



ELSEVIER

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Quality-of-service differentiation in single-path and multi-path routing for wireless sensor network-based smart grid applications



Dilan Sahin^a, Vehbi Cagri Gungor^{a,b}, Taskin Kocak^a, Gurkan Tuna^{c,*}

^a Department of Computer Engineering, Bahcesehir University, Istanbul, Turkey

^b Department of Computer Engineering, Abdullah Gul University, Kayseri, Turkey

^c Department of Computer Programming, Trakya University, Edirne, Turkey

ARTICLE INFO

Article history:

Received 28 September 2013

Received in revised form 19 April 2014

Accepted 13 May 2014

Available online 20 May 2014

Keywords:

Wireless sensor networks

Smart grid

QoS differentiation

Single-path routing

Multi-path routing

ABSTRACT

Electrical grid is one of the most important infrastructure of the modern nation. However, power grid has been aged over 100 years and prone to major failures. The imbalance between power demand and supply, the equipment failures and the lack of comprehensive monitoring and control capabilities are other important signs to take incremental steps for switching to a smarter power grid with effective communication, automation and monitoring skills. This new concept is named as *smart grid*, which is a modern power grid system with advanced communication, monitoring, sensing and control capabilities. Wireless sensor network (WSN) concept places an important role in this modernization process of the power grid with its efficient and low-cost deployment characteristics. However, harsh and complex smart grid environmental conditions, dynamic topology changes, connectivity problems, interference and fading may pose some challenges for the communication performance of WSN technology. For this objective, in this paper, the use of multi-path and single-path QoS-aware routing algorithms under harsh SG environmental conditions is investigated in order to evaluate their service differentiation capabilities in reliability and timeliness domains. In this regard, this study is an important step towards developing novel routing protocols specifically designed for smart grid environments.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

Recently, the increasingly growing population and diminishing power resources have threatened the electric utilities in generating and distributing the necessary electricity and forced them finding new ways to generate the electricity with renewable energy resources. The imbalance between power demand and supply is one of the problems of the electric utilities, since generating electricity more than the actual necessity may result in huge

electricity lost due to the non-existence of the advanced electricity storage options. In addition to the imbalance between power demand and supply, the equipment failures and the lack of comprehensive monitoring and control capabilities are other important signs to take incremental steps for switching to a smarter power grid with effective communication, automation and monitoring skills. This new concept is conceived as *smart grid* (SG), which is a modern power grid system with advanced communication, monitoring, sensing and control capabilities.

In general, SG is a distributed system that many of its components are spread over a wide range of area. Thus, a reliable communication and coordination between distributed components of such systems is required for the safety

* Corresponding author. Tel.: +90 2842240283.

E-mail address: gurkantuna@trakya.edu.tr (G. Tuna).

and reliability of the power delivery system. To this end, effective management and reliable operation of SGs can be achieved with the installation of wireless sensor nodes on the critical power grid equipments. In these systems, collected sensor data can be used to diagnose arising problems quickly, and hence, system breakdowns due to the cascading effect initiated by a single fault in the power grids can be prevented.

Recently, wireless sensor networks (WSNs) have been used in different SG applications, including power fraud detection, wireless automatic metering, overhead transmission line monitoring, load control, fault diagnostics, demand response, outage detection, and distribution automation. All these applications have different quality-of-service (QoS) requirements in terms of reliability, latency, bandwidth, as listed in Table 1. On the other hand, field tests show that SG systems have also harsh and complex environmental conditions, dynamic topology changes, connectivity problems, interference and fading [1,2]. All these effects cause great challenges in the reliability of WSN communications in SG applications. Furthermore, most WSN-based SG applications include a large number of wireless sensor nodes spread over the deployment field. In these applications, the lack of predetermined network infrastructure requires the WSNs to establish multi-hop connections and maintain network connectivity autonomously. Hence, reliable multi-hop routing and QoS differentiation have become an essential issue to design WSN-based SG applications.

Although there has been an increasing interest in SG applications based on WSNs, wireless multi-hop routing in different SG environments still remains unexplored. To the best of our knowledge, there exists no work on performance evaluations of reliable multi-hop routing protocols specifically for harsh SG spectrum environments. To address this need, in this paper, the performance of QoS-aware single-path and multi-path multi-hop routing protocols is investigated for different SG environments. Specifically, we evaluate SPEED and MMSPEED routing protocols in terms of latency, reliability, and overhead to better understand their advantages and disadvantages in different SG spectrum environments. In addition, we also present potential applications of WSNs in SG along with the related research challenges. Consequently, the main contributions of this study can be summarized as follows:

- The research challenges of WSN-based SG applications have been presented.

- A routing approach has been presented to handle the challenges and communication requirements of SG applications.
- Multi-path and single-path QoS-aware routing algorithms which aim service differentiation in reliability and timeliness domains have been explored. The performance evaluations of these routing algorithms, namely SPEED and MMSPEED, under harsh SG environmental conditions have been studied to better develop future routing protocols specifically for SG environments.
- The performance evaluations in this paper are based on the previous work of Gungor et al. [2] which includes field tests using IEEE 802.15.4 compliant wireless sensor nodes deployed in different SG environments including a 500 kV substation, an industrial power control room, and an underground network transformers vault [2]. Log-normal shadowing channel model has been implemented in J-SIM simulator [4] to realistically model the wireless channel in different SG environments.

The remainder of the paper is organized as follows. Section 2 briefly describes various WSN-based SG applications. In Section 3, research challenges for WSN-based SG applications are presented. Related work on reliability-aware and link-quality-aware routing protocols for WSNs is summarized in Section 4. Proposed routing approach and overview of simulation results are presented in Section 5 and in Section 6, respectively. Finally, the paper is concluded in Section 7.

2. WSN-based smart grid applications

The existing power grid has been causing critical problems to the humanity and to the electric utilities due to the structural characteristics of the aging electricity infrastructure. The equipment failures, the lack of comprehensive communication infrastructure and monitoring abilities, and the continues uncertainty to be able to provide demand-response balance are the important signs to take incremental steps for switching to a smarter grid with effective communication, automation and monitoring skills. Hence, WSN-based SG applications are the proper choice to be used in a wide variety of SG environments to provide efficient, low-cost, flexible, expandable communications network for advanced monitoring, analysis and data transmission purposes.

WSN-based SG applications can be grouped into three main categories, e.g., generation side, transmission and distribution side, and consumer side. The consumer side WSN-based SG applications have a focus on home energy management and demands response, while generation side and transmission and distribution side applications have narrowed down their focus on monitoring, controlling the specific equipments of SG. From generation to consumer side, there are tremendous number of WSN-based SG applications, e.g., smart metering, remote power system monitoring and control, electricity fraud detection, fault diagnostics, demand response and dynamic pricing, load control and energy management, and equipment fault

Table 1
Smart grid application requirements [3].

Application	Latency requirements	Reliability requirements (%)
Advanced metering infrastructure	2000 ms	99.0–99.99
Distributed generation	300–2000 ms	99.0–99.99
Electric transportation	2 s to 5 min	99.0–99.99
Asset management	2000 ms	99.0
Demand response	2000 ms	99.0
Wide area situation awareness	20–200 ms	99.0–99.99

diagnostics, underground cable system monitoring, etc. However, the harsh SG environmental conditions pose great challenges which adversely affect the communication capabilities of WSN-based SG applications.

3. Research challenges for WSNs-based smart grid applications

WSN has been one of most exciting and attractive topics in recent years due to the low-cost, scalable, mobile, withstanding characteristics of sensor nodes and the availability of a variety of applications in the area of monitoring, control and sensing [5]. With the advances in miniaturization, WSN technology eases the integration of the electronic networks into everyday applications which have significant effect in increasing the quality of lives of human beings. Sensor nodes are battery-powered and thereby have limited resources which result in some limitations that affect the functionality and the life span of the sensor network. Hence, energy efficiency becomes one of the major concerns of WSN. Scalability, QoS, environmental conditions, unreliable wireless links, etc. are some of the other challenges of WSN-based SG applications. Here below, we briefly explain major research challenges for WSNs-based SG applications.

- *Environmental conditions:* The environmental conditions of electrical power systems may adversely affect the performance of the sensor nodes and decrease the wireless link quality. For instance, while solar radiation, rain, dirt and dust, humidity may be challenging factors on sensors functioning for outdoor environments, RF interference, heating and vibrations may challenge the performance of WSNs in indoor environments [6,7,2].
- *Quality of service requirements (QoS):* Providing QoS in WSN-based SG applications is a very challenging task since many of the applications have distinct QoS requirements in terms of reliability, latency and network throughput. For instance, real-time pricing and demand response are some of the mission critical applications that need strict reliable and communication delay requirements. End-to-end path discovery, path recovery in case of topology changes or resource reservation are some of the important requirements that should be met to provide reliable and secure communications. However, there exist some challenges, such as, dynamic topology changes, unreliability of wireless links and large scale nature of WSNs that make it impossible for sensor network applications to meet these requirements [8].
- *Resource limitations:* Sensor nodes have limited processing capabilities, since they are battery-powered. However, the power management procedure, the communication protocol, data acquisition, processing, transmission and reception and the software preferences all rely on the limited power which have significant effects on the life time of the sensor network. Hence, it is not efficient to use resources of sensor nodes unconsciously since many of the sensor nodes are unattended and it is not always possible to change the batteries of the sensor nodes [9]. To conclude, the

resources of sensor nodes should be wisely used not to limit the system functionality and increase the life time of the network.

- *Unreliability of wireless links:* The communication performance of WSNs suffers from the unreliable nature of the wireless links. Mobility, fading and multi-path effects, asymmetry of the wireless links, nonuniform radio signal strength, high bit error rates, low bandwidth and harsh environmental conditions of SG environment create great instabilities in sensor communications [6]. The correct measurement, proper characterization and the utilization of the wireless link quality is a prerequisite for reliable and efficient communications in WSNs. However, it is very challenging to select a convenient link quality estimation method due to the many factors such as harsh environmental conditions of electric power systems which adversely affect the quality of wireless links and thereby the performance of the WSNs.
- *Communication techniques and system integration:* The communication infrastructure is very critical in SG environment to provide reliable, efficient and secure data transfer between different applications, modules and parts of the system. There is not a unique communication technique to accomplish the above tasks. Hence a combination of communication techniques should be performed to better get the system performance. This would lead some additional challenges about the system integration between these different communication techniques. As a result, the combination of the techniques should be chosen wisely.
- *Scalability and adaptability:* The ability to extend the network scale while including new sensor nodes to the network can be the description of the network scalability. While the number of sensor nodes, thereby the workload of the network increases, keeping up the efficient and reliable routing process becomes a more challenging task which has a direct effect on the performance, scalability and adaptability characteristics of the network. Hence, the design of the routing protocols implemented for WSNs should be scalable, efficient, reliable and adaptive to the changing network dynamics.

4. Related work

This section reviews QoS-aware routing techniques and multi-path routing protocols in two subsections.

4.1. QoS-aware routing techniques

The increasing interest on SG communications have lead the academia to study on designing reliable and secure routing protocols for communication technologies used in SG environments. For WSN technology to be used in SG environment, some specific QoS requirements should be met to provide reliable data transmissions, since SG environment may pose some challenges, e.g., fading, obstacles, link quality variations to wireless data communications.

To overcome these challenges, dynamic-QoS-treatments, e.g., short delay, high reliability or high bandwidth for

various SG applications, should be adopted to data communications of WSNs. In the literature, there have been some routing protocols which address the energy limitations and wireless link quality variations to provide efficient and reliable data transfers. This section discusses some of these schemes.

