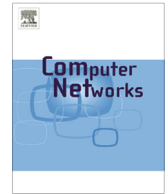




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# On the interdependency between multi-channel scheduling and tree-based routing for WSNs in smart grid environments

Melike Yigit<sup>a,\*</sup>, Ozlem Durmaz Incel<sup>b</sup>, Vehbi Cagri Gungor<sup>a,c</sup>

<sup>a</sup> Department of Computer Engineering, Bahcesehir University, Faculty of Engineering, Ciragan Cad. Osmanpasa Mektebi Sok. No. 4-6, 34353 Besiktas, Istanbul, Turkey

<sup>b</sup> Department of Computer Engineering, Galatasaray University, Faculty of Engineering and Technology, Ciragan Cad. No. 36, 34349 Ortakoy, Istanbul, Turkey

<sup>c</sup> Department of Computer Engineering, Abdullah Gul University (AGU), Faculty of Engineering, Barbaros Mahallesi, Erkiilet Bulvarı, Kocasinan, Kayseri, Turkey

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## ABSTRACT

Field tests show that the link-quality of wireless links in different smart grid environments, such as outdoor substation, varies greatly both in space and time because of various factors, including multi-path, fading, node contentions, radio frequency (RF) interference, and noise. This leads to both time and location dependent capacity limitations of wireless links in smart grid environments. To improve network capacity in such environments, multi-channel communication and the use of proper routing topologies emerge as efficient solutions to achieve simultaneous, interference-free transmissions over multiple channels. In this paper, we explore the impact of multi-channel communication and the selection of efficient routing topologies on the performance of wireless sensors networks in different smart grid spectrum environments. Particularly, we evaluate the network performance using a receiver-based channel selection method and using different routing trees, including routing trees constructed considering the link qualities, Capacitated Minimum Spanning Trees (CMSTs), capacitated minimum spanning tree considering link qualities and Minimum Hop Spanning Trees (MHSTs). We focus on performance measures such as delay and throughput that can benefit from the simultaneous parallel transmissions and show that the use multiple channels together with routing trees that consider network capacity and link quality, i.e., capacitated minimum spanning tree considering link qualities, substantially improve the network performance in harsh smart-grid environments compared to single-channel communication and minimum-hop routing trees.

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## 1. Introduction

Given the increasing age of power grid and growing energy demand, electric utilities face the challenge of ensuring reliable power delivery to the customers at competitive prices. Power grid failures due to the complex

electric distribution systems cause congestion in the power network. All these network congestions, component failures, accidents, and natural catastrophes cause power outages leading to major blackouts all around the world. To address these issues, a new concept of next generation electric power system, the smart grid, has been proposed. The smart grid is a modernized electric power grid aiming to improve productivity, reliability, and safety of the existing grid with the use of advanced communications and sensing technologies [1–4]. It is expected that the smart grid will provide significant energy savings, decrease

\* Corresponding author. Tel.: +90 5542403593.

E-mail addresses: [melike.yigit@stu.bahcesehir.edu.tr](mailto:melike.yigit@stu.bahcesehir.edu.tr) (M. Yigit), [odincel@gsu.edu.tr](mailto:odincel@gsu.edu.tr) (O.D. Incel), [cagri.gungor@agu.edu.tr](mailto:cagri.gungor@agu.edu.tr), [cagri.gungor@bahcesehir.edu.tr](mailto:cagri.gungor@bahcesehir.edu.tr) (V.C. Gungor).

operational costs, and increase safety and power quality. To this end, the cost and design of the communication network in smart grid applications becomes crucial to the performance of the overall electric power system [5].

The recent developments in embedded systems and wireless sensor networks (WSNs) have enabled reliable and cost-effective power grid management systems, which have the capability of monitoring and controlling the real-time operating conditions and performance of the grid [1,6–8]. In these systems, the collaborative and low-cost nature of WSNs brings several benefits over traditional electric monitoring systems, including greater accuracy, improved fault tolerance, extraction of localized events. In this respect, wireless sensor networks enable low-cost and low-power wireless communications for diverse sets of smart grid applications, including automatic wireless metering, line fault and power theft detection, conductor temperature and dynamic thermal rating, distribution automation, outage detection, underground cable system monitoring, real time pricing, tower and poles monitoring, etc. All of these applications are presented Table 1. However, the realization of these currently designed and envisioned WSN-based smart grid applications and to meet the general application demands in terms of delay, reliability and throughput directly depends on reliable communication capabilities of the deployed sensor network in harsh power grid environments.

