comparing its performance to the performance of baseline single path routing, MCMP and LDPR algorithms and the impact of different routing parameters such as the

(1) For each epoch, the sink of a WSN broadcasts a route update beacon with itself as the transmitting node and a hop count set to 0;
(2) All the nodes hearing the beacon from either the sink or another node mark the source of the beacon as probable parent and build their forwarding tables as described below
(3) Build the Forwarding queue $\mathcal{F}_q[\imath]$;
(4) *forwarding* $= \phi$;
(5) $L_\imath^d = (D - D_\imath)/h_\imath$; $L_\imath^r = \sqrt[h_\imath]{\mathrm{R}_\imath}$;
(6) **While** $|\mathcal{F}_q[\imath]| > 0$ **do**
(7) Update $\Delta_{\imath\jmath}^d(t)$ and $\Delta_{\imath\jmath}^r(t)$.
(8) **if** inequality (17) hold for $d_{\imath\jmath}$ and $\Delta_{\imath\jmath}^d(t)$) **then**
(9) *add link $\ell_{\imath\jmath}$ to *forwarding* and confirm $\jmath$ as parent of $\imath$;
(10) *Dequeue($\mathcal{F}_q[\imath]$);
(11) **end if**
(12) **endo while**
(13) Check *forwarding* for reliability constraints (18) and (19).
(14) Node forwards the beacon message with its address as source of the beacon, increment the hop count, adjust $r_{\imath\jmath}$, $d_{\imath\jmath}$ and broadcast the update beacon.
(15) Recursively, nodes will mark as their probable parent the node from which they hear the beacon from and broadcast the beacon.

Algorithm 1: The ECM forwarding protocol.

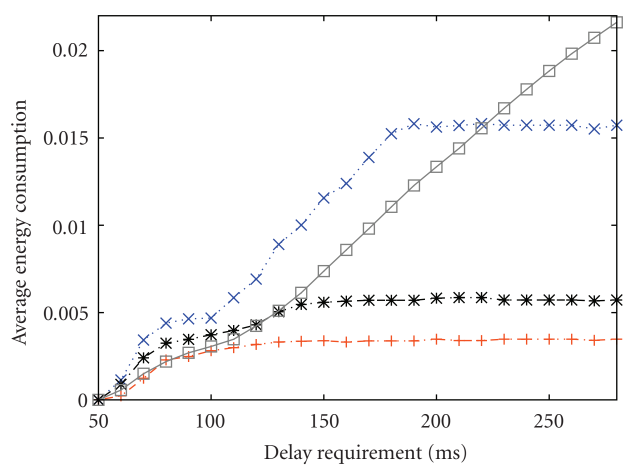


(a) Average packet delay

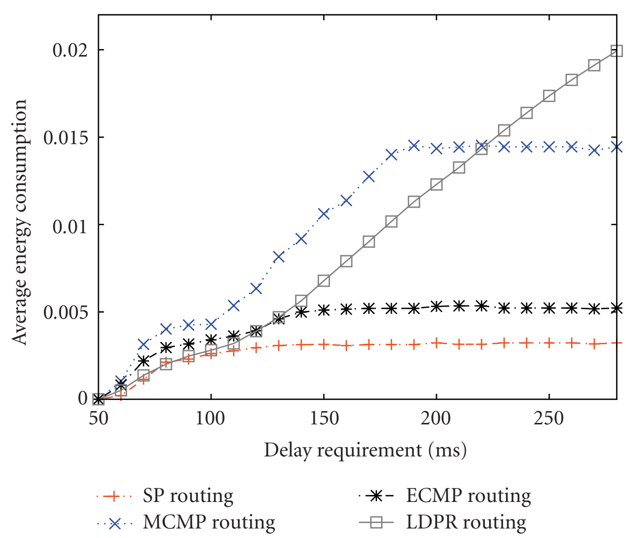


(b) Packet delivery ratios

Figure 3: Comparing delay and packet delivery.



(a) Average energy consumed ($n = 2$)



(b) Average energy consumed ($n = 4$)

Figure 4: Comparing the energy consumption.