Link quality estimation is one of the key requirements of WSN, since getting the proper information about the link quality is very important to choose the best path for the wireless communications [10] and better utilize the limited resources of sensor node, e.g., battery, processing and memory limitations. Hence, a routing protocol which is well aware of the reliability and link quality of the specific application is needed to be able to meet the requirements for efficient and reliable data transfers. Here are some of the routing algorithms which take into account these specific requirements. In the following, QoS-aware routing techniques are reviewed based on their distinct features.

The work in [11] proposes the design of a routing protocol for energy-constrained wireless sensor networks. The design parameters of an energy-efficient routing protocol is specified by finding the ways how to measure, characterize, and utilize the wireless link quality. Their motivation is to obtain a good cost metric to find the link quality of the sensor network with a few measurements that will cost less energy consumption of the sensor nodes.

The work in [6] aims to understand the reasons for unreliable wireless communications and data packet losses which are well summarized as the followings; signal attenuation caused by the distance, asymmetry in wireless links, nonuniform radio signal strength, fading and multi-path effects and interference due to hidden terminal problem. Moreover, they provide suggestions on the enhancements to well-known protocols to increase the reliability levels of packet delivery.

In [10] Krogman et al. point out that most of the researches on link quality estimations (LQEs) have avoided the sensitivity of the protocols to the LQEs errors which results in inaccurate LQEs and error propagation in LQE-based routing metrics. Hence, they propose two classes of link quality-based routing metrics, one is related to end-to-end reachability (EER) protocols and the other is about energy consumption (EC) protocols to predict their sensitivities to LQE errors. From the experiments, they showed that while EER protocols are more prone to LQE errors on large-scale and multi-hop networks, EC metrics are robust to LQE errors.

Chen et al. propose link quality estimation based routing protocol (LQER) which considers both energy and link quality to avoid poor link connectivity and reduce the possibility of retransmissions to be able to increase the lifetime of WSNs and data reliability [12]. Before making the routing decisions, they estimate the link quality by creating a connectivity graph based on hop count field. LQER metrics provides improvements on energy efficiency of WSN, but it does not guarantee the end-to-end deadline.

Daabaj et al. propose a reliability-oriented routing scheme which is based on per-hop energy balancing and probability network connectivity, and provides high success rate of packet delivery and less energy consumption [14].

Adaptive Forwarding Scheme (AFS) is proposed to provide service differentiation based on data prioritization which is directly related to controlling the reliability of a sensor network's communication [15]. The forwarding behavior of a packet is determined according to its priority level which means that the desired reliability level is proportional to its priority, in other words, to the number of copies of a packet. However, AFS needs the global topology of the network which makes it insufficient in providing QoS provisioning in timeliness domain.

RAP provides real-time communication in large scale sensor networks [16]. It guarantees end-to-end deadlines of packets by providing minimum communication and processing overhead. Since RAP is a best-effort service, it does not guarantee the reliability requirements of data packets.

In [9] an energy-aware routing algorithm that considers the average energy and minimum distance values and link reversing to prevent routing holes, is proposed. When a data packet is ready to be relayed, the most appropriate sensor node, with greater energy than the average energy, and with shortest distance to the destination node is selected. Each node is aware of its location from a GPS. The proposed algorithm prolong the network life time and increase the successfully packet delivery, however, the providing end-to-end delay is out of the scope.

EARQ is an energy aware routing protocol for real-time and reliable communication in wireless industrial sensor networks [18]. EARQ is an estimation based routing algorithm which selects the appropriate communication links to the sink node based on the estimations that are made according to the information obtained from neighbor nodes. The energy cost, delay and reliability of a path are all the estimated information that provide real-time and reliable data delivery. EARQ provides an even distribution of energy expenditure of sensor nodes which extend the network life time.

Gungor et al. present a resource-aware and link quality based routing metric (RLQ) which can adapt to varying wireless channel conditions, and exploit the heterogeneous capabilities in WSANs [19]. The proposed metric takes into account both the residual energy levels of sensor nodes and link quality statistics of communication links. Hence, RLQ achieves extending the network life time while providing reliable data communications. However, RLQ metric sacrifices in providing end-to-end deadline of data packets.

Breath is an adaptive protocol which provides energy-efficient, reliable and timely data transmissions for WSN-based industrial control applications [20]. Breath protocol provides the desired packet delivery options and delay probabilities while achieving to prolong the network lifetime. Park et al. provided a complete test-bed implementation of the protocol in an indoor environment to run experiments to see the performance of the protocol in reliability and timeliness domain. It is observed that Breath guarantees both reliability and delay requirements of data packets while maximizing the network lifetime by considering duty-cycle, routing, MAC, and physical layers all together [20].

Akkaya and Younis propose an energy and QoS-aware routing protocol in [25]. The protocol uses a class-based

queuing system and takes multiple routes into account based on distance, remainder energy levels and error rates. In this way, it simultaneously provides best-effort service and real-time traffic.

In [21] Sen presents a routing protocol which addresses different level of QoS, e.g., energy-efficiency, reliability, low latency and fault tolerance under different application scenarios without reconfiguration and redeployment of the wireless sensor nodes.

SPEED [30] is a reactive routing protocol and supports real-time communication by minimizing end-to-end delay. Each node makes localized routing decisions and evaluates packet progress speed based on distance and delay. SPEED uses relay ratio to determine whether a packet is to be dropped or relayed when desired speed requirement is not satisfied. It forwards a packet to the node with speed level higher than the pre-defined speed. Energy efficient SPEED (EESPEED) [22], a successor of SPEED, is a proactive routing protocol and takes residual energy of nodes into account and tries to find energy-efficient paths. Routing decisions are made based on delay, energy and speed. Like its predecessor, it does not guarantee packet reliability.

Instead of developing novel routing protocols for QoS differentiation, Nefzi and Song address service differentiation by proposing a novel scheme called CoSenS, a Collect then Send burst Scheme [23]. They retain the use of CSMA/CA as access protocol due to its simplicity, versatility and good scalability properties. CoSenS address the weaknesses of CSMA/CA and greatly enhances end-to-end delay, reliability and deadline meet ratio for urgent traffic. Similarly, Villaverde, Rea and Pesch presents a route selection algorithm called InRout for handling QoS requirements while considering sensor node resources [24]. A performance evaluation study given in [24] demonstrates the benefits of the InRout algorithm which satisfies typical QoS requirements for industrial monitoring applications.

4.2. Multi-path routing protocols

Different from single-path routing protocols in which a single-path between a source and a sink is determined and used, multi-path routing protocols provide multiple paths between the source and the sink. Multi-path routing brings several advantages such as load balancing, reliability and fault tolerance, and aggregated bandwidth. On the other hand, it results in a few disadvantages such as route coupling, and increased end-to-end delay and network load. Mainly, multi-path routing protocols can use several parameters as routing metrics and be classified into two main categories. While protocols in the first category transmit different packets to the destination point through different paths, protocols in the second category transmit multiple copies of the same packet to the destination point through multiple paths to improve network reliability. Although the approach of transmitting multiple copies of the same packet improves network reliability and supports packet prioritization, it may cause contention and congestion. In the following, multi-path routing protocols are reviewed based on their distinct features.

The work in [13] proposes a multi-path forwarding protocol, RelnForM, to provide reliability in sensor networks

by sending the multi-copied packets to the sink node through multiple paths. The information of local knowledge of sensor conditions, e.g., channel error, hops to sink, out-degree, and neighborhood at each node are used to enable a lightweight and localized mechanism for reliability in information dissemination [13]. However, RelnForM is inadequate in providing service differentiation in timeliness domain.

Reliable energy aware routing (REAR) protocol is proposed in [17] which provides multi-path routing protocol and takes into consideration of residual energy-capacities of sensor nodes before establishing routing paths. In packet forwarding process, the source node broadcasts a message to find out which multi-path has higher energy level to transmit the packet. Nodes with higher energy levels respond to the broadcasted message and are selected as the relaying nodes. REAR protocols provides extending the network life time, however, does not guarantee the end-to-end deadline mechanism.

MMSPEED [8,33] is a multi-path and multi-speed routing protocol aiming to provide QoS differentiation in both reliability and timeliness domains. By guaranteeing multiple packet delivery speed options, it provides multiple QoS levels in the timeliness domain. It also meets reliability requirements of different applications in the reliability domain by probabilistic multi-path forwarding. It employs localized geographic packet forwarding augmented with dynamic compensation and is therefore scalable and adaptable to large scale WSNs.

Sanati et al. in [26] propose a new routing protocol called EAMMSPEED. EAMMSPEED is basically an energy-efficient MMSPEED using an energy aware packet delivery approach to provide QoS guarantee. It takes energy level of nodes into account when making routing decisions.

In [27] Poojary and Pai propose a new routing algorithm called MPDT. MDPT is basically a multi-path data transfer protocol providing simultaneous multiple paths for communication between any two nodes. It prolongs network lifetime and is immune to some specific attacks from security point of view.

Krogmann et al. in [28] propose a reliable, real-time routing protocol based on multi-path routing for highly time-constrained Wireless Sensor and Actuator Networks (WSANs). The protocol called 3R consists of a newly designed routing metric and a routing algorithm utilizing this metric. The proposed metric enables strong QoS support based on parallel transmissions and in this way transmission delays in WSANs is significantly reduced.

EQSR proposed in [29] is an energy-efficient and QoS aware multi-path routing protocol. It decides the best next hop based on energy level of sensor nodes, available buffer size and signal to noise ratio (SNR) and minimizes energy consumption in order to increase network lifetime. It achieves service differentiation in timeliness domain and increases packet reachability using redundant data.

A brief comparison of the selected routing protocols mentioned above is listed in Table 2.

All the studies reviewed in this section either propose a novel routing protocol or extend an existing routing protocols adding or improving their features. SG environments pose several challenges to almost all SG applications and

Table 2

Comparison of selected routing protocols based on meeting the reliability and delay requirements.

Protocol	Description	Reliability requirement	Delay requirement	Energy Aware	Network life time
EARA [9]	Energy-aware routing algorithm	Reliability-sensitive	Not delay sensitive	Energy-aware	Extends network life time
LQER [12]	Link quality estimation based routing protocol	Reliability-sensitive	Not delay sensitive	Energy-aware	Extends network life time
RelnForM [13]	Reliable information forwarding protocol	Reliability-sensitive	Not delay sensitive	Out of scope	Out of scope
AFS [15]	Adaptive forwarding scheme	Reliability-sensitive	Not delay sensitive	Out of scope	Out of scope
RAP [16]	Real-time communication protocol	Not reliability-sensitive	Delay sensitive	Out of scope	Out of scope
REAR [17]	Reliable energy aware routing	Reliability-sensitive	Not delay sensitive	Energy-aware	Extends network life time
EARQ [18]	Energy aware routing for industrial control applications	Reliability-sensitive	Delay sensitive	Energy-aware	Extends network life time
RLQ [19]	Resource-aware and link quality based routing metric	Reliability-sensitive	Not delay sensitive	Energy-aware	Extends network life time
Breath [20]	Adaptive protocol for industrial control applications	Reliability-sensitive	Delay sensitive	Energy-aware	Extends network life time

specific attention should be given to addressing these challenges. In this respect, a novel routing approach has been presented to handle the challenges and communication requirements of SG applications. In addition, this paper investigates the advantages of SPEED and MMSPEED routing protocols in terms of different QoS parameters in different SG environments. The motivation of choosing these routing protocols as case of study is due to their characteristics concerning the support of only one type of traffic for SPEED and multiple classes of traffic for MMSPEED. This point is important for our performance evaluations since it enables us to study the approach in case of a single service and multiservice protocols. SPEED protocol yields soft real-time routing for only one class of traffic, by maintaining a progression speed across the WSN. On the other hand, MMSPEED protocol extends SPEED by offering multiple types of service to packets according to their class of traffic.

