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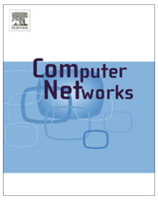

Routing protocol design guidelines for smart grid environments

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ABSTRACT

The evaluation of the current electric power grid with novel communication facilities is one of the most challenging and exciting issues of the 21st century. The modern grid technology is called the smart grid in the sense that it utilizes digital communication technologies to monitor and control the grid environments, which ultimately require novel communication techniques to be adapted to the system. Wireless sensor networks (WSN) have recently been considered as a cost-effective technology for the realization of reliable remote monitoring systems for smart grid. However, problems such as noise, interference and fading in smart grid environments, make reliable and energy-efficient multi-hop routing a difficult task for WSNs in smart grid. Our main goal is to describe advantages and applications of WSNs for smart grid and motivate the research community to further investigate this promising research area. In this study we have investigated and experimented some of the well-known on-demand, table-driven and QoS-aware routing protocols, in terms of packet delivery ratio, end-to-end delay, and energy consumption to show the advantages and disadvantages of each routing protocol type in different smart grid spectrum environments. The environmental characteristics which are based on real-world field tests are injected into ns-2 Network Simulator and the performance of four different multi-hop routing protocols is investigated. Also, we have shown that traditional multi-hop routing protocols cannot deliver adequate performance on smart grid environments. Hence, based on our simulation results, we present some guidelines on how to design routing protocols specifically for smart grid environments.

1. Introduction

The smart grid is the modernization of the existing electric power grid, which mainly has a centralized energy generation and a unidirectional energy distribution. The current power grid suffers from the limited and unreliable communication and monitoring facilities, which cause the existing grid to be unreliable and ineffective [8]. By integrating various digital communication technologies to the power grid, new functionalities and applications for different electricity consumers (industrial, commercial, residential) will be realized.

With the increased use of various digital control and communication techniques for smart grid applications and development of smart grid communications standards, the reliability, security and efficiency of the electric grid will be enhanced. By establishing bi-directional flows of communication and control capabilities, a sustainable and effective electricity generation, transmission, distribution, and utilization for current and future generations is envisioned. Moreover, with the new grid smooth transition to renewable sources, reduced greenhouse gas emissions and resistance to both physical and cyber attacks are also targeted [9].

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There is a tradeoff between the utilization of wired communication and sensor systems and WSNs into the smart grid. Utilization of wired communication systems can be regarded as a more robust infrastructure, however, it would necessitate much more investment and maintenance costs. Also wired sensors would decrease the network scalability which ultimately will cause inflexibility in the new grid. On the other hand, WSNs will be one of the most feasible means to realize embedded electric power grid monitoring and diagnostic systems [35]. In these systems, sensors are deployed on the critical equipment of the smart power grid to measure various system parameters, such as conductor temperature, voltage and dynamic thermal rating line fault detection, outage detection [11–14]. These sensor measurements will then be sent to utility control centers via sink nodes, which may reside in the network gateways. The existing WSNs applications on smart grid vary on a wide range. Some of the applications are: automatic meter reading, equipment diagnostics, automation of distribution, detection of outage, remote monitoring, fraud detection, etc. [23–26]. However, as stated in [6], there exist many problems of deploying WSNs in smart-grid applications. These problems can be summarized as follows:

- ***Harsh environmental conditions:*** In WSN-based smart grid applications, due to the obstructions and the noisy environment, the wireless links show different characteristics over time and space. Thus, wireless link capacity is limited and changes continuously.
- ***QoS provisioning:*** The wide variety of WSN applications has different QoS requirements making QoS provisioning a difficult task. Furthermore, due to the time sensitive nature of the sensor data, it is regarded as a vital subject to transmit the data to controller in time.
- ***Sensor parameters:*** The adaptability of WSNs in smart grid is important, since it enables end-users to cope with dynamic link-quality and topology changes in smart grid environments. In this respect, choosing the appropriate sensor parameters, such as energy scheme, transmission range, and multi-hop routing protocol, is critical to meet application objectives.
- ***Large-scale deployment and ad hoc architecture:*** In most of the smart grid applications, large number of sensor nodes is utilized. Also WSNs are obliged to establish multi-hop network connections because the network infrastructure is not predetermined. Hence, reliable multi-hop routing becomes a vital issue to design a WSN-based smart grid application.

In spite of the recent interest in smart grid applications based on WSNs, wireless multi-hop routing in different smart grid environments is still a vastly unexplored area. To address this need we evaluated and tested different types of routing protocols, such as on-demand (AODV and DYMO), table-driven (DSDV) and QoS-aware (TUQR) routing protocols, in terms of packet delivery ratio, end-to-end delay, and energy consumption to show the advantages and disadvantages of each routing protocol type in different smart grid spectrum environments. In this work, we present and describe the advantages challenges of WSNs for smart grid, specifically on the network layer and motivate the research community to further investigate this research area. Consequently, the main contributions of this study can be summarized as follows:

- Performance evaluations of different types of multi-hop routing protocols, such as on-demand (AODV and DYMO), table-driven (DSDV) and QoS-aware (TUQR) routing protocols, have been conducted specifically under harsh smart grid spectrum environments. Based on these evaluations, important design guidelines on how to develop routing protocols specifically for smart grid environments have been presented.
- The smart grid environmental characteristics (which are taken from real-world field tests using IEEE 802.15.4 compliant wireless sensor nodes [6]) are injected into ns-2 Network Simulator. Upon request, the complete experimental data will be made available. This can help the research community develop novel wireless communication protocols for smart grid applications.