Field tests in [1] show that the link-quality of wireless links in different smart grid environments, such as outdoor substation, main power control room, and underground network transformer vaults, changes greatly with location and time because of multi-path, fading and noise. On top of these factors, contention on the wireless medium and RF interference due to parallel transmissions limit the capacity of WSNs specifically in smart grid environments. To improve network performance in these environments, multi-channel communication can be utilized to overcome the impact of interference and achieve simultaneous transmissions over multiple channels. With the parallel transmissions, network performance can be improved both in terms of delay and capacity, such as throughput. However, the design and implementation of sensor nodes is constrained by energy, memory, and processing capabilities, which require simple but effective multi-channel scheduling algorithms for WSNs to be deployed in smart grid spectrum environments.

Until now, several multi-channel algorithms have been proposed to improve the performance [9–13] of WSNs. However, it is not explored how the existing multi-channel scheduling algorithms for WSNs will perform under

varying and harsh conditions of smart power grid. This motivates us to explore the performance and the impact of multi-channel communication in WSNs for smart grid applications. Besides the impact of interference which can be eliminated with multi-channel communication, previous work shows that the capacity of WSNs is also limited by the topology of the network [14]. Hence, it is imperative to evaluate the impact of different routing topologies on the network performance in such environments.

To address these needs, in this paper, we investigate the network performance of WSNs for efficient data collection, i.e. convergecasting, in different smart-grid environments with harsh operating conditions. In particular, we investigate the network performance in terms of delay and network capacity, considering multi-channel communication to alleviate the effects of interference, using suitable network tree topologies and retransmission of lost packets in case of lost packet over unreliable links. We investigate the performance of a state of the art multi-channel MAC protocol [14], named Receiver-Based Channel Assignment (RBCA), together with different routing topologies in different smart grid spectrum environments, e.g., 500 kV outdoor Substation (Subs), main power control room (MPR) and underground network transformer vaults (UTV). Importantly, all these performance evaluations are based on real-world field tests using IEEE 802.15.4 compliant wireless sensor nodes deployed in different smart grid environments [1]. As the multi-channel scheduling algorithm, we utilize the RBCA algorithm. The reason behind this selection is that, the performance of RBCA was evaluated for WSNs with perfect link qualities and it was shown that it can efficiently improve the network performance in terms of latency compared with other multi-channel MAC protocols, such as TMCP [12]. Besides, RBCA is easy to implement and its source code is available for other researchers.

To evaluate the impact of the routing topology on the network performance, we consider different routing topologies, namely, routing trees constructed considering the link qualities, Capacitated Minimum Spanning Trees (CMSTs), capacitated minimum spanning trees considering link qualities and minimum hop spanning trees. CMST topologies were shown to minimize latency with perfect link qualities in [14], however, their performance was not evaluated for WSNs operating in smart grid environments with varying link qualities. Constructing routing topologies considering the link qualities can certainly contribute to avoid bad-quality links and improve network performance. Hence, as the second approach, we investigate the performance with routing topologies constructed according to the Packet-Reception-Rate (PRR) metric. Besides, we combine the CMST and PRR-based routing topologies and investigate the possible capacity improvements. Finally, we consider the impact of retransmissions on the network performance both in terms of latency and capacity, considering the lost packets due to unreliable links in smart grid environments.

Overall, our contribution is to investigate the performance of multi-channel WSNs for smart grid and to quantify how multi-channel communication combined with different routing trees will perform under harsh conditions

**Table 1**  
Summary of WSN-based smart grid applications.

Applications	Subsystem
Advanced Metering Infrastructure	Demand-side
Real Time Pricing	Demand-side
Building and Industrial Automation	Demand-side
Conductor Temperature and Dynamic Thermal Rating	Utility-side
Line Fault and Outage Detection	Utility-side
Wind Farm Monitoring	Generation-side
Solar Farm Monitoring	Generation-side

of smart power grid and meet the general application requirements, such as delay, throughput and reliability. All the simulation results in this paper provide precious understanding about multi-channel scheduling and topology construction for WSNs in harsh smart grid environments.