5. Overview of evaluated routing protocols

The main objective of this paper is to analyze the behavior of a multi-path and multi-speed (MMSPEED) routing protocol in different LOS and NLOS SG environments including 500 kV outdoor substation, main power control room and underground network transformer vaults. MMSPEED routing protocol is a novel packet routing mechanism that guarantees QoS provisioning in two quality domains, e.g., reliability and timeliness domains [8]. It provides several packet delivery options for timeliness domain and probabilistic multi-path forwarding for reliability domain.

5.1. MMSPEED

MMSPEED routing protocol provides service differentiation and QoS provisioning in the timeliness and reliability domains for wireless sensor networks [8]. The significant contribution of MMSPEED routing protocol is to achieve improving the capabilities of a wireless sensor network

to well scale while enabling different data flows to meet their reliability and timeliness requirements. To achieve the above goals, MMSPEED uses probabilistic multi-path forwarding technique which controls the number of packet delivery paths to meet the required reliability level, and adopts SPEED protocol to provide multiple delivery speed options to differentiate the QoS in timeliness domain. With these advances, it provides three important achievements that could not be guaranteed at the same time by the existing routing protocols, e.g., service differentiation in both timeliness and reliability domains, localized packet delivery without global topology information and avoiding less reliable transmissions over wireless links [8]. Geographic routing mechanism is adopted to achieve localized packet routing without end-to-end path setup. Hence, it is assumed that sensor nodes are aware of their geographical location and locations of their neighbors within their radio range.

In the timeliness domain, to be able to provide multiple speed options for data packets, MMSPEED introduces virtual overlay of multiple speed layers on top of a single physical network. To achieve the virtual layering, MMSPEED uses two important methods; virtual isolation concept and dynamic compensation. Lower-speed packets may adversely affect the performance of higher-speed packets. Hence, to minimize these effects, virtual isolation makes a classification for packets according to their speed levels and place them into the priority queues. Moreover, dynamic compensation is used to compensate the local decisions to provide the end-to-end deadline requirements of data packets. For this purpose, MMSPEED calculates a minimum required speed level, $ReqSpeed(x)$ for a packet x to be able to meet its deadline requirement, $deadline(x)$, hence, the source node selects a proper speed level for a packet x based on its distance to the destination, d , e.g., $dist_{s,d}(x)$. The $ReqSpeed(x)$ is calculated as follows,

$$ReqSpeed(x) = \frac{dist_{s,d}(x)}{deadline(x)} \quad (1)$$

Then, the most appropriate speed layer l is picked as follows,

$$Speed_i = \min_{j=1}^L \{Speed_j | Speed_j \geq ReqSpeed(x)\} \quad (2)$$

where L is the number of speed options. Later, a neighbor node i whose progress speed estimation is $Speed_{s,i}^d = (dist_{s,d} - dist_{i,d}) / delay_{s,i}$ is higher than $Speed_i$ is selected by the proper speed layer to relay the packet.

However, the packet may face with longer delays than the original estimations while traveling among many hops. This situation can be noticed by an intermediate node m by comparing expected latency to the destination using the current speed and remaining time to the deadline. Since there is no globally synchronized clock, this comparison can be made by measuring *elapsedtime* at each node and attaching this information to the packet, hence the further node, m' , can measure the remaining time to deadline without any additional information and update the deadline. After the new deadline is set to the packet, node m can compensate this sufficiency by resetting the speed level with the following,

$$ReqSpeed(x) = \frac{dist_{m',d}(x)}{deadline(x)} \quad (3)$$

With the above mentioned techniques, MMSPEED provide network-wide speed options for a packet to meet its end-to-end deadline requirement.

In the reliability domain, MMSPEED adopts the idea of utilizing the alternative longer paths to increase a packet's reaching probability to the destination. Hence, MMSPEED controls multiple communication paths according to the reliability level of a packet. MMSPEED uses two important methods to achieve the above goal; multi-path forwarding and dynamic compensation. Each node uses local error estimations and geographic hop distances of its neighbor nodes to estimate which immediate node it should forward the packet and how many forwarding paths it should use to meet its reliability requirement. These decisions are locally made and they are prone to mistakes, hence to compensate these decisions, dynamic compensation technique is used to meet the reliability requirement of each packet. A detailed explanation can be made as follows. Each node i is capable of calculating the recent average of packet loss percentage e_{ij} to the immediate node j . The total packet losses contain intentional packet drops for congestion control and errors on the channel. Hence, node i can easily estimate the reachability level of a packet to the destination d through neighbor node j as follows,

$$RP_{ij}^d = (1 - e_{ij})(1 - e_{ij})^{[dist_{j,d}/dist_{i,j}]} \quad (4)$$

where $dist_{j,d}/dist_{i,j}$ is the hop count estimation between node j and destination d . This equation is the reachability estimation of a packet via a single node j . Furthermore, to be able to meet the end-to-end reachability of a packet, more than one path may be needed. Hence, to determine how many paths needed for a required reliability level, the following adjustments should be made.

$$TRP = 1 - (1 - TRP)(1 - RP_{ij}^d) \quad (5)$$

where TRP is the total reaching probability of a packet, $(1 - TRP)$ is the probability in case of none of the paths can relay the packet successfully, $(1 - RP_{ij}^d)$ is the

probability in case one path through node j will relay the packet to the destination unsuccessfully, hence, $(1 - TRP)(1 - RP_{ij}^d)$ is the probability that all of the paths will fail relaying the packet to the destination node, finally, $1 - (1 - TRP)(1 - RP_{ij}^d)$ is the probability that at least one path will certainly relay the packet to the destination. With TRP estimation, the multiple forwarding node selection can be accomplished, however, the estimations are based on local decisions which may be incorrect. Hence, dynamic compensation should take place to prevent incorrect decisions.

Overall, MMSPEED protocol tries to provide service differentiation by combining above mechanisms. First of all, MMSPEED places the packet into the proper speed layer to meet the deadline requirement and then, finds multiple forwarding nodes to deliver it using MAC layer multi-cast service [8]. To conclude, MMSPEED routing protocol efficiently meets the requirements of different traffic types with different reliability and timeliness requirements, provides scalability for large sensor networks and self-adaptability for network dynamics [8].

5.2. SPEED

SPEED protocol is a real-time, stateless communication protocol for sensor networks which provides end-to-end deadline guarantees by maintaining the desired speed levels with a feedback control and non-deterministic geographic forwarding [30]. SPEED protocol differs from other real-time protocols, e.g. RAP [16], with its ability to handle long term congestion, and it differs from other reactive routing algorithms, e.g. DSR [31] and AODV [32], with its stateless structure in which only immediate neighbors information is maintained, and there is requirement for routing tables or per destination states [30]. Here are some of the advances of SPEED protocol that make it efficient and real-time protocol in providing QoS provisioning in timeliness domain [30]:

- SPEED protocol adopts a backpressure re-routing scheme to handle large-delay links with minimum overhead.
- Non-deterministic forwarding is used to be able to balance the data flows among the several routes which is quite a necessity in terms of bandwidth and energy utilizations.
- SPEED makes a difference with its localized behavior. No routing tables are used in SPEED protocol, it is assumed that each sensor node knows its location, hence, there is no need to apply flooding or creating broadcasting storms to find communication paths. With this way, the scarce resources, e.g. energy, bandwidth, are better utilized.
- In SPEED protocol, end-to-end delay of a packet is proportional to the distance of the packet destination, since uniform packet delivery option is adopted among the network.

SPEED protocol uses a packet progress speed concept that enables each node to find a proper neighbor node for relaying the data packet. Every sensor node has a

packet progress speed calculate according to its distance to the destination node, and the packets are forwarded to the neighbor node that has the highest progress speed. In case of a heavy load, the packets are dropped to relieve the network and in case, there exist a congested area, a back-pressure packet is generated and sent to the previous nodes to warn them about the congested area and prevent them to sent any more packets to that area. Network scalability, end-to-end delay requirements are all provided by SPEED protocol, however, there is only one network-wide speed which is inadequate to differentiate different traffic with different deadline requirements. This inadequacy is compensated by MMSPEED routing protocol by adopting multiple delivery speed options to differentiate the QoS in timeliness domain.

6. Performance evaluations

In this paper, a routing approach is proposed to achieve service differentiation in different SG environments. In the literature, there have been a few routing protocols which take into account both reliability and latency requirements. The proposed routing algorithm achieves distinguishing different QoS domains, e.g., reliability and timeliness, in SG environment which has harsh environmental conditions that posse additional challenges for WSN technology to provide reliability and latency requirements. Hence, the wireless channel should be modeled by taking account multiple parameters that can affect the signal quality. Since log-normal shadowing model takes into account both fading and distance affects in the surrounding of transmitters and receivers, it is the preferred propagation model in this work. Gungor et al. have modeled the wireless channel in six different SG environments and presented the specific radio propagation parameters for those environments in Table 3. Simulation parameters used in the study are listed in Table 4.

Gungor et al. have depicted that the signal to noise ratio $\gamma(d)$ at a distance d from the transmitter is given by:

$$\gamma(d)_{dB} = P_t - PL(d_0) - 10\eta \log_{10} \left(\frac{d}{d_0} \right) - X_\sigma - P_n \quad (6)$$

P_t is the transmit power in dBm, $PL(d_0)$ is the path loss at a reference distance d_0 , X_σ is a zero mean Gaussian random variable with standard deviation σ , η is the path loss exponent, and P_n is the noise power in dBm.

In the light of these propagation parameters, log-normal shadowing model is implemented for different SG

Table 3
Mean power loss and shadowing deviation in electric power environments.

Propagation environment	Path loss (n)	Shadowing deviation (σ)
500 kv Substation LOS	2.42	3.12
500 kv Substation NLOS	3.51	2.95
Underground transformer vault LOS	1.45	2.45
Underground transformer vault NLOS	3.15	3.19
Main power room LOS	1.64	3.29
Main power room NLOS	2.38	2.25

Table 4
Simulation parameters.

Number of nodes	100
Number of traffic flows	2, 4, 8, 12, 16
Packet length	256 Bytes
Traffic type	CBR
Channel model	Log normal shadowing
MAC protocol	802.11e EDCF

environments, and a test band is generated with 100 nodes in J-SIM simulation environment developed in [8]. Some of the nodes are assigned as the source nodes and the one as a sink node. The simulations are performed for four different scenarios with different reliability and timeliness requirements to provide service differentiation:

- Scenario 1: Deadline value is 0.3 and Reliability value is 0.5.
- Scenario 2: Deadline value is 1.0 and Reliability value is 0.5.
- Scenario 3: Deadline value is 1.0 and Reliability value is 0.7.
- Scenario 4: Deadline value is 1.0 and Reliability value is 0.2.

Two flow groups are used during each simulation and the network traffic with 2, 4, 8, 12, 16 sources for each domain are generated. The following performance metrics are used for performance evaluations:

- *Average delay*: It is the average delay time of all the packets that are successfully received by the sink node.
- *On-time reliability*: It is the ratio between successfully received packets that meet the deadline requirement value and the total number of packets.
- *End-to end delay*: It represents the time to receive all data by the sink node.
- *Control packets*: They consist of ACK, RTS, CTS and retransmission RTS that are the MAC layer control packets, location update packets and back-pressure packets.

There are three main SG environments that Gungor et al. have made the experimental study on the statistical characterization of the wireless channel. They measured the background noise, wireless channel characteristics, and attenuation of these environments in LOS and NLOS scenarios as depicted in Table 3. From the experiments, it is observed that in substation environment, high amount of noise due to the several obstacles resulted in high path loss, in underground transformers vaults, there are many equipment, such as, power transformers, network protectors, voltage regulators, circuit breakers, meters, that creates high amount of noise which adversely affect the quality of wireless communications, since main power control room is an indoor environment, there are quite less obstructions that affect the link quality as it does in other environments. Performance evaluations have been made according to these three environments, since they have different special characteristics which directly affect the performance of multi-path routing from reliability and timeliness domains.