The paper is organized as follows. In Sections 2, WSN-based smart grid characteristics and applications are summarized and the opportunities and challenges of applying WSNs in smart grid are reviewed. In Section 3, the related work on smart grid communications is presented. In Sections 4 and 5, evaluated WSN routing protocols, performance evaluations and an overview of simulation results are explained, respectively. The paper is concluded in Section 6.

2. Smart grid characteristics and applications

The transition to smart grid requires re-establishing and modifying many technologies of the current electric grid. In this sense, smart grid is expected to meet the following principal characteristics towards the demands of the 21st century [17]:

- ***Self-heals:*** The modern grid will be fault tolerant by performing continuous self assessments. To avoid system failures and recover the system timely, it needs to rapidly detect, analyze and respond to system faults. This requires robust and effective communication protocols especially for WSN-based smart grid applications.
- ***Includes consumer:*** In existing power grid, consumers are not informed and non-participative with the power grid. To reduce the cost of delivered electricity, consumers will involve into the decision process of electrical power grid.
- ***Resists to attacks:*** In order to improve public safety, the new grid will be able to protect the system from any cyber and physical attacks.
- ***Accommodates all generation and storage options:*** The modern grid will have very large numbers of diverse distributed power generation (e.g. wind energy, renewable energy) and power storage devices deployed to complement the large generating plants.

- ***Has optimization of asset and operation efficiency:*** Today's electrical grid has minimal integration of limited operational data with asset management processes and communication technologies. The smart grid will be able to monitor and optimize the capital assets by minimizing operation and maintenance expenses.

It is very challenging to meet all aforementioned characteristics. Importantly, the network designers and application developers should balance the tradeoffs among the different application requirements while developing communication protocols and architectures.

Overall, as shown in Fig. 1, there are several potential WSN-based smart grid applications that can be realized in different smart grid environments, such as in power stations, transmission sub-systems, distribution subsystems, customer premises. These applications vary from the usage of sensors, integrated smart meters, and appliances within the customer's premises; networks of field components between distribution and control substations to customers' and market's premises.

vIn the literature, different WSN solutions for the smart grid have been proposed [6,11–13]. In [11], an online and self-powered WSN-based conductor temperature monitoring application is introduced. This information is required by various controlling units, such as local energy management system and central utility, for monitoring and controlling purposes in smart grid. WSN-based smart grid applications, which deal with blackouts, have been proposed in [11–13]. These studies show that electrical earth and currency faults, earthling of phase line, and other environmental problems may cause devastating problems on smart grid, which may ultimately cause blackouts.

For the time being, the blackouts and lower power quality costs billions of funds each year because of the lack of a robust online monitoring system. For example, still in many areas of the United States, outage is detected only if a customer calls to report it by phone. By utilizing WSNs, reliable online monitoring control systems can be achieved. Besides these, inspecting and maintaining the failures of poles and towers in the power grid in a timely manner is vitally essential to system integrity and reliability of the system because blackout repairs cost huge amounts. Hence, various management systems and measurement techniques for smart grid are proposed in the literature so far. Another WSN-based smart grid application is online monitoring of conductor gallop, which is the high-amplitude, low-frequency oscillation of overhead power lines due to the wind. While it may cause mechanical failures, which ultimately cause blackouts, it is very important to detect conductor galloping. In [11], numerical modeling of the system behavior is presented with the tests performed on the experimental results. A solution, which has been focused on avoiding conductor galloping by using certain anti-vibration or to limit the bundle oscillations within safe values have been presented and discussed.

WSN-based power distribution fault identification tools are often essential for effective outage restorations in smart grid. In the power grid, power distribution faults can be caused by tree and animal contact to power lines or towers [11]. In [28], two popular classification methods; logistic regression (LR) and artificial neural network (ANN) applied on power distribution fault cause are illustrated to overcome the problems caused by animals and trees.

Another usage of WSNs in smart grid will be developing solutions to power fraud issues. With the usage of Wireless Automatic Meter Reading (WAMR), power fraud can be tackled or minimized [13]. The lack of online monitoring also disables the existing power distribution grid to detect outages. This puts the current system in an unreliable situation. With the online and bi-directional data flow characteristics of WSNs, reliability can be increased by implementing outage detection and online monitoring systems [14]. In Table 1, an overview of some of these potential applications and their corresponding power grid segments are summarized. In the following section, the related work on smart grid communications has been presented.

3. Related work on smart grid communications

Recent developments in the power industry point out that standardization is a key issue in smart grid in order to enable end-to-end data exchange between various components of the smart grid [18,19]. In [9], priority areas for standardization and a list of standards that need to be refined, developed and implemented have been shown.