The remainder of this paper is organized as follows. In Section 2, an overview of related work on WSN multi-channel scheduling are described. In Section 4, the evaluated multi-channels scheduling algorithms are explained. Network model and assumptions is presented in Section 3. Performance evaluations, overview of simulation results are clarified in Sections 5 and 5.5, respectively. Finally, the paper is concluded in Section 6.

## 2. Related work

In the related literature, different WSN-based smart grid studies have been presented [1,2,15–22]. These studies can be divided into three different subsystems that are power supplier, electric utility and demand side. Each of them has separate requirements and priorities. Therefore, studies balance the tradeoffs among the different parameters when designing protocols and architectures for using WSNs in smart grids.

As the examples of demand side subsystem, Advanced Metering Infrastructure (AMI), Real Time Pricing and Building and Industrial Automation proposals have been studied [15,18–20]. All these applications provide many advantages to electric utilities by removing the need for human readers, and enabling online pricing models and asset protection, leading to significant decrease in operational cost of the electric utilities. Examples of utility side studies [1,16,17] include conductor temperature and Dynamic Thermal Rating Systems to meet electric utilities requirements by measuring temperature of electric cables for increasing the power carrying capabilities, and Line Fault and Outage Detection studies that offer implementation of online outage detection and faults diagnostics systems by enabling two way communications with WSNs in power grid [1,17,23]. For supplier side studies, Yang et al. [16] presented Wind Farm Monitoring and Solar Farm Monitoring WSN-based smart grid applications.

Multi-channel communication has been shown to be an efficient method to improve the network performance in terms of delay and capacity since it enables simultaneous transmissions over multiple channels which cannot be performed on a single-channel due to interference and collisions [24]. Channel assignment can be performed at the link level, node level or cluster level and assignments can be static, semi-dynamic and dynamic. In static assignment, radios are assigned channels for permanent use [12] whereas in semi-dynamic assignment [9,11,13] the radios are assigned static channels, either for receiving or transmitting, but it is possible to change the channel for communicating with the radios that operate on different channels. Dynamic assignment approaches [10,25], on the other hand, consider that nodes can dynamically switch their interfaces from one channel to another between successive data transmissions.

Multi-channel protocols for WSNs also differ according to the medium access scheme that they utilize. Some of the protocols utilize contention-based medium access [10,13], where some others utilize contention-free TDMA approaches [9,11,25]. For a detailed review on multi-channel communication in WSNs the reader can refer to [24].

Compared to a standardized solution where channel hopping is utilized, such as TSCH [26], our motivation in selecting the RBCA method is that, its performance was evaluated for WSNs with perfect link qualities and it was shown that it can efficiently improve the network performance in terms of latency compared with other multichannel MAC protocols, such as TMCP [12] and it builds upon the child-parent relationship on routing trees. Additionally, RBCA is easy to implement and its source code is available for other researchers. However, RBCA does not exploit the channel diversity utilized in dynamic channel hopping approaches.

More than showing the performance or suitability of the RBCA protocol for WSNs in industrial environments, in this paper we aim to explore the relationship between multi-channel communication and the type of routing tree for improving the capacity in smart grid environments. Hence, in this regard, one could also use the Time Slotted Channel Hopping (TSCH) mechanism for multi-channel communication and focus on the impact of routing trees on the performance. TSCH, which is included in IEEE802.15.4e standard, provides energy efficient and reliable communication with minimizing collision and frequency diversity [27]. Energy efficiency and reliability are obtained by using TSCH with the synchronization of nodes via slotframe structure and with channel hopping, respectively. After the synchronization, a schedule is established to define the slots and channel offsets of each nodes for making transmission [26]. For scheduling both centralized [27] and distributed [28] approaches can be considered. A centralized scheduling approach of TSCH can be adapted to our study in the channel and time slot assignment phase. Instead of assigning static channels to the nodes, like in RBCA, TSCH's slotframe structure and the hopping mechanism can be utilized to exploit the frequency diversity and hence to better cope with possible changing interference conditions on different channels. Adoption of TSCH mechanism in our approach is the future work for this study.

An alternative solution to improve the network capacity is to utilize transmission power control. Instead of transmitting signals with maximum power, transmissions with just enough power has been shown to improve the network capacity [29]. Although these studies on utilizing multi-channel communication and transmission power control provide valuable foundations in the design of WSNs, most of these algorithms have focused on minimizing schedule length and latency assuming excellent link qualities and none of them has focused on the performance of WSNs in different smart grid environments. In this paper, the impact of multi-channel communication on the performance of wireless sensors networks in different smart grid spectrum environments has been examined.