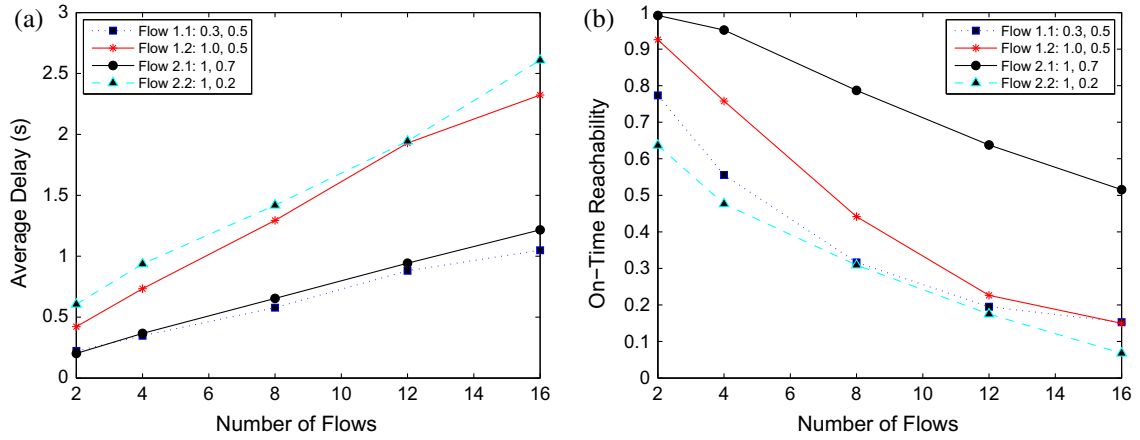


Fig. 1. Shadowing model-service differentiation for 500 kV substation LOS. (a) Average delay and (b) on-time reliability.

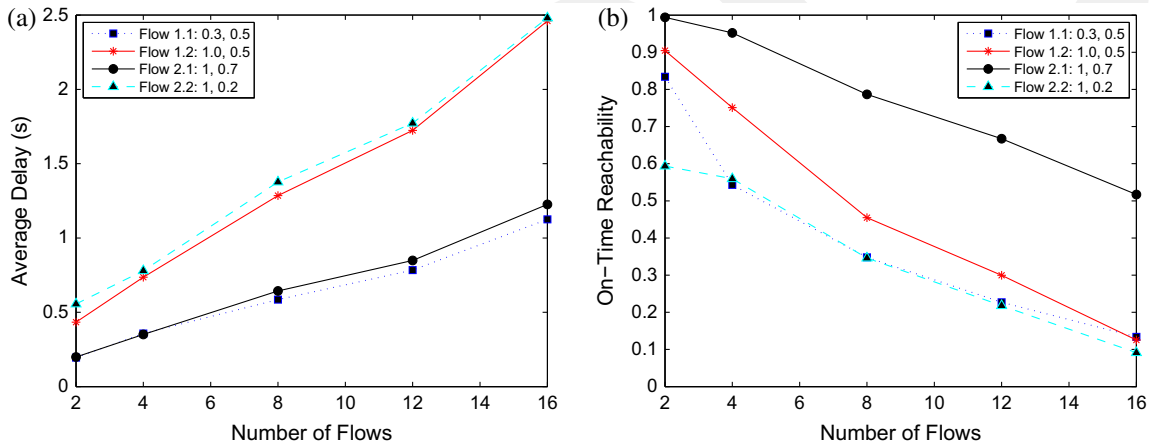


Fig. 2. Shadowing model-service differentiation for 500 kV substation NLOS. (a) Average delay and (b) on-time reliability 500 kv substation NLOS.

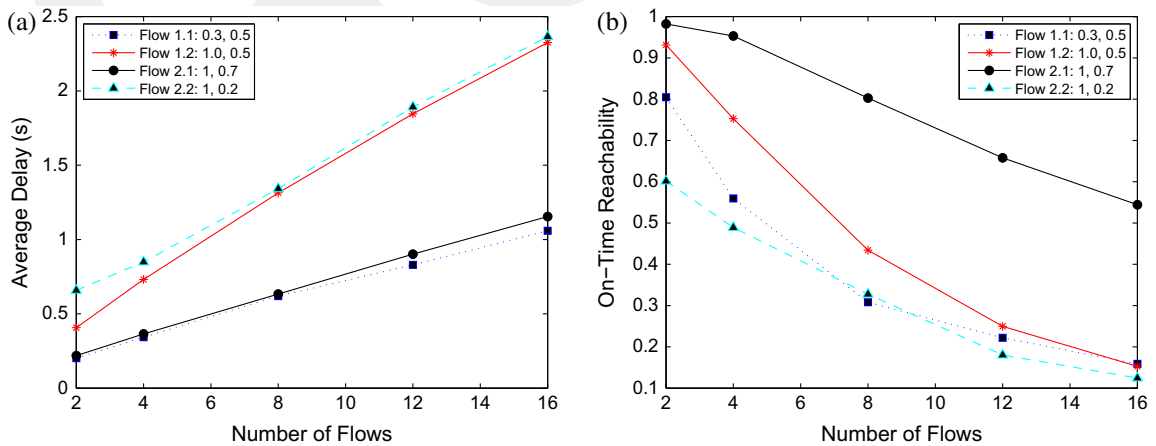


Fig. 3. Shadowing model-service differentiation for underground transformer vault LOS. (a) Average delay and (b) on-time reliability.

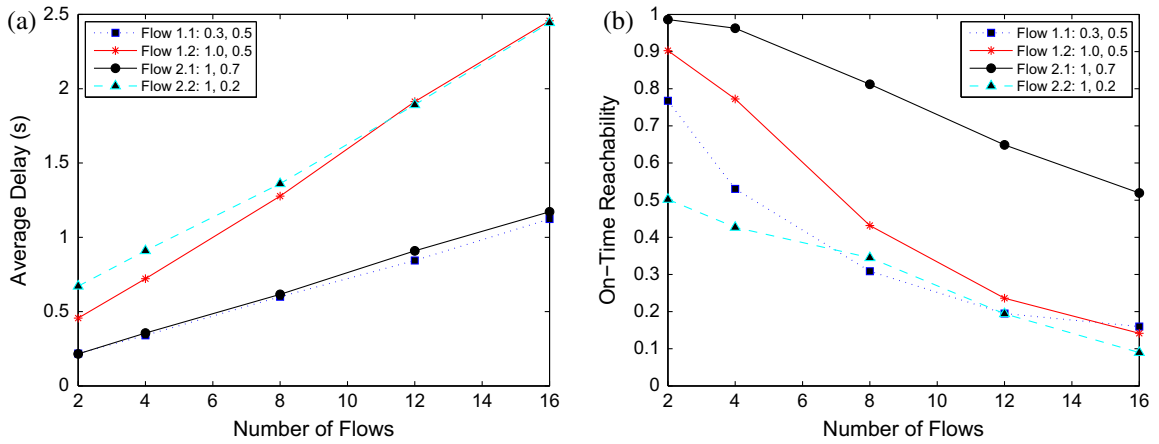


Fig. 4. Shadowing model-service differentiation for underground transformer vault NLOS. (a) Average delay and (b) on-time reliability.

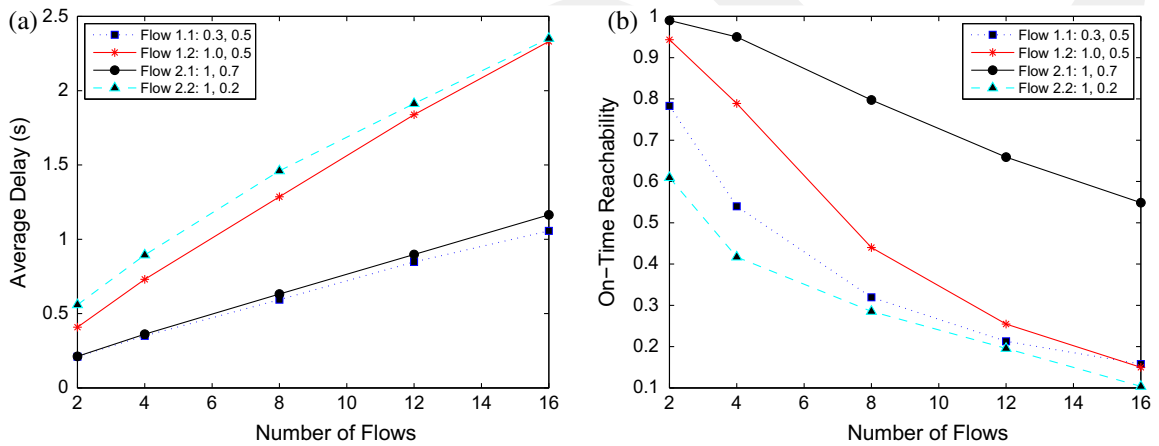


Fig. 5. Shadowing model-service differentiation for main power room LOS. (a) Average delay and (b) on-time reliability.

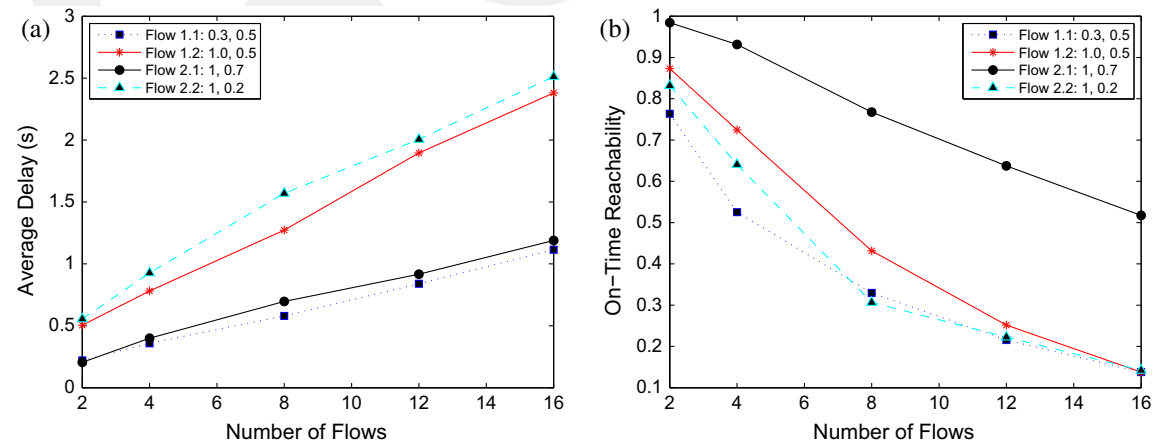


Fig. 6. Shadowing model-service differentiation for main power room NLOS. (a) Average delay and (b) on-time reliability.

Table 5

The network capacity is briefly depicted for shadowing model for SG environment, $n = 2.42$ and $\sigma = 3.12$.