Among these standardization efforts, there are various studies for smart grid communications such as in [20,38], ZigBee performance is evaluated under different smart grid environments. It is also shown that ZigBee presents promising performance results when the WiFi interference is moderate [10,15]. ZigBee is a promising technology for

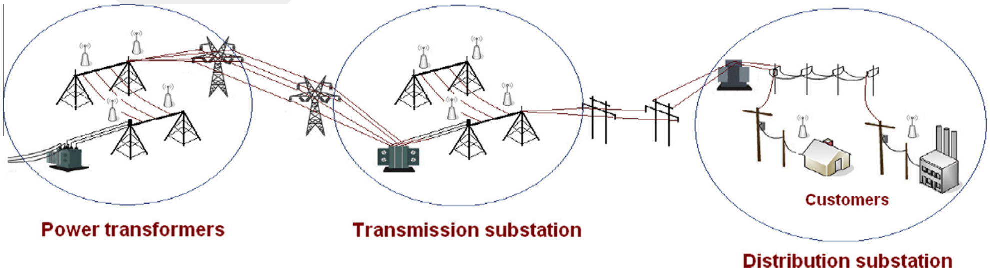

Fig. 1. Deploying WSN-based smart grid applications on power transformers, transmission substations, distribution substations and customer premises.

Table 1
Examples of WSN applications for smart grid.

Application	Feature	Usage segment
Automatic Meter Reading (WAMR) Systems	Online pricing, online metering, self power usage control	Consumer
Blackout detection	Detecting electrical earth, currency faults, earthling of phase line, environmental problems, etc.	Transmission, distribution
Conductor galloping detection	Avoiding or limiting by using certain anti-vibration techniques	Transmission, distribution
Tree and animal contact detection	Logistic regression and artificial neural network, applied on power to overcome the problems caused by animals and trees	Transmission, distribution
Power fraud detection	With the usage of WAMR systems, power fraud can be tackled or minimized	Consumer

the smart grid applications . However, the frequency bands of the WiFi and ZigBee fall in the same spectrum. Therefore, in [21] a frequency interference avoidance algorithm, including interference detection and smart channel selection is proposed. Also in [22], an application of cognitive radio communications for smart grid WANs is proposed. It is stated that, the cognitive radio links based on the IEEE 802.22 standard are desirable in smart grid networks since they do not require initial capital investment in the licensed spectrum.

It is foreseen that WSNs will provide grid-wide monitoring of utility assets in terms of enhancing system reliability and asset utilization. To support this idea, an overview of the highlights and gaps in currently available sensor technologies, both from a performance and cost point is stated in [11]. In [23], an application of low cost IPv6 based WSN in distributed generation is proposed. The WSN used in the proposed scheme is based on IEEE 802.15.4 link layer technology. It is also shown that with application of WSN, it is possible to overcome the power sharing challenges in distributed generations and improve the system reliability. Also in [24], a linear network model and its insufficiencies in supporting future smart grid applications is analyzed. To deal with this issue, they propose the extension of the wireless communication capability of the relay sensors. However, in this study, the performance evaluations of this proposed network model against realistic channel parameters is missing.

Although all these studies provide solid and valuable foundations in smart grid communications, none of them focuses on employment of multi-hop WSN routing protocols for smart grid applications. Hence, there is a need for performance evaluations of multi-hop routing protocols in different smart power grid spectrum environments. In the following section, we give an overview of routing protocols used in our performance evaluations.

4. Overview of evaluated routing protocols

Application requirements of the smart grid raise new challenges at the network layer of the protocol stack with respect to routing and data forwarding [36]. Hence, there is a need to analyze the advantages and disadvantages of different types of routing protocols in various smart grid environments. In this study we have investigated and experimented some of the well-known on-demand, table-driven and QoS-aware routing protocols, in terms of packet delivery ratio, end-to-end delay, and energy consumption in line-of-sight (LOS) and non-line-of sight (NLOS) smart grid propagation environments.

4.1. AODV

The AODV routing protocol was intended to be used in MANETs. It determines unicast routes to destinations within the ad hoc network and uses destination sequence numbers to ensure loop free communication avoiding problems such as “counting to infinity” associated with classical distance vector protocols. The AODV routing algorithm is an on-demand (reactive) algorithm meaning that it builds routes between nodes only when desired by source nodes. When a source node wants to send a packet to a destination, it broadcasts a route request (RREQ) packet across the network. Other AODV nodes forward this message and record the node that they heard it from. These forwarding nodes set up backwards pointers to the source node in their route tables. A node receiving the RREQ may send a route reply (RREP) if it is either the destination or if it has a route to the destination with corresponding sequence number greater than or equal to that contained in the RREQ. Otherwise, the neighbor will re-broadcast the RREQ. If the source receives a RREP containing a greater sequence number or contains the same sequence number with a smaller hop count, it may update its routing information for that destination and begin using the better route [1,7].