As mentioned, our aim is to investigate the network performance in terms of capacity and delay. Besides the elimination of interference utilizing multi-channel

communication, it is clear that the network capacity is also limited by the topology of the network. For instance, network capacity certainly differs if we have a star topology with single-hop or line topology with multiple hops to the sink node. Florens et al. [30,31] focus on the scheduling problem in WSNs by utilizing different network topologies, that are line, multi-line and tree networks, and show that the capacity of the network substantially differs according to the underlying topology.

Network capacity using tree-based data collection (convergecasting) has been also studied in previous work [14,32–35]. In [14], it was shown that once the impact of interference on the network capacity is eliminated with multiple channels, the network capacity is limited with the topology of the network. Furthermore, it was shown that Capacitated Minimum-hop Spanning Trees (CMSTs) result in the best performance in terms of fast data collection in WSNs. Based on this work, we evaluate the performance of CMST-based topologies considering WSNs operating in different smart grid environments with varying link qualities. Since we are dealing with unreliable links, we compare the performance of CMST with tree topologies constructed according to the PRR metric. We also evaluate the network performance with the combination of these two approaches where the tree topology is constructed both considering the CMST and PRR metrics.

More importantly, while we investigate the performance we consider the harsh operating smart grid environments of WSNs where link qualities vary both spatially and temporally because of harsh environmental conditions such as interference, numerous abrasive environments, high humidity levels, vibrations and dust [1], as opposed to regular smart grid environments that have less interference and corrosive environments, ideal humidity levels, low vibrations and less dust. By considering these severe channel conditions we evaluate the impact of the number of retransmissions on the network performance, both in terms of delay and capacity. As mentioned, we use a realistic link quality model based on the field tests which were performed in different smart grid environments [1] using IEEE 802.15.4 compliant wireless sensor nodes.

### 3. Network model and background

In this section, we explain the design constraints of our problem together with the background information and assumptions.

We model the WSN as a graph  $G = (V, E)$  where  $V$  is the set of nodes, and  $E = \{(i, j) | i, j \in V\}$  is the set of edges representing the wireless links. We assume that all the nodes have a single half-duplex transmitter, such that they cannot receive and transmit at the same time and cannot receive from multiple transmitters at the same time.

#### 3.1. Modeling interference

There are two commonly-used interference models in the literature. One of them is the protocol model and

second is the physical interference model [36]. In the protocol model, packets are received by the receiver if other senders do not transmit a packet at the same time. In this way, graph coloring-based scheduling algorithms can be used. However, interference has cumulative effects in a wireless network and according to Gronkvist et al. [37,38]; this cumulative effect cannot be solved by the protocol model. Otherwise, physical model can solve these cumulative effects by using Signal to Interference Noise Ratio (SINR). In the physical model, the successful reception of a packet from node  $i$  to node  $j$  is affected by the ratio between the received signal strength at  $j$  and the cumulative interference caused by all other concurrently transmitting nodes and the ambient noise level. Hence, a packet is received successfully at  $j$  if the signal-to-interference-plus-noise ratio,  $SINR_{ij}$ , is greater than a certain threshold  $\beta$ , i.e.,

$$SINR_{ij} = \frac{P_i \cdot g_{ij}}{\sum_{k \neq i} P_k \cdot g_{kj} + \mathcal{N}} \quad (1)$$

where  $P_i$  is the transmitted signal power at node  $i$ ,  $\mathcal{N}$  is the ambient noise level, and  $g_{ij}$  is the propagation attenuation (link gain) between  $i$  and  $j$ . In this study we use the physical interference model for creating a realistic wireless communication environment.

#### 3.2. Modeling link quality for smart grid environments

We use the log normal shadowing model for modeling the wireless links. This model is used for different experimental studies and it has been shown that it provides more accurate multi-path channel models for wireless environments with obstructions. The parameter selection is based on the field studies presented in [1] for link qualities and channel characteristics of different smart grid environments. These field tests have been performed in different harsh electric-power-system environments, such as 500 kV Substation, industrial power control room and Underground Transformer Vault, using IEEE 802.15.4 compliant wireless sensor nodes measuring noise, channel characteristics, attenuation and link quality in these environments. In this respect, channel parameters used in our experiments are shown in Table 2.