	System performance	Delay performance	On-time reachability
Deadline 1.0, reachability 0.7	Up to 22 flows	Up to 25 flows	Up to 20 flows
Deadline 1.0, reachability 0.2	Up to 20 flows	Up to 10 flows	Up to 23 flows
Deadline 0.3, reachability 0.5	Up to 9 flows	Up to 8 flows	Up to 10 flows
Deadline 1.0, reachability 0.5	Up to 12 flows	Up to 11 flows	Up to 13 flows

6.1. Performance evaluations from reliability domain point of view

Multi-path routing uses probabilistic multi-path forwarding technique in reliability domain depending on the reliability requirement to exploit the packet delivery paths. To differentiate the reliability domain, the same deadline requirement of 1.0 is used for all flows. The flows are divided into two flow groups with different reliability requirements; flow group 2.1 has high reliability requirement of 0.7 and flow group 2.2 has low reliability requirement of 0.2. As shown, flow 2.1 and flow 2.2 lines in

Figs. 1a, 2a, 3a, 4a, 5a, and 6a show the average delays with fixed deadline requirements for each SG environment. Since the required packet speed is lower, it is expected to see that multi-path routing route will be farther away from the optimum path [33]. In the light of this statement, multi-path routing provides a clear differentiation with different reliability requirements. For instance, it has supported up to 25 flows under 0.7 reliability requirement and up to 10 flows under 0.2 reliability requirement in 500 kV Substation LOS environment as listed in Table 5.

Figs. 1b, 2b, 3b, 4b, 5b, and 6b show the on-time reachability for each group of flows, since the source 1.1 and the

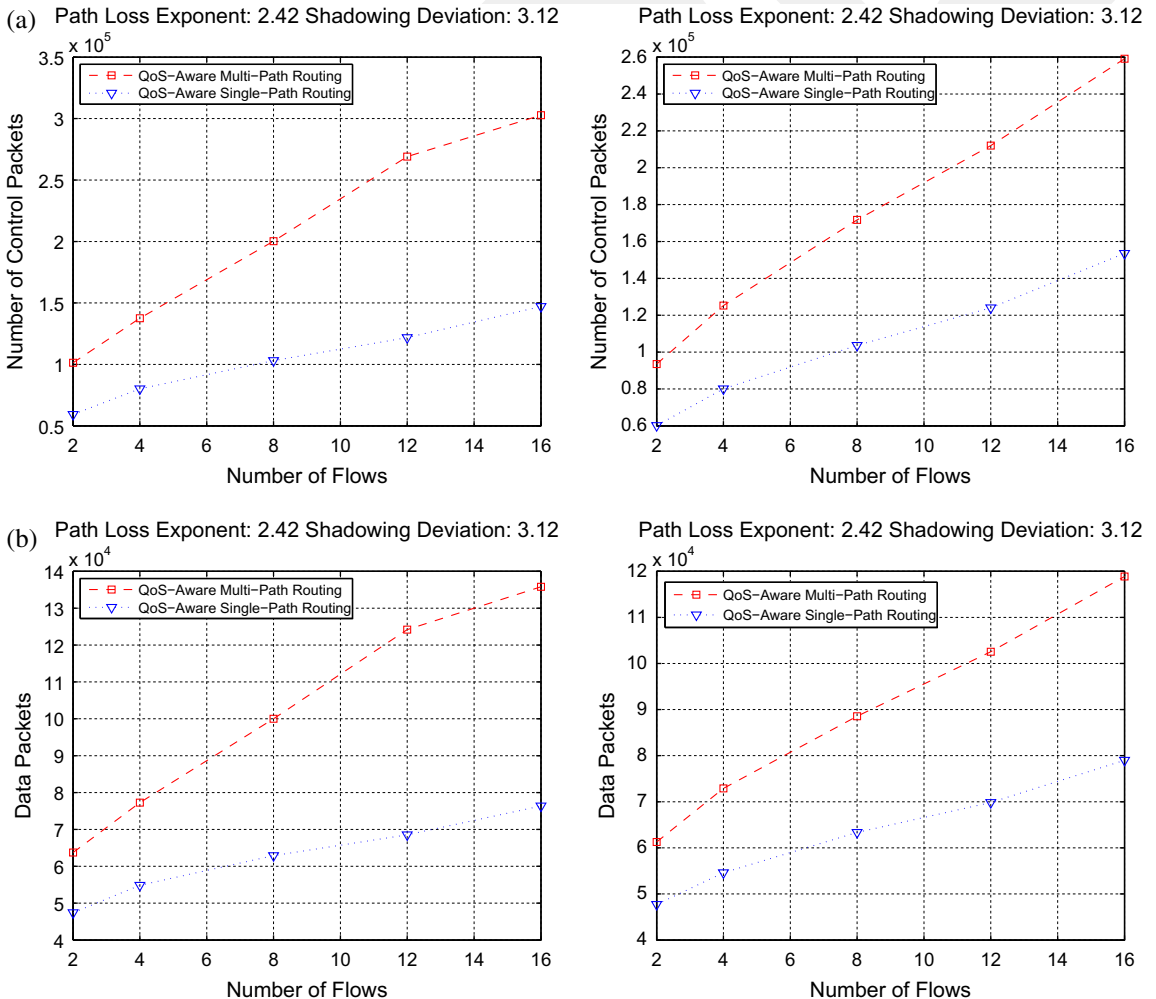


Fig. 7. Overhead versus number of flows for $n = 2.42$ and $\sigma = 3.12$. (a) Control packets and (b) data packets.

source 1.2 have the same reliability requirement of 0.5, there is no big performance differentiation in the reliability domain. However, source 2.1 and source 2.2 have different reliability requirements (source 2.1 has reliability requirement of 0.7 and source 2.2 has reliability requirement of 0.2). We expect to see a service differentiation in reliability domain. It is clearly shown that multi-path routing provides the reliability differentiation for each flow.

It is observed that there is a performance degradation for LOS and NLOS 500 kV substation SG environments for on-time reachability levels, since in NLOS environments, the wireless performance can be limited by the obstacles. Therefore, it is obvious to see that for source group 2.2 (reliability requirement of 0.2), the on-time reachability level in 500 kV Substation LOS environment is a little bit higher than the on-time reachability level in 500 kV Substation NLOS environment as depicted in Figs. 1b and 2b. However, there is no such a big performance difference in source groups 1.1 with high reliability requirement, since QoS-Aware Multi-Path Routing provides guaranteed service for high reliability requirement flow groups.

The same performance degradation is observed in underground transformers vault LOS and underground transformers vault NLOS SG environments. For source group 2.2 (reliability requirement of 0.2), there is a quite performance degradation in NLOS underground transformers vault as depicted in Figs. 3b and 4b. It is obvious to see such a performance differentiation between NLOS and LOS underground transformers vault, since there are a lot of equipment, e.g., power transformers, network protectors, voltage regulators, circuit breakers, meters, housed in underground transformers vault which can affect the wireless communication in NLOS environment. As it is observed in 500 kV NLOS and LOS SG environments, for source groups 1.1 (reliability requirement of 0.2), there is no such a big performance difference in on-time reachability in NLOS and LOS underground transformers vault environments.

The performance of source 2.2 in main power room NLOS environment is surprisingly higher than the performance of source 2.2 in main power room LOS. Since main power control room is an indoor environment, this

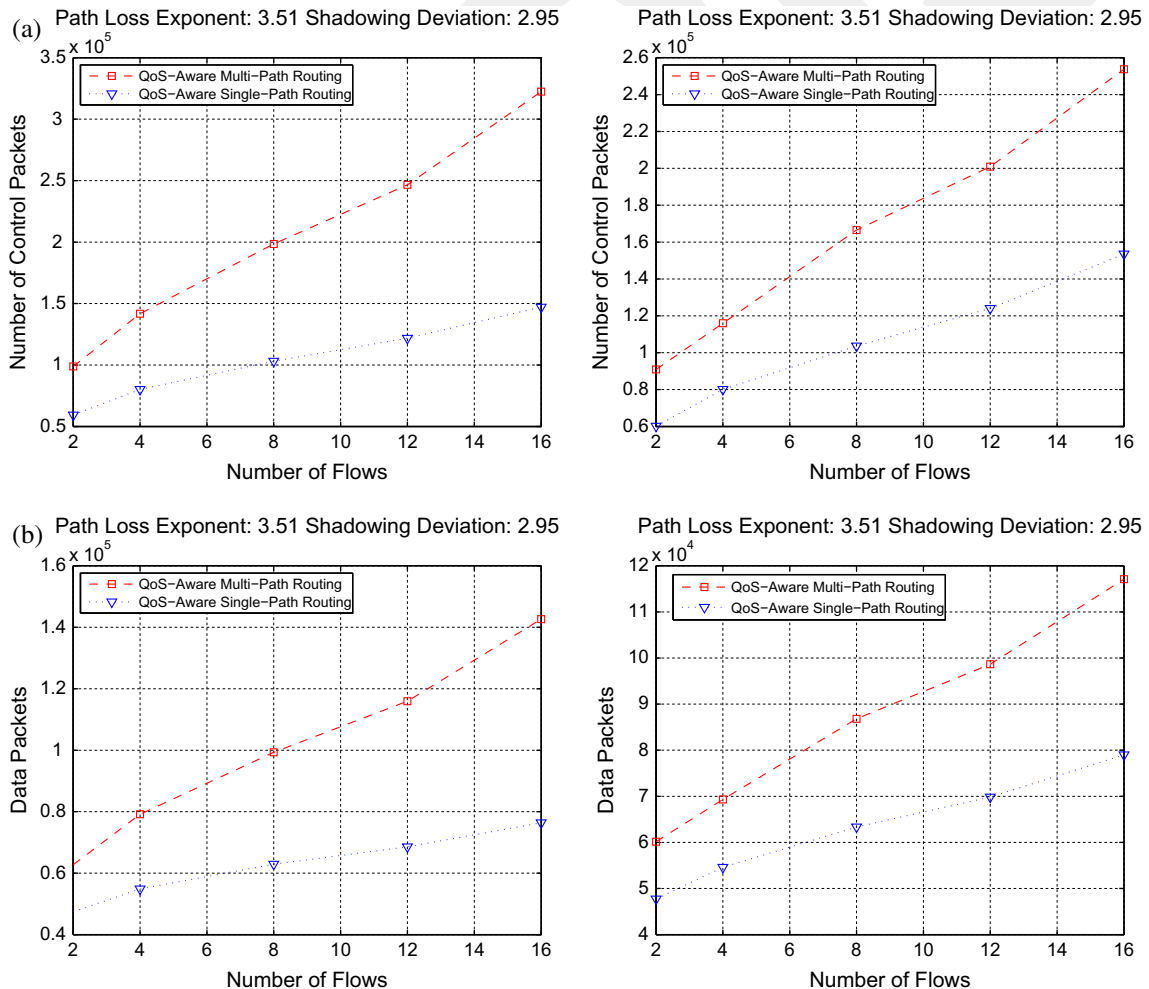


Fig. 8. Overhead versus number of flows for $n = 3.51$ and $\sigma = 2.95$. (a) Control packets and (b) data packets.

performance difference can be tolerated. On the other hand, while there are no performance differentiation occurred in 500 kV Substation and underground transformers vault environments for source group 1.1, the main power control room LOS shows quite higher performance source group 1.1 (reliability requirement of 0.2) than the main power control room NLOS shows.

6.2. Performance evaluations from timeliness domain point of view

MMSPEED adopts single-path routing to provide multiple delivery speed options to differentiate the QoS in timeliness domain. Hence, the same reliability requirement of 0.5 is used for all flows. The flows are divided into two flow groups with different deadline requirements; flow group 1.1 has short deadline requirement of 0.3 s. and flow group 1.2 has long deadline requirement of 1.0 s. As shown, flow 1.1 and flow 1.2 lines, as increasing number of sources, in Figs. 1a, 2a, 3a, 4a, 5a, and 6a, the flows with 0.3 s. of deadline have showed a great performance in providing the end-to-end deadline requirements. It is very obvious that

MMSPEED has achieved a clear differentiation with different deadline requirements for different flow groups. For instance, it has supported up to 8 flows under 0.3 s deadline requirement and up to 11 flows under 1.0 s deadline requirement in 500 kV Substation LOS environment as listed in Table 5.