4.2. DSDV

DSDV is a table-driven routing protocol designed for MANETs which was based on classical Bellman-Ford routing algorithm. The main contribution of the DSDV algorithm to the Bellman-Ford routing algorithm was to solve the Routing Loop problem [2]. In DSDV, every node has a full topological view of the network by maintaining a list of all destinations and hop counts to each destination. Each entry is marked with a sequence number. It uses full dump or incremental update to reduce network traffic generated by route updates. The broadcast of route updates is delayed by settling time. Routing information can always be readily available, regardless of whether the source node requires the information or not. DSDV solve the problem of routing loops and count to infinity by associating each route entry with a sequence number indicating its freshness. In DSDV, a sequence number is linked to a destination node, and usually is originated by that node (the owner). A non-owner node updates a sequence number of a route when it detects a link break on that route. A route with a newer sequence number is preferred and in the case that two routes have the same sequence number, the one with a better cost metric is preferred.

4.3. DYMO

DYMO is a multihop on-demand routing protocol which is intended for use in ad hoc networks and provides adaptation to frequently changing node topologies. Since DYMO has not yet been implemented commercially, the IETF standards are still in progress. Using AODV as the basis, DYMO borrows "Path Accumulation" from Dynamic Source Routing (DSR) and removes unnecessary Route Reply (RREP), precursor lists and Hello messages (Route exploration messages), thus simplifying AODV. It retains sequence numbers, hop count and Route Error (RERR) messages from AODV [4]. There two basic operations in DYMO which are "route discovery" and "route management". In order to find a route for the target node, in route discovery process, the source node broadcasts a RREQ message throughout the network. If the target node successfully gets the RREQ message, it then responds with a RREP message to the source node. Each node on the way that receives the RREP records a route for the target node. When the source node receives the RREP it means a route is established between the source and target nodes. When a packet is received for a route that is no longer available, the source node will be notified. A RERR is sent to the packet source to indicate the current route is broken. Once the source receives the RERR, it re-initiates route discovery if it still has packets to deliver. In this study we have used the DYMO-UM agent which is developed by Pedro M. Ruiz and Francisco Ros for NS-2 implementations [3].

4.4. TUQR

TUQR is developed by Zagli and Song [27]. In this work, a new protocol for QoS routing in ad hoc networks is developed to reduce the effects of distrustful environments by keeping a number of suitable paths as high as possible and distributing the decision mechanism among the nodes on the path. Among others, TUQR is a newer protocol. It aims to achieve QoS routing in ad hoc networks while reducing the effects of distrustful environments by keeping a number of suitable paths as high as possible and distributing the decision mechanism among the nodes on the path. In TUQR, each node is assumed to be capable of supplying: (i) The information delay time to neighbors by checking periodically. (ii) The average time that an individual packet spends in outgoing packet queue. In this protocol, neither of the nodes in the network have information about the path that will be followed by data packets. Instead, starting with the source node, each node just knows which neighbor(s) is/are declared to be capable of forwarding data packets under given delay constraint to the given destination. A forwarding node picks one of these neighbors according to the current local connection status and given delay constraint it forwards the data packet to that neighbor. This process is repeated on each node until the packet reaches to one of adjacent nodes of destination. This approach, as a whole, tries to avoid to be affected by wireless link status changes, by reacting them in a timely fashion and keeps the packet on its way using all possible resources of the network.

5. Performance evaluations

We have performed simulations in ns-2 Network Simulator. The ns-2 is a C++ based discrete event simulator equally good for simulating both the wired and wireless networks [5]. It is used by many researchers for analyzing protocols since its accuracy on the produced results between the real and simulated environments is well appreciated. In addition, we used the log-normal shadowing model as the channel model. This model uses a normal distribution with variance σ to distribute the received power in the logarithmic domain [16]. Recent experimental studies show that this model provides more accurate multipath channel models compared to the Rayleigh and Nakagami models for wireless environments with obstructions [6]. In this model, the signal to noise ratio $\gamma(d)$ at a distance d from the transmitter is given in Eq. (1),

$$\gamma(d)_{dB} = P_t - PL(d_o) - 10\eta\log_{10}\left(\frac{d}{d_0}\right) - X_\sigma - P_n \tag{1}$$

where Pt is the transmit power in dBm, $PL(d0)$ is the path loss at a reference distance $d0$, η is the path-loss exponent, $X\sigma$ is a zero mean Gaussian random variable with standard deviation σ, and Pn is the noise power in dBm.

The simulations are conducted in six different scenarios which correspond to environments of a 500 kV substation (LOS), a 500 kV substation (NLOS), an underground transformer vault (LOS), an underground transformer vault (NLOS), a main power room (LOS) and a main power room (NLOS). The log-normal shadowing model parameters are obtained from our previous work [6], where numerous field tests on IEEE 802.15.4-compliant wireless sensor nodes have been conducted in real-world power delivery and distribution systems at Georgia Power, Atlanta, GA, USA.

In this study, the comparison of the routing protocols is achieved by deploying 100 nodes in a 50 m × 50 m grid field in ns-2 and the simulation time is set to 1000 s. The number simulation times are 25 for each type of routing protocol for each type of smart grid environments. Also at every run, different prime number seed values are set.