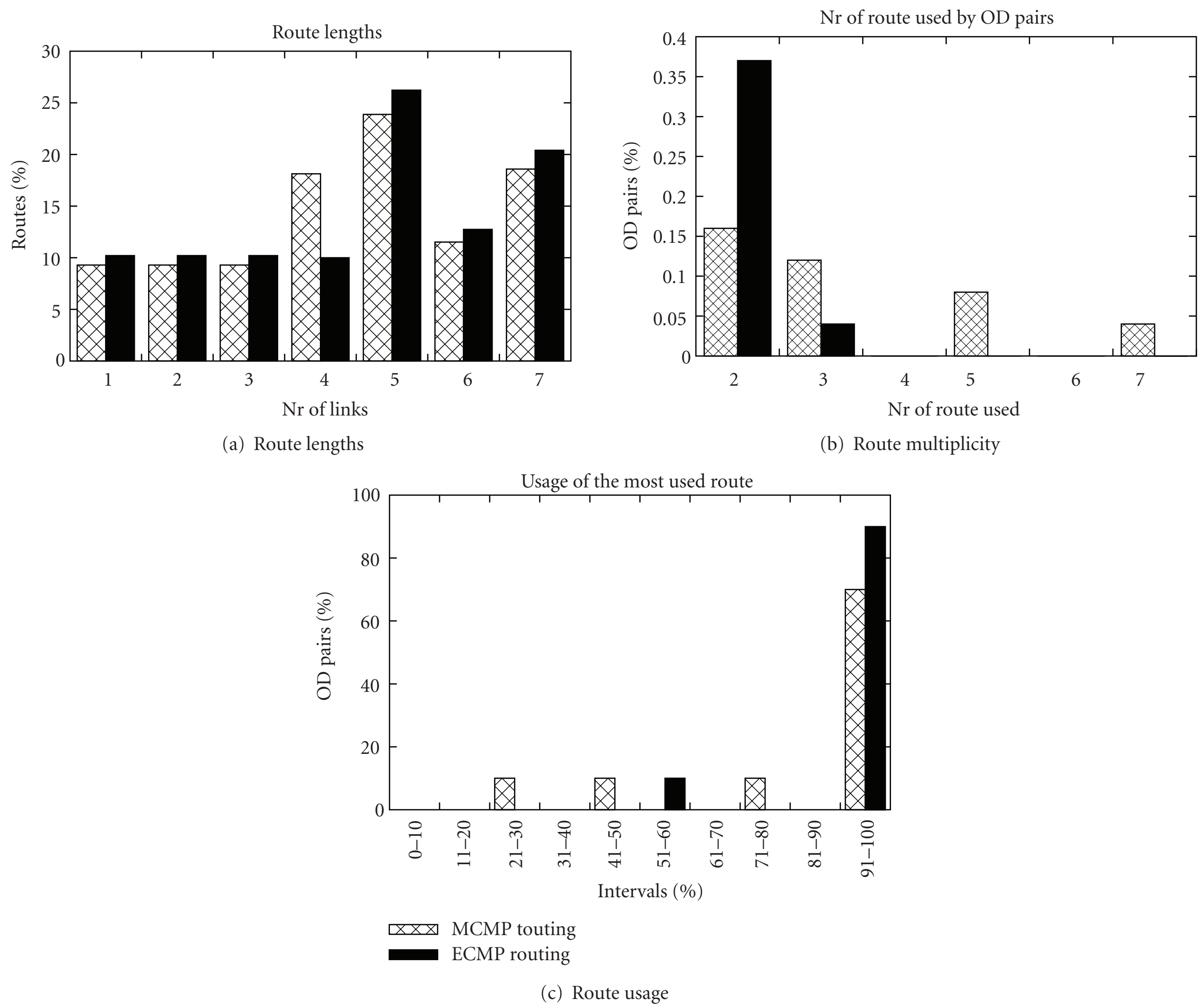


Figure 5: Quality of path: path length, multiplicity, and usage.

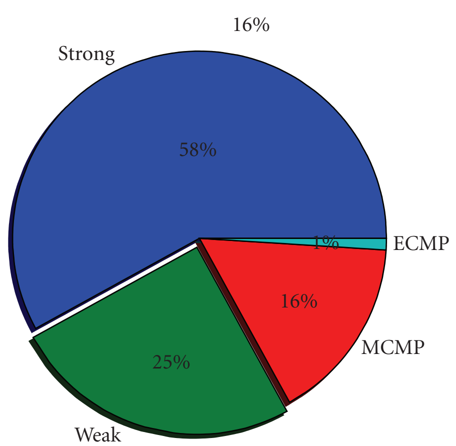


Figure 6: Quality of path: path correspondence.

sensing intensity (number of sensor nodes generating data) and the probability of meeting the reliability constraints (β) on the efficiency of the ECMP model. LDPR is a multipath routing algorithm that uses node disjoint paths. For some experiments, we assume a test network of 100 sensor nodes randomly deployed in a sensing field of 100 m × 100 m square area and the transmission range is 25 m. Among these sensor nodes, approximately 70% to 80% are chosen to generate data. We conducted other experiments using a 50-node test network with similar configuration parameters.