The performance differentiation of flow groups in 500 kV substation LOS and NLOS is clearly distinctive as depicted in Figs. 1a and 2a. The average delays in 500 kV substation NLOS SG environment for source groups 1.1 and 1.2, are higher than they are in 500 kV substation LOS, since NLOS environment has more obstructions which may adversely increase the delay of wireless communications. Furthermore, as it can be easily predicted, source group 1.2 with higher delay requirement (delay requirement of 1.0) has higher average delay performance than source group 1.1 with low delay requirement (delay requirement of 0.3) has.

The clear distinction in average delay performances is also observed in underground transformer vault NLOS and LOS SG environments. Since, the special environment of underground transformer vault poses additional

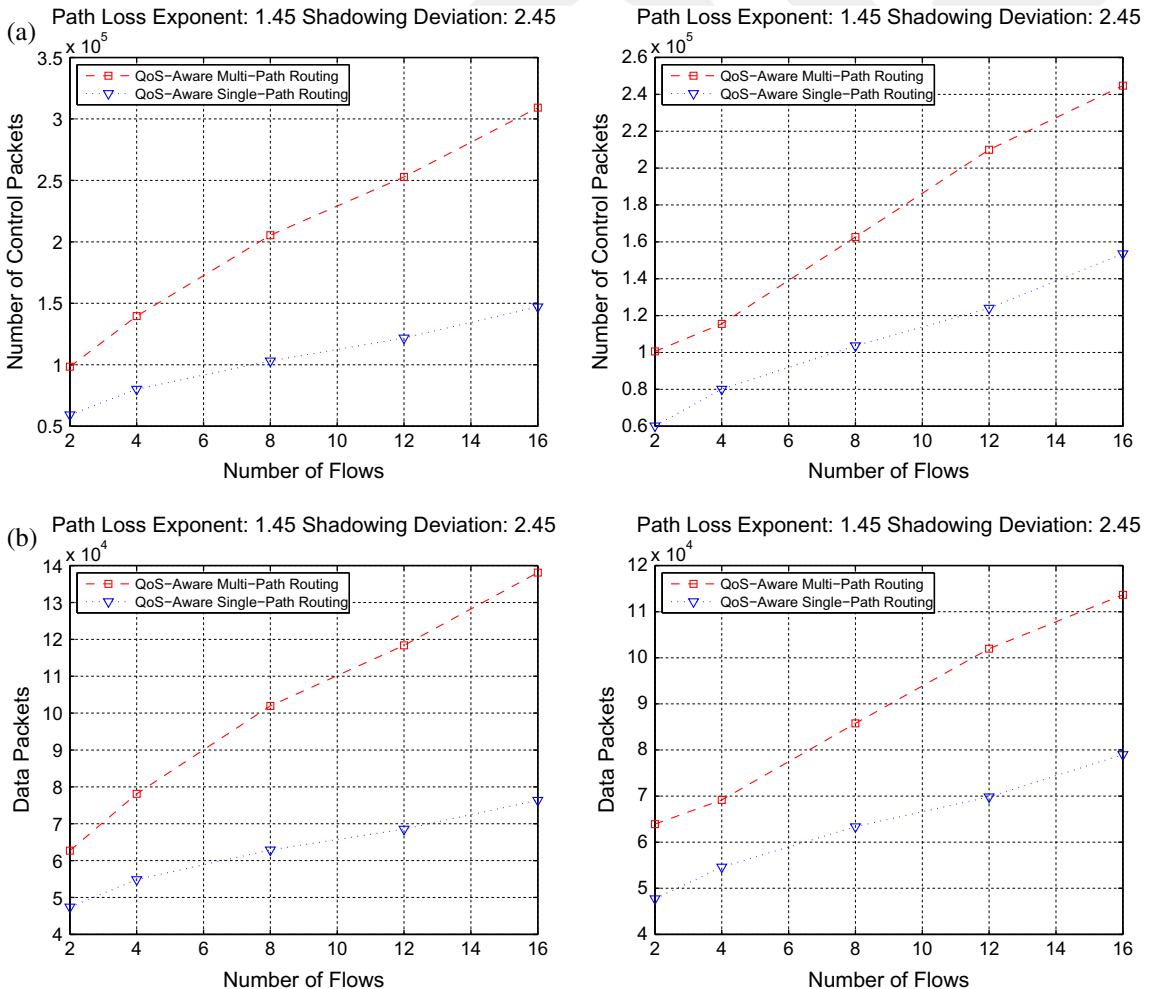


Fig. 9. Overhead versus number of flows for $n = 1.45$ and $\sigma = 2.45$. (a) Control packets and (b) data packets.

obstructions, the average delays are a little bit higher than they are in other two environments. Figs. 3a and 4a show that source groups 1.1 and 1.2 have higher average delays in NLOS environment than they are in LOS environment. Moreover, as it is observed in 500 kV substation environment, the source group 1.2 (delay requirement of 1.0) has a significant higher average delay than the source group 1.1 (delay requirement of 0.3) since, high delay requirement provides a flexibility to the routing algorithm to tolerate the additional delays.

In main power control room, it is clearly shown that there are performance differentiation in average delays of source groups 1.1 and 1.2 in LOS and NLOS scenarios. The QoS-aware multi-path routing is able to provide lower average delay for source group 1.1 with delay requirement of 0.3 to be able to meet the timing requirement. Hence, source group 1.2 with delay requirement of 1.0 shows higher average delay than source group 1.1 as depicted in Figs. 5a and 6a. However, as it is observed in reliability point of view, the LOS and NLOS performance evaluations are not as they are predicted. Surprisingly, source group

1.2 in LOS scenario has higher average delay than it is in NLOS scenario.

6.3. Overhead analysis

In this section, the overhead analysis of MMSPEED and SPEED protocols are presented. Two types of overhead are introduced, the first type is data packets and the second type is control packets which include location update packets, timeliness back-pressure packets, and reliability back-pressure packets. The overhead of each protocol is depicted in Figs. 7–12 as increasing number of flows. The flows are divided into four source groups with different reliability and timeliness requirements. Each of four figures represent the overhead analysis of data and control packets in a different SG environment. The first two figures in the vertical plane represent the data and control packets in reliability domain, while other two represent the data and control packets in timeliness domain.

For six different SG environments, the total number of control packets and data packets of MMSPEED are larger

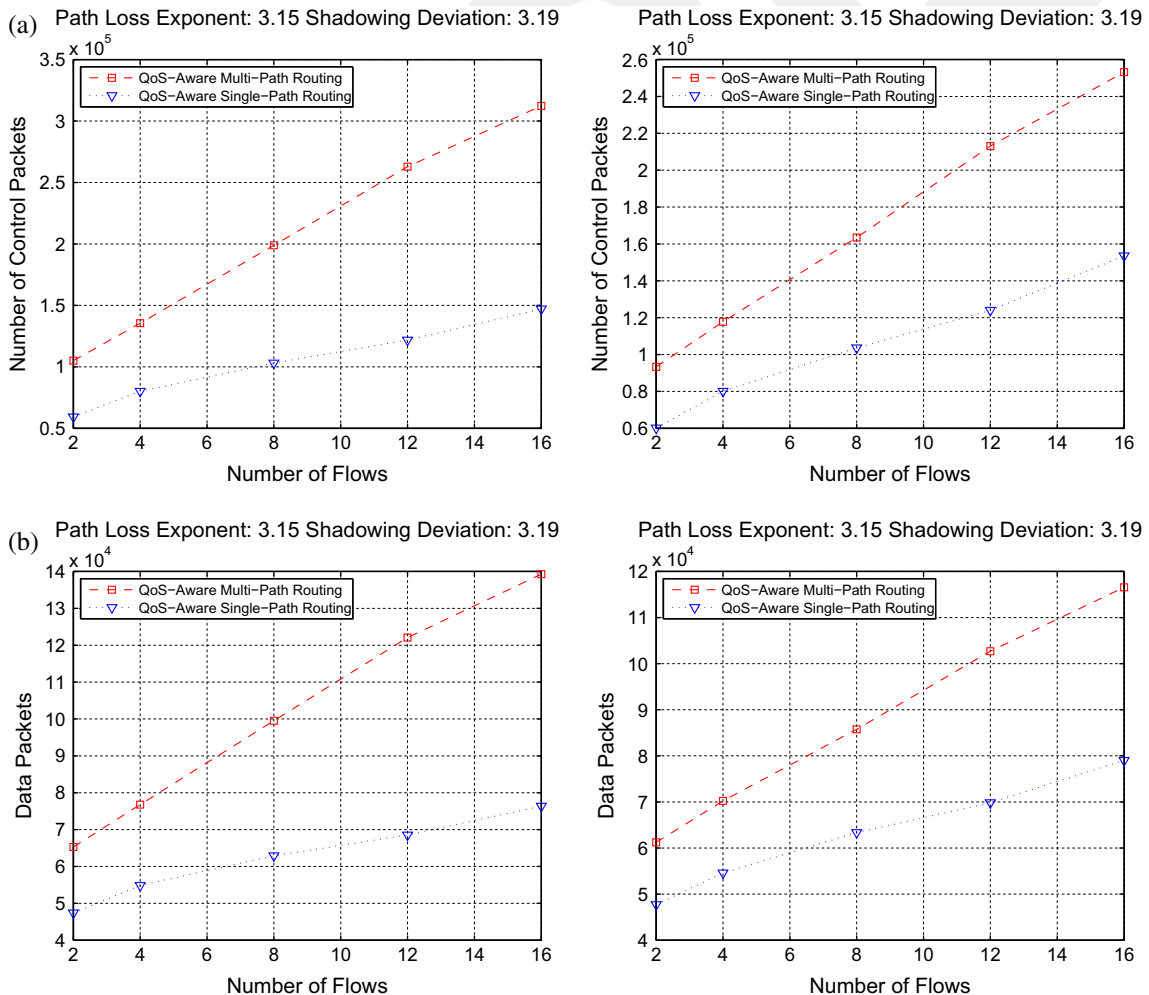


Fig. 10. Overhead versus number of flows for $n = 3.15$ and $\sigma = 3.19$. (a) Control packets and (b) data packets.

than SPEED protocol. This can be explained as follows. The reaching capability of a packet to the final destination increases while the number of paths used for packet transmission increases, hence, MMSPEED exploits the redundant paths to the final destination point even they might not be the shortest paths, just to provide end-to-end reliability of a packet [8]. For this reason, multi-path forwarding technique is adopted by the proposed routing approach which transmits the duplicate copies of the packets to meet the reliability requirement and uses multiple hops by considering the fact that each copy of the packet meets end-to-end deadline requirement. Moreover, the multi-cast capability of multi-path routing in the MAC layer creates additional bits. Hence, the total number of data and transmissions of control packets are quite larger than that of single-path routing.

For six different SG environments, the total number of control packets in LOS environment are quite larger than control packets in NLOS environment. The control packets are used to reliably and successfully transmit the data packets to the destination. Since the number of successfully transmitted packets are larger in LOS SG environment

than NLOS environment, it is very clear to see such a difference. On the other hand, such a difference is not observed for data packets. The total number data packets in NLOS environment are larger than LOS environment. This can be explained as follows. In NLOS environment, to be able to meet the QoS requirements, so much effort is needed to put since there are a lot of obstructions that may adversely affect the performance of the routing protocol. Larger number of data packets is a sign for such an effort. Multi-path routing algorithm in NLOS SG environments send many duplicate or retransmitted data packets by using multi-paths and multi-hops to be able to provide QoS requirements.