The topology of the simulated network is presented in Fig. 2. As it can be seen from the figure, one node in the bottom right is selected as the sink and 5 nodes from the upper left corner are selected to be CBR (Constant Bit Rate) senders. The CBR packet size is set to 32 bytes due to energy efficiency issues and the interval is set to 10 packets/s. To promote randomness, we run the simulations with different seed values and take the averages of the results. Nodes are equipped with a single transmitter/receiver with IEEE 802.15.4 CSMA/CA based medium access control layer. The parameters used in our performance

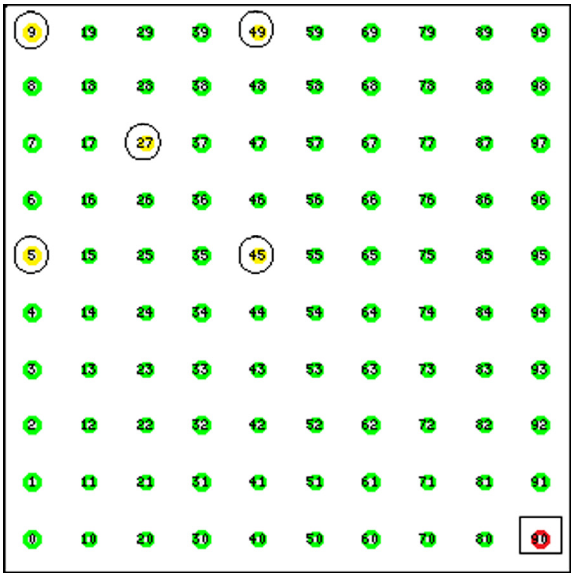

Fig. 2. Topology of the network, the nodes 5, 9, 27, 45 and 49 are senders and the node 90 is the sink node.

Table 2
Simulation parameters.

Number of nodes	100
Number of traffic flows	5
Packet length	32 Bytes
Queue type	Drop tail
Frequency band	868 MHz
Radio propagation model	Log-normal shadowing
MAC protocol	IEEE 802.15.4
Data rate	10 pkts/s
Routing protocols	AODV, DSDV, DYMO, TUQR
Simulation time	1000 s
Number of simulations for each protocol	25

Table 3
Log-normal shadowing model parameters.

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 network transformer vault (LOS)	1.45	2.54
Underground network transformer vault (NLOS)	3.15	3.19
Main power room (LOS)	1.64	3.29
Main power room (NLOS)	2.38	2.25
Non-smart grid environment	1.4	4

evaluations are listed in Table 2 and the log-normal shadowing model parameters are listed in Table 3. Also as a benchmark, we have extended our simulations on a non-smart grid environment. It can be followed from Table 3 that the path loss exponent and standard deviation parameters of a non-smart grid environment is chosen to be 1.4 and 4.0 respectively which reflects an indoor environment [41].

In the performance evaluations, we investigate the following performance metrics:

- ***Packet Delivery Ratio*** is the ratio between the number of successful packets and the total number of transmitted packets.
- ***Average Network Delay*** is the average time to receive all data on the destination nodes.
- ***Energy Consumption*** represents the overall average percentage of the consumed energy by nodes.

5.1. Packet delivery ratio

Packet Delivery Ratio (PDR) is the ratio between the number of the successful delivered CBR packets and the number of the generated CBR packets. As shown in Eq. (2) this is calculated by dividing the number of packets received by the destination ($\sum CBR_r$) through the number of packets transmitted by the application layer of the source ($\sum CBR_t$). It is an important metric which indicates the congestion level of the network. PDR measures the protocol performance from loss ratio experienced at the network layer that is affected by factors such as packet size, and network load. The higher the delivery ratio, the more complete and correct is the routing protocol.

$$PDR = \frac{\Sigma CBR_r}{\Sigma CBR_t} \tag{2}$$

In Fig. 3, the PDR (%) values of the AODV, DSDV, DYMO, and TUQR routing protocols which correspond to both LOS and NLOS smart grid environments of an outdoor 500-kV substation, an indoor main power room and an underground network transformer vault are shown, respectively. As we can see from Fig. 3 that the TUQR produces the maximum and the AODV produces the minimum PDR results in average. We can also infer from Fig. 3 that the average performance of both routing protocols produce better results in LOS environments than in NLOS environments. For example, DSDV produces 51% and 32% PDR results in 500-kV substation (LOS) and 500-kV substation (NLOS) environments consecutively. AODV produces 50% and 45% PDR results in the main power room of LOS and NLOS environments. The same evaluations are also valid for the other protocols. This can be due to the worse conditions in the NLOS environments that, when the network is disconnected, the routing protocols react to errors by trying to find alternative routes. If the disconnections are frequent, the data is queued at the nodes, waiting to be forwarded, and starts to get dropped as queues fill up which ultimately increases latency.