In our experiments, the link reliability and delay are random variables with the reliability uniformly distributed in the range $[0.9, 1]$ and the delay in $[1, 50]$ ms range. As considered, the delay includes the queuing time, transmission time, retransmission time and the propagation time. The delay requirements 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. The probability of meeting the delay and reliability constraints α and β is set to 95%. The size of a data packet is 150 bytes and is assumed to have an energy field that is updated during the packet transmission to calculate the total energy consumption in the network. We have applied different

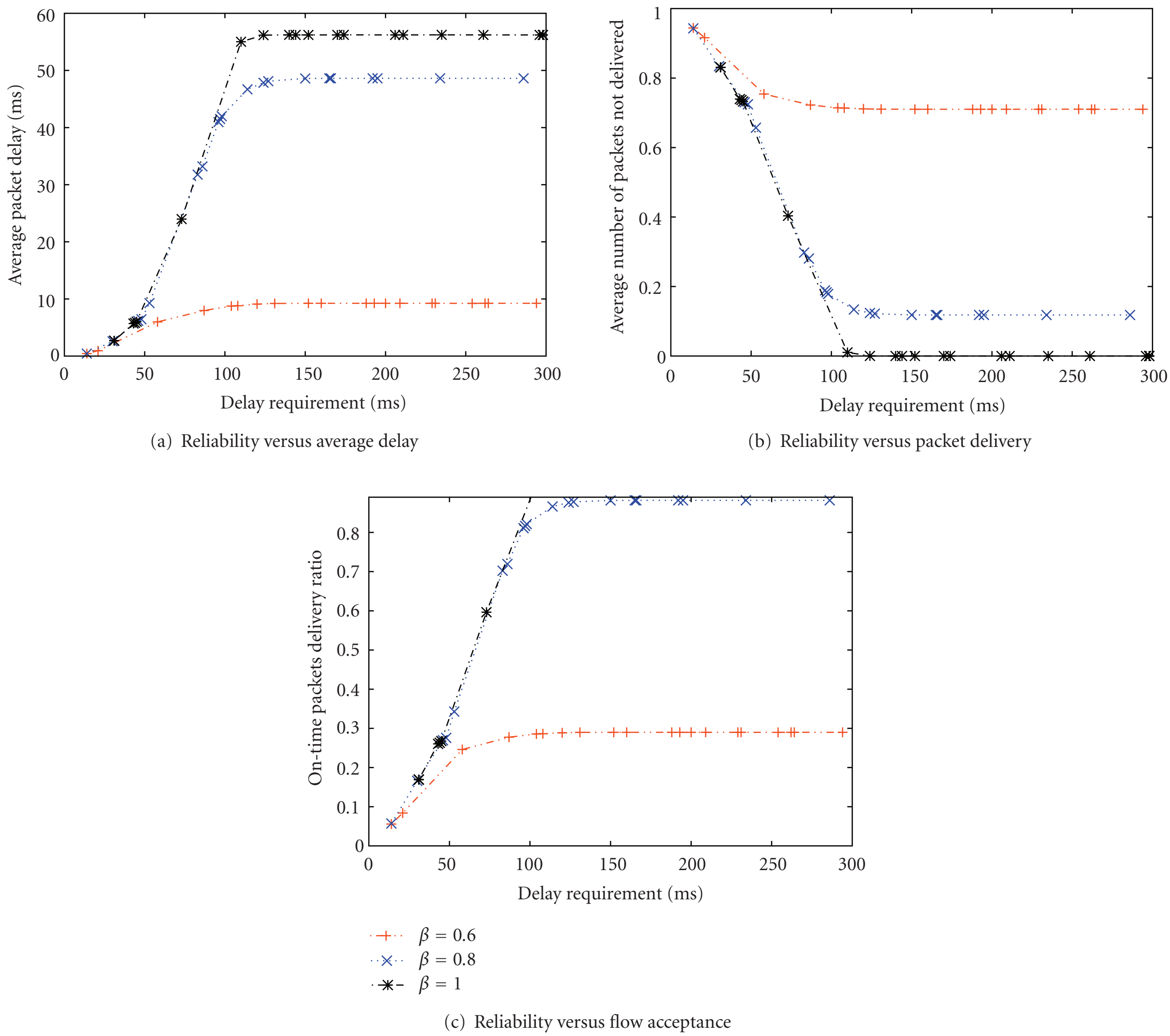


Figure 7: The impact of reliability on TE parameters.