6.4. Overview of simulation results

Providing QoS differentiation for both reliability and timeliness domains in different SG environments is quite challenging. Hence, the goal of our work was towards accomplishing this challenging task. Our contributions in this paper is summarized as the followings:

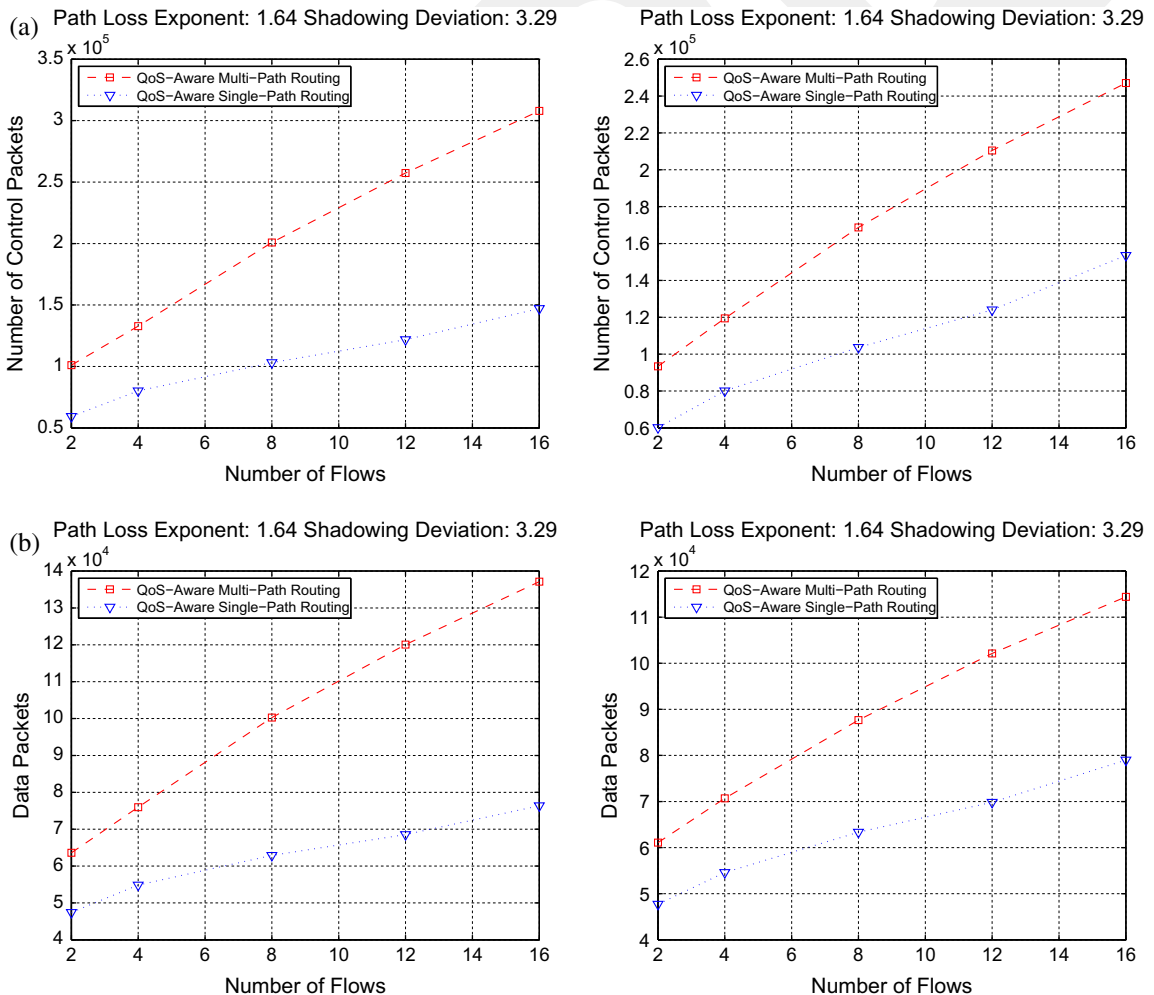


Fig. 11. Overhead versus number of flows for $n = 1.64$ and $\sigma = 3.29$. (a) Control packets and (b) data packets.

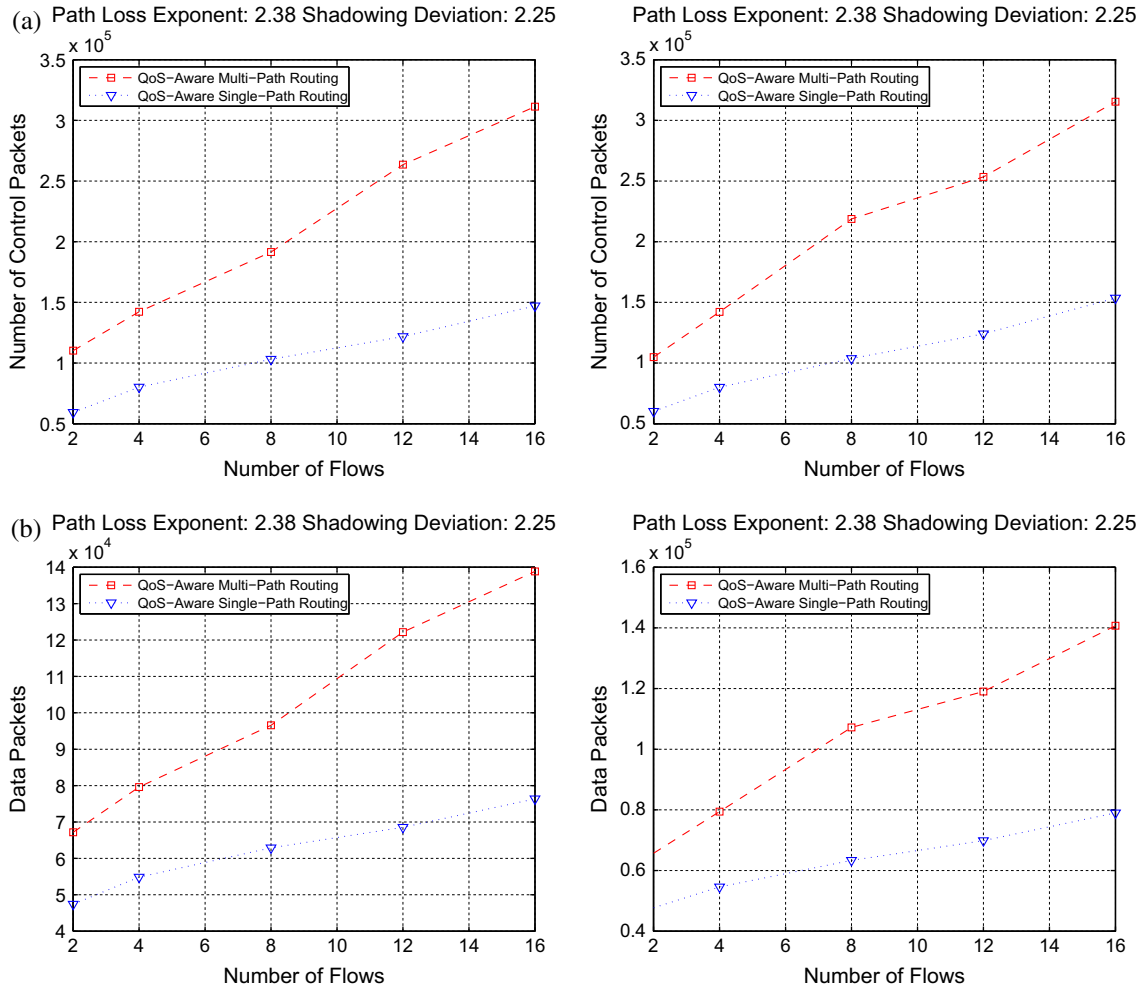


Fig. 12. Overhead versus number of flows for $n = 2.38$ and $\sigma = 2.25$. (a) Control packets and (b) data packets.

- A multi-path routing approach has been proposed for SG environment and log-normal shadowing model has been implemented for specific SG environments to better model the channel.
- The performance of the proposed routing approach has been tested for three different SG environments including a 500 kV substation, an industrial power control room, and an underground network transformer vault.
- A SG network consisting of 100 sensor nodes have been implemented on J-SIM network simulator.
- Extensive simulations have been generated to see the performance of the proposed approach in terms of average delays, on-time reachabilities and control packets.
- The performance results of both MMSPEED and SPEED routing protocols in different SG environments for have been compared.
- The effects of multi-path routing on network traffic density in different SG environments have been briefly presented.

From the evaluations, multi-path routing provides a clear differentiation with different reliability requirements,

as up to 25 flows under 0.7 reliability requirement and up to 10 flows under 0.2 reliability requirement have been supported in 500 kV Substation LOS environment. A clear differentiation with different deadline requirements is also provided since, up to 8 flows under 0.3 s deadline requirement and up to 11 flows under 1.0 s deadline requirement have been supported in 500 kV Substation LOS environment. As a result, multi-path routing accomplishes a significant service differentiation in both reliability and timeliness domain for SG environments.

7. Conclusion

Smart grid is the key solution to modernize the existing power grid which has been causing critical problems to the humanity with its aging infrastructure, hence the integration of advanced communication techniques has an important role in this process. Afterwards, the deployment of wired communication techniques means huge investment and maintenance costs and creates the inflexibility in extending the network range. Hence, WSNs will be the

perfect choice due to the low cost and rapid deployment characteristics for the smart grid environment. There are some requirements to design reliable and energy efficient WSNs and most of the routing protocols can meet just some of these requirements, however the proposed multi-path routing protocol provides a great service differentiation with different QoS requirements with different traffic flows in smart grid environments.

In this paper, research challenges of WSN-based potential smart grid applications have been summarized. Afterwards, a related work on reliability-aware and link-quality-aware routing protocols for WSNs has been studied. A routing approach is proposed which provides service differentiation in reliability and timeliness domain in different smart grid environments. Finally, performance evaluations have been carried out in different smart grid environments.

7.1. Future work

Our simulations are based on specific radio propagation parameters obtained from real sensor node implementations [2] and a multi-path routing approach is proposed for service differentiation. However, there are still open-research issues for routing algorithms in this specific environment. Here is a list of future work towards this promising research area:

- Due to the nature of multi-path routing, some additional features such as multi-path, multi-speed, more power consumption may be observed, however power consumption is not our focus in this paper, hence we can just do the estimations of the energy efficiency of the proposed protocol in SG environment. SG environment is a harsh and complex environment, hence a much more decrease on the link quality between sources and the sink can be observed [34,35]. This would cause multi-path routing protocol to try to find more redundant paths to send the data packets to meet QoS requirements and more retransmissions may occur. Hence, the energy consumption will be increased. In the future, we may work on measuring the actual power consumption of multi-path routing protocol in SG environment.
- Due to the dynamic nature of wireless channels, accomplishing an accurate link quality estimation is a challenging task [36]. In our experiments, Packet Reception Rate (PRR) is used as a link quality estimator. In future, we may try using a different link quality estimator and improve the performance results.
- Multi-path routing uses geographic routing mechanism based on location awareness using GPS technology which is an expensive, more energy consuming technology and it may lead some incorrect information about the location positions of the nodes at indoor coverage. Hence, some location position estimation algorithms can be used to improve the estimation results in future.
- In future, by using adaptive transmission power control techniques, we can dynamically change the communication range of the network.

Acknowledgment

This work was supported by Abdullah Gul University Foundation and the European Union FP7 Marie Curie International Reintegration Grant (IRG) under Grant PIRG05-GA-2009-249206.