In the harsh conditions of the smart grid environments, disconnections are so frequent eventually causing the routing protocols to perform poorly. This situation is more obvious for the AODV protocol. AODV can be regarded as a base and benchmark protocol for MANETs, however it is proven that AODV has a huge overhead in a static network traffic due to the fact that high frequency of periodic rediscovery of neighbors is not necessary [39,40]. As expected, the DYMO gives better PDR results than the AODV in all

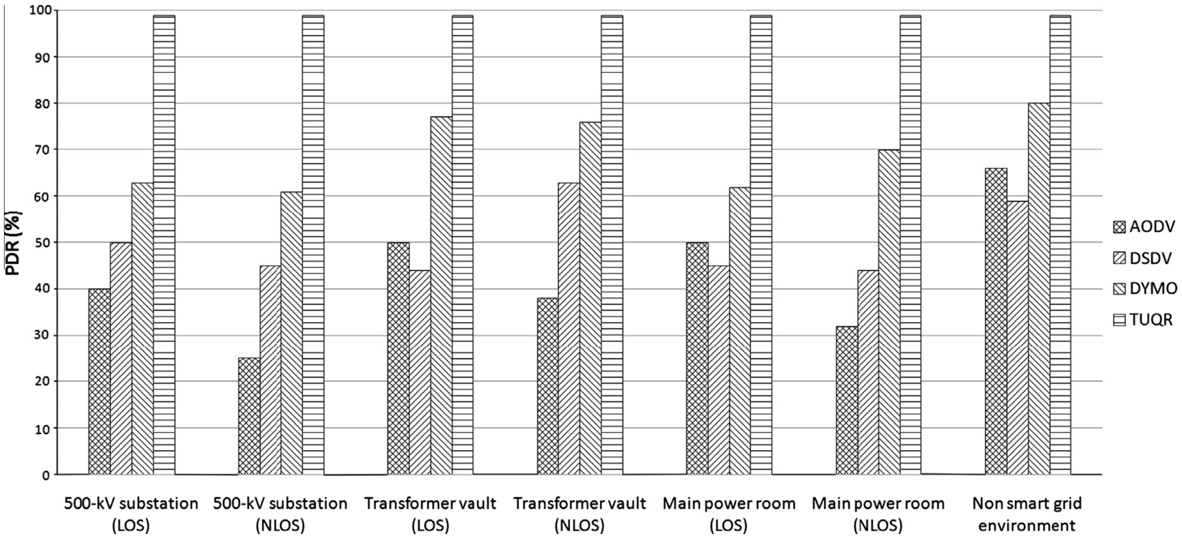

Fig. 3. Packet delivery ratio (PDR) of AODV, DSDV, DYMO and TUQR routing protocols in different smart grid environments.

the environments. This can be because of the fact that, DYMO removes unnecessary RREQ, precursor lists and Hello messages, thus simplifying the AODV.

5.2. Average network delay

Average Network Delay (Avg_d) is the average time it takes a data packet to reach the destination divided by the connection pairs (cp) of the simulation. As shown in Eq. (3) this metric is calculated by subtracting the time at which first packet was sent by source (t_s) from the time at which the first data packet arrived to the destination (t_d). This delay includes all possible delays that are caused by route discovery latency, queuing in the interface queue, retransmission at the MAC layer and propagation through the environment.

$$Avg_d = \frac{\Sigma(t_d - t_s)}{cp} \tag{3}$$

In Fig. 4 the Average Network Delay results which correspond to the AODV, DSDV, DYMO and TUQR routing protocols in LOS and NLOS smart grid environments are shown. It can be seen in Fig. 4 that in both six environments, DYMO and DSDV protocols produce minimum network delay, which put these algorithms to be a good candidate for smart grid environments when the average delay metric alone is chosen to be a performance metric. However, in ad hoc environments both PDR, average network delay and energy consumption values have to be taken into account in order to choose an appropriate multi-hop routing protocol. As can be seen from Figs. 4 and 5, the average delay and energy consumption values of the DSDV and DYMO protocols are not sufficient to be good candidates. In addition, the delay results of the TUQR and AODV protocols are also very high in average. When the PDR results are high we could expect the delays to be higher proportionally but surprisingly, the average delay results can be considered low.

5.3. Average energy consumption

The average energy consumption of all nodes in the simulations is calculated by setting the ns-2 energy model parameters. These parameters, such as transmit power and received power are set to 35.28 mW and 31.32 mW consecutively. At the very beginning of the simulations, the initial power of each node is set to 100 J. By iteration, the energy consumption of each node in six different smart grid environments is calculated by subtracting each node's final energy value from the initial energy value. All of the energy consumption values for each node are aggregated and averaged. In the simulations, the energy model of the ns-2 is utilized. The energy model is a node attribute which represents the level of energy in a wireless node [5]. In the energy model, an initial energy value is applied to all nodes at the beginning of the simulation. For calculation ease we set the initial energies of all nodes to 100 J.

When we look at Fig. 5, we can infer that in NLOS environments, the energy consumption is higher than in LOS environments because of the high number of retransmissions and packet drop ratios of the harsh NLOS environments. For example the average energy consumption of the DYMO is 1.4% in 500-kV substation LOS environment and 1.6% in 500-kV substation NLOS environment. One interesting result is taken from the TUQR routing protocol where the energy consumption of this protocol is very high with respect to other protocols. The reason this protocol consumes extremely high energy is that; as stated in [27], TUQR is designed for multi-hop networks where energy consumption is not a constraint and thus, several retransmissions occur until the packet is delivered to the destination.