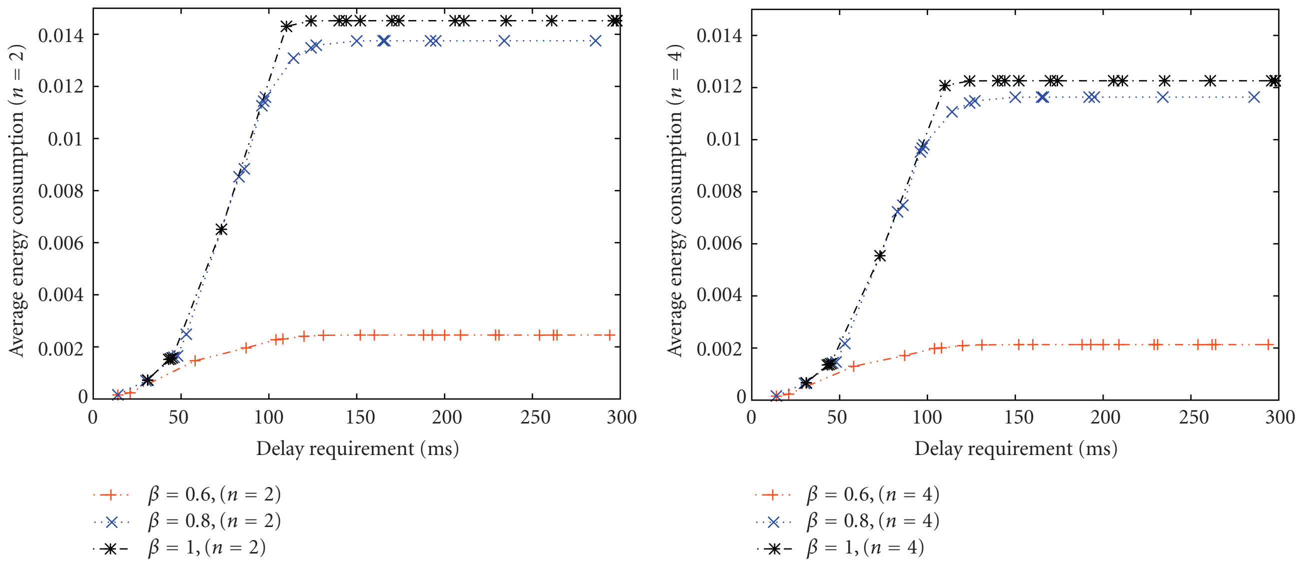
random seeds to generate different network configuration during the 10 runs. Each simulation lasted 900 sec where in the same run the four algorithms are simulated for comparison.

4.1. Experimental Results. The performance parameters considered in our experiments include the *average energy consumption*, the *packet delivery ratio*, the *average data delivery delay*, the *average energy consumption*, and the *quality of paths* used by the algorithms.

(i) *Average Energy Consumption.* As a certain number of nodes are selected to transmit results to the gateway, the network might consume energy differently depending on the network topology and the number of information transmitting nodes. The average energy consumed is an indication of the energy consumption in transmission and reception of all packets in the network. This metric reveals the efficiency of an approach with respect to the life time of a wireless sensor network.

(ii) *Packet Delivery Ratio.* The packet delivery ratio is one of the most important metrics in real-time applications which indicates the number of packets that could meet the 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.

(iii) *Average Data Delivery Delay.* The average data delivery delay is the end-to-end delay experienced by successfully received packets. In our case, we consider the play-back delay which is expressed by the maximum time taken by different packets of the same flow travelling on different parallel paths in a multipath setting.