References

- [1] J. Gao, Y. Xiao, J. Liu, W. Liang, C.L.P. Chen, A survey of communication/networking in smart grids, *Future Gener. Comp. Syst.* 28 (2) (2012) 391–404.
- [2] V.C. Gungor, L. Bin, G.P. Hancke, Opportunities and challenges of wireless sensor networks in smart grid, *IEEE Trans. Indust. Electron.* 57 (10) (2010) 3557–3564.
- [3] Dept. of Energy, Communications Requirements of Smart Grid Technologies, 2010.
- [4] DRCL J-Sim <<http://www.j-sim.org>>, 2005.
- [5] N. Saputro, K. Akkaya, S. Uludag, A survey of routing protocols for smart grid communications, *Comp. Netw.* 56 (11) (2012) 2742–2771.
- [6] J. Shin, U. Ramachandran, M. Ammar, On improving the reliability of packet delivery in dense wireless sensor networks, in: Proceedings of the 16th International Conference on Computer Communications and Networks, 13–16 August 2007, pp. 718–723.
- [7] M. Erol-Kantarci, H.T. Mouftah, Wireless multimedia sensor and actor networks for the next generation power grid, *Ad Hoc Netw.* 9 (4) (2011) 542–551.
- [8] E. Felemban, C.-G. Lee, E. Ekici, R. Boder, S. Vural, MMSPEED: multipath multi SPEED protocol for QoS guarantee of reliability and timeliness in wireless sensor networks, *IEEE Trans. Mob. Comput.* 5 (6) (2006) 738–754.
- [9] I.F. Khan, M.Y. Javed, F. Arif, Quality assurance of energy aware routing algorithm for wireless sensor networks, in: Proceedings of the 2nd International Conference, Computer and Automation Engineering, vol. 1, 26–28 February 2010, pp. 168–170.
- [10] M. Krogmann, T. Tian, G. Stromberg, M. Heidrich, M. Huemer, Impact of link quality estimation errors on routing metrics for wireless sensor networks, in: Proceedings of the 5th International Conference on Intelligent Sensors, Sensor Networks and Information Processing, 7–10 December 2009, pp. 397–402.
- [11] D. Lai, A. Manjeshwar, F. Herrmann, E. Uysal-Biyikoglu, A. Keshavarzian, Measurement and characterization of link quality metrics in energy constrained wireless sensor networks, in: Proceedings of IEEE Global Telecommunications Conference, 1–5 December, vol. 1, 2003, pp. 446–452.
- [12] J. Chen, R. Lin, Y. Li, Y. Sun, LQER: a link quality estimation based routing for wireless sensor networks, *Sensors* 8 (2) (2008) 1025–1038.
- [13] B. Deb, S. Bhatnagar, B. Nath, RelnForm: reliable information forwarding using multiple paths in sensor networks, in: Proceedings of the IEEE International Conference on Local Computer Networks, 2003, pp. 406–415.
- [14] K. Daabaj, M. Dixon, T. Koziniec, K. Lee, Trusted routing for resource-constrained wireless sensor networks, in: Proceedings of the IEEE/IFIP International Conference on Embedded and Ubiquitous Computing, 2010.
- [15] S. Bhatnagar, B. Deb, B. Nath, Service differentiation in sensor networks, in: Proceedings of the Fourth International Symposium on Wireless Personal Multimedia Communications, September 2001.
- [16] C. Lu, B.M. Blum, T.F. Abdelzaher, J.A. Stankovic, T. He, RAP: a real-time communication architecture for large-scale wireless sensor networks, in: Proceedings of the Real-Time and Embedded Technology and Applications Symposium (RTAS 2002), September 2002, pp. 55–s66.
- [17] K.Y. Shin, J. Song, J. Kim, REAR: reliable energy aware routing protocol for wireless sensor networks, in: Proceedings of the 9th International Conference on Advanced Communication Technology, 12–14 February, vol. 1, 2007, pp. 525–530.
- [18] J. Heo, J. Hong, Y. Cho, EARQ: energy aware routing for real-time and reliable communication in wireless industrial sensor networks, *IEEE Trans. Indust. Inform.* 5 (1) (2009) 3–11.
- [19] V.C. Gungor, C. Sastry, S. Zhen, R. Integlia, Resource-aware and link quality based routing metric for wireless sensor and actor networks, in: Proceedings of IEEE International Conference on Communications, 24–28 June 2007, pp. 3364–3369.

- [20] P. Park, C. Fischione, A. Bonivento, K.H. Johansson, A. Sangiovanni-Vincent, *Breath: an adaptive protocol for industrial control applications using wireless sensor networks*, *IEEE Trans. Mob. Comput.* 10 (6) (2011) 821–838.
- [21] J. Sen, *An adaptive and multi-service routing protocol for wireless sensor networks*, in: *Proceedings of the 16th Asia-Pacific Conference on Communications (APCC)*, October 31–November 3 2010, pp. 273–274.
- [22] M.S. Kordafshari, A. Pourkabirian, K. Faez, A.M. Rahimabadi, *Energy-efficient SPEED routing protocol for wireless sensor networks*, in: *Proceedings of the Fifth Advanced International Conference on Telecommunications*, 2009, pp. 267–271.
- [23] B. Nefzi, Y.-Q. Song, *QoS for wireless sensor networks: enabling service differentiation at the MAC sub-layer using CoSenS*, *Ad Hoc Netw.* 10 (4) (2012) 680–695, <http://dx.doi.org/10.1016/j.adhoc.2011.06.009>.
- [24] B.C. Villaverde, S. Rea, D. Pesch, *InRoute – a QoS aware route selection algorithm for industrial wireless sensor networks*, *Ad Hoc Netw.* 10 (4) (2012) 458–478, <http://dx.doi.org/10.1016/j.adhoc.2011.07.015>.
- [25] K. Akkaya, M. Younis, *Energy and QoS aware routing in wireless sensor networks*, *Clust. Comput.* 8 (2–3) (2005) 179–188, <http://dx.doi.org/10.1007/s10586-005-6183-7>.
- [26] S. Sanati, M.H. Yaghmaee, A. Beheshti, *Energy aware multi-path and multi-SPEED routing protocol in wireless sensor networks*, in: *Proceedings of 14th International CSI, CSICC 2009*, Tahrán, December 2009, pp. 640–645.
- [27] S. Poojary, M.M.M. Pai, *Multi-path data transfer in multimedia wireless sensor networks*, in: *Proceedings of the Fifth International Conference on Broadband and Wireless Computing, Communication and Applications*, Fukuoka, Japan, November 2010, pp. 379–383.
- [28] M. Krogmann, M. Heidrich, D. Bichler, D. Barisic, G. Stromberg, *Reliable, real-time routing in wireless sensor and actuator networks*, *ISRN Commun. Network.* 2011, 8 <<http://dx.doi.org/10.5402/2011/943504>> (Article ID 943504).
- [29] B. Yahya, J. Ben-Othman, *Energy efficient and QoS based routing protocol for wireless sensor networks*, *J. Paral. Distrib. Comput.* 70 (8) (2010) 849–857.
- [30] T. He, J. Stankovic, C. Lu, T. Abdelzaher, *SPEED: a stateless protocol for real-time communication in sensor networks*, in: *Proceedings of the IEEE International Conference on Distributed Computing Systems*, 2003, pp. 46–55.
- [31] D.B. Johnson, D.A. Maltz, *Dynamic source routing in ad hoc wireless networks*, in: *Mobile Computing*, Kluwer Academic Publishers, 1996, pp. 153–181 (Chapter 5).
- [32] C.E. Perkins, E.M. Royer, *Ad-hoc on demand distance vector routing*, in: *Proceedings of the WMCSA'99*, February 1999.
- [33] S. Darabi, N. Yazdani, O. Fatemi, *Multimedia-aware MMSPEED: a routing solution for video transmission in WMSN*, in: *Proceedings of the 2nd International Symposium on Advanced Networks and Telecommunication Systems*, 15–17 December, 2008, pp. 1–3.
- [34] G. Tuna, V.C. Gungor, K. Gulez, *Wireless Sensor Networks for Smart Grid Applications: A Case Study on Link Reliability and Node Lifetime Evaluations in Power Distribution Systems*, *Int. J. Distrib. Sens. N.* 2013 (2013) 11, <http://dx.doi.org/10.1155/2013/796248>. Article ID 796248.
- [35] N. Kilic, V.C. Gungor, *Analysis of low power wireless links in smart grid environments*, *Comput. Netw.* 57 (5) (2013) 1192–1203.
- [36] B.E. Bilgin, V.C. Gungor, *Adaptive error control in wireless sensor networks under harsh smart grid environments*, *Sens. Rev.* 32 (3) (2012) 203–211.



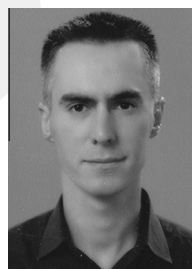
Dilan Sahin received B.S. degrees in computer engineering and in software engineering from Bahcesehir University, Istanbul, Turkey, in 2010. Currently, she is a Research Assistant with the Computer Engineering Department, Bahcesehir University, Istanbul, Turkey. Her current research interests are in wireless sensor networks and smart grid communication and applications.



Vehbi Cagri Gungor received his B.S. and M.S. degrees in Electrical and Electronics Engineering from Middle East Technical University, Ankara, Turkey, in 2001 and 2003, respectively. He received his Ph.D. degree in electrical and computer engineering from the Broadband and Wireless Networking Laboratory, Georgia Institute of Technology, Atlanta, GA, USA, in 2007. Currently, he is an Associate Professor and Chair of Computer Engineering Department, Abdullah Gul University (AGU), Kayseri, Turkey. His current research interests are in smart grid communications, machine-to-machine communications, next-generation wireless networks, wireless ad hoc and sensor networks, cognitive radio networks, and IP networks. Dr. Gungor has authored several papers in refereed journals and international conference proceedings, and has been serving as an Editor, and program committee member to numerous journals and conferences in these areas. He is also the recipient of the IEEE Transactions on Industrial Informatics 2012 Best Paper Award, the IEEE ISCN 2006 Best Paper Award, the European Union FP7 Marie Curie IRG Award in 2009, Turk Telekom Research Grant Awards in 2010 and 2012, and the San-Tez Project Awards supported by Alcatel-Lucent, and the Turkish Ministry of Science, Industry and Technology in 2010.



Taskin Kocak received the Ph.D. degree from Duke University, Durham, NC, in 2001. He is currently a Full Professor of computer engineering with Bahcesehir University, Istanbul, Turkey. Previously, he was on the faculties of the University of Bristol, Bristol, UK, and the University of Central Florida, Orlando. His research interests are in computer networks and communications and hardware design (computer architecture and VLSI). His research activities have produced over 100 peer-reviewed publications, including 38 journal papers, and have been supported by American, British, Japanese and Turkish funding agencies and companies, including Northrop Grumman, Toshiba Research Europe, Great Western Research, ClearSpeed Technology, KDDI, Turk Telekom, and Alcatel-Lucent. He served as an associate editor for the *Computer Journal* (2007–2009) and as a guest editor for a special issue of the *ACM Journal on Emerging Technologies in Computing Systems*.



Gurkan Tuna serves as an Asst. Prof. at Edirne Vocational School of Technical Sciences, Trakya University, Edirne, Turkey. He received his B.S. degree in computer engineering from Yildiz Technical University, Istanbul, Turkey, in 1999, and his M.S. degree in computer engineering from Trakya University, Edirne, Turkey, in 2008. He received his Ph.D. degree in electrical engineering from Yildiz Technical University, Istanbul, Turkey, in 2012. Tuna has authored several papers in international conference proceedings and refereed journals. He has been serving as a reviewer for international journals and conferences. His current research interests include smart grid, ad hoc and sensor networks, robotic sensor networks, multirobot simultaneous localization and mapping, and cooperative exploration strategies.