6. Overview of simulation results

One important feature of the smart grid is the integration of reliable and secure data communication networks

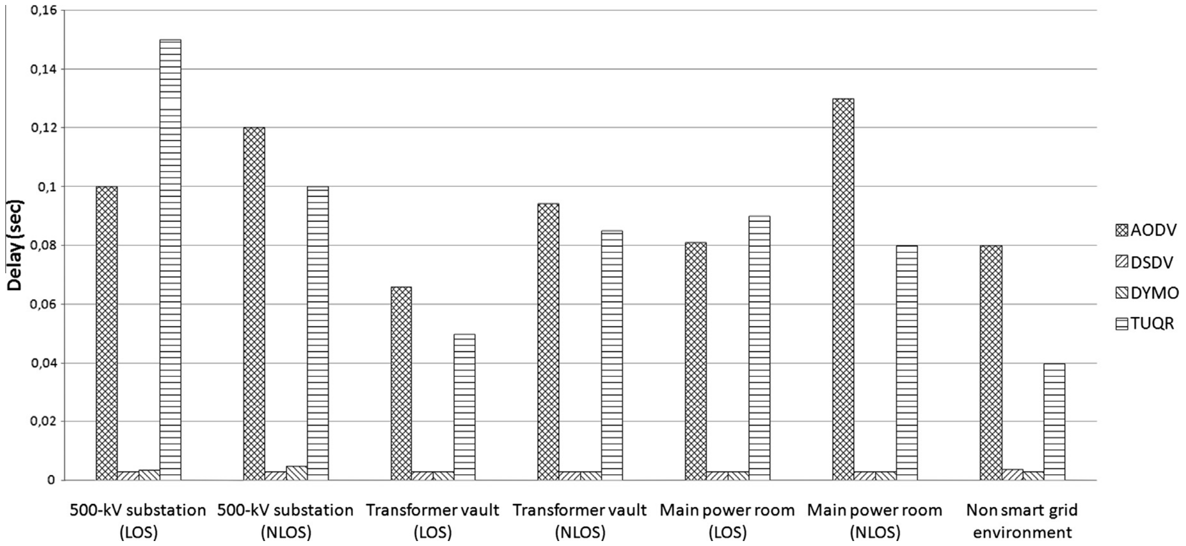

Fig. 4. Average network delay of AODV, DSDV, DYMO and TUQR routing protocols in different smart grid environments.

to manage the complex power systems effectively [37]. However, there are many physical channel impairments, such as low link quality, low data rate, high or variable latency [6] in smart grid environments. In our simulation tests we have observed that these conditions affect overall wireless multi-hop routing performance in WSN-based smart grid applications. The results of the performance evaluations can be summarized as follows:

- The energy consumption of the sensor nodes is higher in NLOS environments because of the high number of retransmissions and packet drop ratios. In addition, we have observed that on-demand routing protocols use energy slightly more efficiently than the table-driven protocols.
- If just PDR is chosen to be the only metric to select the appropriate routing protocol, TUQR seems to be a good candidate. However, the average delay and power consumption of this protocol is extremely high.
- The number of deployed nodes in the area affects the routing performance directly. As shadowing model states; when deploying nodes so close to each other, the probability that two nodes cannot communicate will be high, although it can also happen with a certain probability that two nodes beyond the deterministic transmission range (which bases on the transmit power, transmitter/receiver power threshold values of the sensors). In our simulation results we observed this phenomenon, where by deploying 100 nodes, we have achieved the most effective results.
- The harsh electric-power-system environments, in terms of the shadowing deviation and path loss exponent parameters, affect the performance values of routing algorithms. When we compare the overall performance