(a) Reliability versus energy consumption ($n = 2$)

(b) Reliability versus energy consumption ($n = 4$)

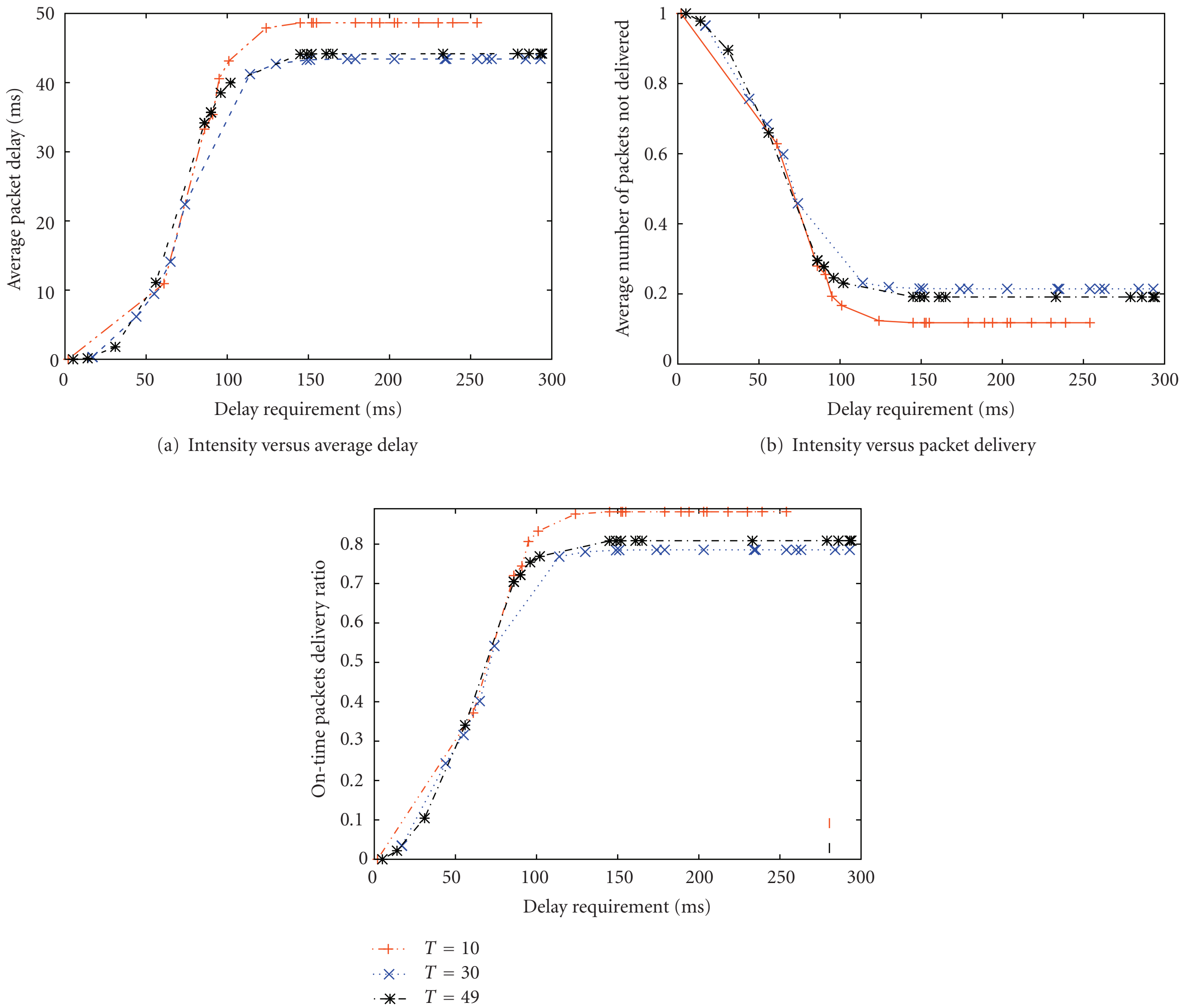
Figure 8: The impact of reliability on TE parameters.

(iv) *Quality of Paths.* The quality of paths used by MCMP and ECMP schemes indicates the path length (number of hops of paths used), path usage (frequency of reuse of the same paths), and path multiplicity (average number of paths used to send data to the base station). The value of these parameters provides an indication on the reliability and stability of the algorithms used.

4.2. Experiment 1*: Comparing the Four Routing Algorithms.* Using 100*nodes* with a sensing intensity of 80%, we conducted a first set of experiments to compare the performance of the four algorithms when looking at three performance parameters: average packet delay, packet delivery ratio, and average energy consumption for both $n = 2$ and $n = 4$. The results are depicted by Figure 3. As illustrated by Figure 3(a), while as expected the shortest path routing (SP) performs better than the other algorithms in terms of average delay, the ECMP algorithm outperforms MCMP on all delay requirements and LDPR under loose delay requirements. We note that the relative performance of the SP algorithm is balanced by its poor performance in terms of average number of undelivered packets revealed by Figure 3(b). Looking at the packet delivery, we find from Figure 3(b) that the MCMP algorithm performs better than the other algorithms since it routes its traffic over more paths as revealed by the path correspondance between ECMP and MCMP. When compared to the ECMP algorithm, this relative performance is in agreement by the quality of paths of both algorithms depicted by Figure 6 which reveal that the MCMP algorithm routes its traffic on more routes than ECMP. Figure 3(b) reveals that while performing better than LDPR under stringent delay constraints, ECMP performs worse under loose delay constraints. Shortest path routing delivers the least packets since it uses only one path to route its traffic.

Figures 4(a) and 4(b) reveal that ECMP outperforms the other algorithms in terms of energy consumption except the SP algorithm. This results from its capability to maintain the forwarding links on the least energy transmitting paths by selecting only a small set of closest neighbors to node. These energy patterns are in agreement with Figure 6 which show the percentage of paths which are identical to both algorithms (Strong correspondence), the number of paths where both algorithms differ by one hop (weak correspondence), and the percentage of paths used by ECMP only and those used by MCMP only. This figure reveals that the MCMP algorithm splits its traffic on more paths than the ECMP algorithm: while there is only 1.00% of routes used by the ECMP algorithm only, the MCMP algorithm has 16.00% more routes than ECMP. This reveals that, by using smaller path sets, the ECMP algorithm can achieve more energy savings compared to the MCMP scheme.

4.3. Experiment 2*: The Quality of Paths.* The results in Figure 5(a) reveal that in general the ECMP scheme uses more longer paths (in terms of number of hops) compared to the MCMP scheme. Thus, the paths used by ECMP scheme 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 scheme uses smaller path sets resulting in lower energy consumption. This justifies the results depicted by the Figure 4 on average energy revealing that the ECMP algorithm performs better than the other algorithms. Finally, the two schemes use approximately 99.6% single paths, and when these algorithms start using more than one path, the results depicted by Figure 5(b) reveal that the ECMP scheme uses smaller path sets compared to the MCMP scheme. Thus



(a) Intensity versus average delay

(b) Intensity versus packet delivery

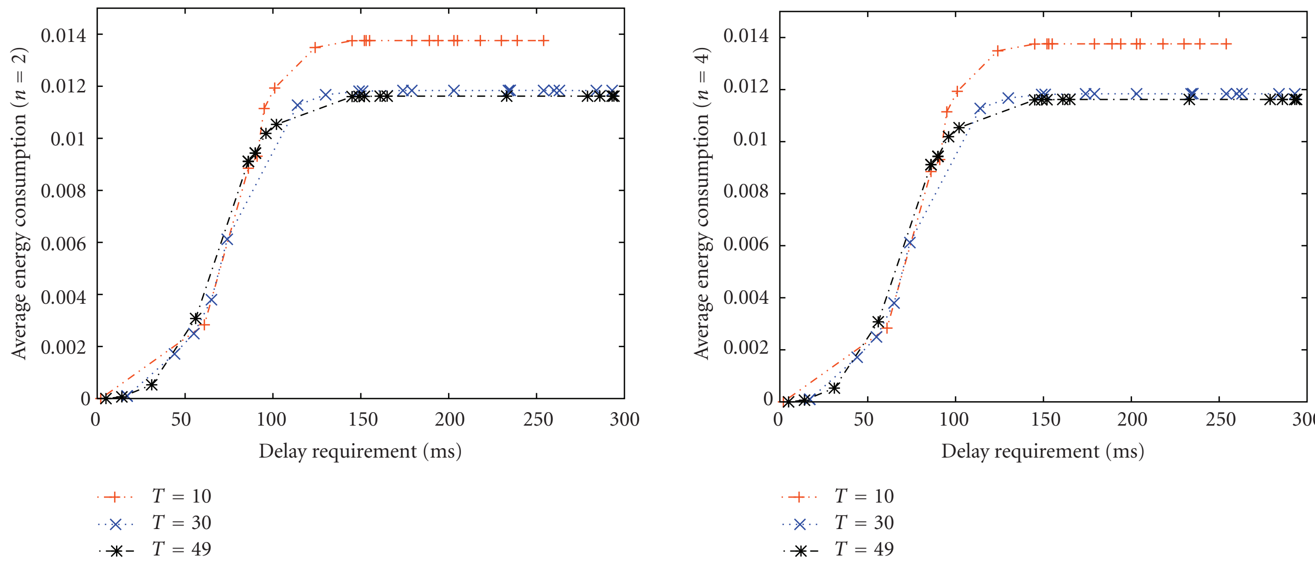
(c) Intensity versus flow acceptance

Figure 9: The impact of sensing intensity on TE parameters.