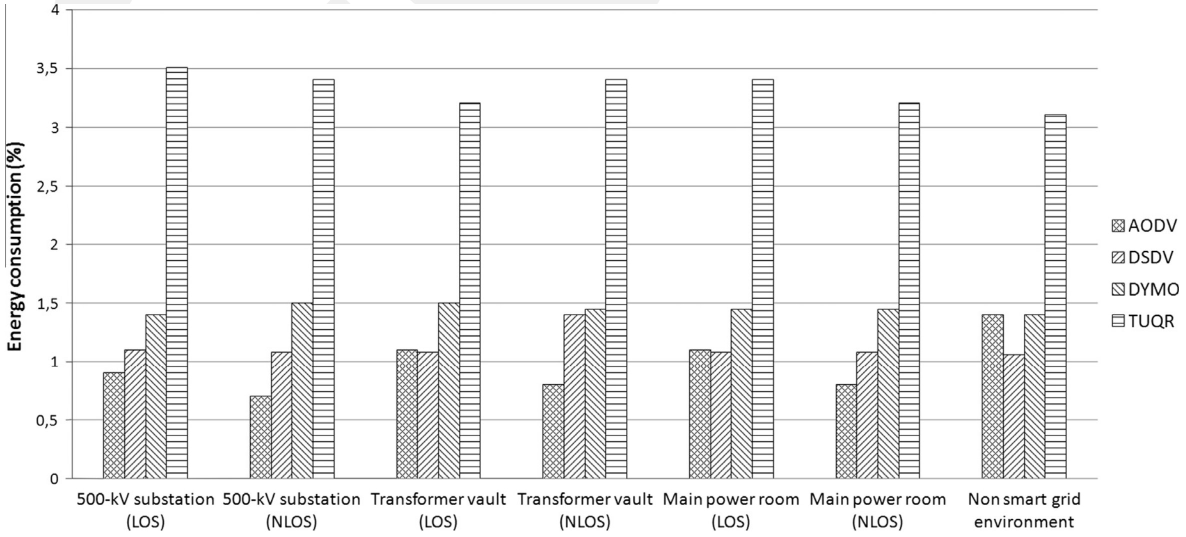

Fig. 5. Average energy consumption of AODV, DSDV, DYMO and TUQR routing protocols different smart grid environments.

results of LOS and NLOS environments, we have observed that LOS environments produce better PDR results than the NLOS environments. The harsh conditions cause packet delays and packet drops which ultimately affect the overall performance.

7. Routing design guidelines

Due to the harsh network characteristics of smart grid environments, such as background noise, high attenuation, and wireless propagation phenomena, WSNs suffer from volatile links and intermittent connectivity when deploying multi-hop networks [6,8,13,14,29,34]. These intermittent links cause an extra challenge for determination of the most appropriate communication protocols in such environments. While traditional multi-hop routing protocols cannot deliver adequate performance, novel and particular routing design solutions for the smart grid has to be re-visited.

As the design of a novel routing protocol must be based on the characteristics of its target environment, the determination of routing metrics to be used has an impact on the overall routing performance [30]. Hence, based on the simulation results, we present some design guidelines on the network layer. Major design guidelines are summarized as follows:

- ***Path determination scheme:*** In multi-hop wireless networks, a routing protocol finds a route from the source to a destination according to a routing metric. The hop-count metric is one of the most widely used one; however, it cannot reflect the quality of a link. In smart grid environments, wireless links have varying characteristics due to obstructions, fading, and noisy environment. Thus, the wireless link capacity is limited and varies continuously that traditional multi-hop routing algorithms perform poorly by utilizing the hop-count routing metric. This phenomenon is shown in our simulation results which are illustrated in Figs. 3–5. Therefore, when designing a reliable routing protocol, effects of link loss ratios and interference among links of a path should be taken into account [31]. It is stated in [29] that the quality of a link depends highly on the environmental characteristics and interference. Also, the interference from the neighboring channels has a major influence on the packet delivery rate. It is also shown in [33] that the link quality estimation metrics have better performance than conventional metrics, such as hop-count. Hence, adding interference-awareness and a link-quality-aware metric to routing in smart grid environments can significantly enhance the overall network performance by alleviating the resulting interference and preserving more optimal paths for the subsequent arriving connections [32]. As an alternative, the information regarding the total packet delivery delay time from source to destination metric can also be used as proposed in TUQR [27]. With this metric, packets will be forwarded via the route which has the minimum communication delay to improve packet delivery performance.
- ***Packet forwarding scheme:*** In multi-hop routing, intermediate nodes forward packets according to their route table, which store the next hops for reaching to the destination. Choosing the appropriate forwarding scheme for a specific environment is so crucial that when combining a wrong type of routing metric with a forwarding scheme may result in non-optimal routes [30]. For the smart grid environments, where connectivity and mobility are low, but the nodes may not have enough resources in terms of energy and memory, we need a more reliable packet forwarding scheme. Instead of deploying basic “store-and-forward” scheme, a more opportunistic scheme of the “store-carry-and-forward” can be deployed [30]. In this type of forwarding scheme, nodes will decide whether to forward a packet immediately or keep it for a while in order to be able to eventually deliver the packets from source to destination.

8. Conclusion

In this paper, the performance of four different multi-hop routing protocols is investigated for different smart power grid environments, e.g., 500 kV outdoor substation, main power control room and underground network transformer vaults. Specifically, different types of multi-hop routing protocols, such as on-demand (AODV and DYMO), table-driven (DSDV) and QoS-aware (TUQR) routing protocols, have been compared in terms of packet delivery ratio, end-to-end delay, and energy consumption to show the advantages and disadvantages of each routing protocol in various environments. Furthermore, we introduce potential applications of WSNs along with the related technical challenges. Our goal here is to describe advantages and applications of WSNs for smart grid and motivate the research community to further investigate this promising research area. The simulation results show that none of the routing protocols give satisfactory performance results in terms of packet delivery ratio, end-to-end delay, and energy consumption. Hence, novel QoS-based routing algorithms have to be developed for the WSN-based smart grid applications.

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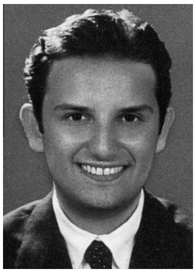

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