the MCMP scheme tends to consume more energy than the ECMP scheme. This is in agreement with the design of each of these schemes and justifies the results in Figures 4(a) and 4(b) concerning the network energy consumption. The results depicted by Figure 5(c) on the route usage reveal that the ECMP scheme uses its preferred paths more often than the MCMP scheme. This reveals the stability of the ECMP scheme compared to the MCMP scheme.

4.4. Experiment 3: The Impact of Reliability on ECMP. Using a 50-*node* test network, we conducted another set of experiments to evaluate the impact of the probability of meeting the reliability constraints on the ECMP algorithm. The results depicted by Figure 7(a) show that the average delay increases with the probability of meeting the reliability constraints. This reveals that reliability and delay may become two competing constraints in a QoS routing model where both constraints are at stake increasing the probability of meeting the reliability constraints worsens the average delay. Figure 7(b) reveals a different performance pattern where the number of undelivered packets decreases with the increase of probability β. This is in agreement with the reliability as defined in this paper since higher reliability is expressed by higher path multiplicity providing the potential to carry much more traffic. Figure 7(c) follows the same positive trend as the packet delivery by showing that higher reliability results in a higher ratio of packets delivered on time.

Both Figures 8(a) and 8(b) reveal the same performance pattern where more energy is consumed at higher reliability. This is also in agreement with the reliability as expressed by this paper as the number of paths sharing the packets routed by the network. Higher path multiplicity will lead to higher energy consumption.



(a) Intensity versus energy consumption ($n = 2$)

(b) Intensity versus energy consumption ($n = 4$)

Figure 10: The impact of sensing intensity on energy.

4.5. Experiment 4*: The Impact of Sensing Intensity on ECMP.* We conducted a fourth set of experiments to evaluate the impact of sensing intensity on the performance of the ECMP algorithm. These experiments were conducted using a 50-*node* test node where the number of data generating nodes (sensing intensity) were varied. The results presented in Figure 9 reveal that while ECMP performs higher average packet delivery under high sensing intensity as depicted by Figure 9(a), the performance achieved by ECMP in terms of packet delivery and on-time packet delivery is better under low sensing intensity. The results presented in Figure 10 also reveal that ECMP achieve lower energy consumption under lower sensing intensity.

5. Conclusion and Future Work

This paper proposed and evaluated the performance of an energy-aware traffic engineering algorithm for wireless sensor networks referred to as Energy Constrained Multipath (ECMP). In contrast to a previously proposed benchmark in [21] referred to as MCMP, the ECMP algorithm selects its forwarding links based on a location-aware model that uses preferably the closest neighbors to reduce transmission power with the expectation of routing packets on the least energy consuming paths. Using simulation, we evaluated the efficiency of both algorithms compared to single path routing and a link disjoint path routing in terms of several performance parameters. The results revealed the efficiency of the ECMP algorithm and its relevance as an efficient algorithm to be used in wireless sensor networking settings. As modelled in this paper, the ECMP algorithm minimizes energy consumption through closest neighbour selection to reduce the transmission power. We also proposed the first steps for the implementation of the model in terms of a simple packet forwarding protocol which is built upon the breadth-first nature of the ECMP model. It is expected that further energy improvements may be achieved by the ECMP by including into the ECMP picture the remaining energy of receiver in order to energy balance the wireless sensor network. The design and implementation of such an energy balancing algorithm/protocol has been reserved for future research work. As traditionally deployed, sensor nodes are energy- and range-limited devices sharing a single communication channel to achieve energy saving and scalability. Multichannel wireless sensor networks another option that has been recently investigated by researchers such as in [27]. Multi-path routing in wireless sensor networks may lead to different issues and provide different results depending on whether multi-channel or single-channel deployment has been considered. The evaluation of the QoS provided by our model by considering the issue of contention in single channel routing and comparing single- and multi-channel deployments is another avenue for future work.

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