In log normal shadowing path loss model, the signal to noise ratio  $\gamma(d)$  at a distance  $d$  from the transmitter is given by:

$$\gamma(d)_{db} = P_\tau - P_L(d_0) - 10\eta \log_{10} \frac{d}{d_0} - X_\sigma \quad (2)$$

where  $P_\tau$  is the transmit power in dBm,  $PL(d_0)$  is the path loss at a reference distance  $d_0$ ,  $\eta$  is the path loss exponent,  $X_\sigma$  is a zero mean Gaussian random variable with standard deviation ( $\sigma$ ).

#### 3.3. Data collection model

We assume all the sensor nodes except the sink node generate packets and transmit them over a routing tree to the sink node, i.e. we focus on convergecasting data towards a sink node. Since the nodes are equipped with

**Table 2**  
Path loss and shadowing deviation in electric power environments [1].

Propagation environment	Path loss ( $\eta$ )	Shadowing deviation ( $X_\sigma$ )
500 kV Substation	2.42	3.12
Underground Transformer Vault	1.45	2.45
Main Power Room	1.64	3.29

half-duplex transceivers our first constraint in the data collection is that if a node is transmitting it cannot be scheduled to receive or transmit to another node. Similarly, it cannot receive from multiple transmitters at the same time. Additionally, since we focus on the physical interference model, another constraint is that, a transmitter  $i$  cannot be scheduled to transmit if the SINR at its receiver node  $j$  is not greater than the threshold,  $\beta$ , for a successful transmission.

### 3.4. Receiver-based channel assignment and medium access

The RBCA algorithm [14] is a TDMA based multi-channel MAC protocol that is particularly designed to work on tree-based routing topologies.<sup>1</sup> In order to avoid pair-wise, per-packet channel negotiation overheads, RBCA statically assigns the channels to the receivers (i.e., parents) of the routing tree, and the children of a common receiver transmit on that channel to communicate with the parent. At the channel selection stage, RBCA assigns the channels where the receiver experiences no interference or the minimum interference using the physical interference model. With this method, potential interference between simultaneous transmissions is eliminated.

For TDMA scheduling, RBCA runs a timeslot assignment algorithm with the key idea to schedule transmissions in parallel along multiple branches of the routing tree, and to keep the sink busy in receiving packets for as many time slots as possible. Therefore, there is no collision and collided packets in our model since each node is assigned a guaranteed timeslot by using TDMA. Only packet losses are due to the unreliable links. It considers a TDMA protocol where time is divided into slots, and consecutive slots are grouped into equal-sized nonoverlapping frames. For the schedule computation, RBCA uses the same constraints of the data collection explained in Section 3.3. Performance of the RBCA algorithm was compared with other state-of-the-art multi-channel MAC protocols, such as TMCP [12], and it was shown that RBCA performs to be efficient in terms of eliminating interference and maximizing parallel transmissions.

The reason why we utilized the RBCA protocol is that, it was shown to perform well for WSNs to eliminate the impact of interference and improve the network performance in environments with perfect link qualities. However, its performance was not evaluated for WSNs operating in harsh smart grid environments with varying link qualities both in space and time. In this study, our aim is to explore its performance for WSNs in harsh environments.

## 4. Impact of routing topologies on data collection performance in WSNs

In [14], it was shown that, once interference is eliminated with multi-channel communication, the network performance is limited by the routing topology. To evaluate the impact of the routing topology on the network performance, we consider different routing topologies, namely, routing trees constructed considering the link qualities (Packet Reception Rate (PRR)), Capacitated Minimum Spanning Trees (CMSTs), capacitated minimum spanning trees considering link qualities (Packet Reception Rate (PRR)) and Minimum Hop Spanning Trees (MHSTs). These algorithms are briefly explained in the following subsections.

### 4.1. Capacitated Minimum Spanning Tree – CMST

Capacitated Minimum Spanning Tree (CMST) is a minimum cost spanning tree that contains a root ( $r$ ) node and subtrees which are connected to root node according to capacity constraint  $c$ .  $c$  means that subtrees attached to root ( $r$ ) node cannot have more than  $c$  nodes [39]. When nodes in subtrees have weights, in this situation summation of weights in a subtree must be smaller than or equal to  $c$ . Edges between the root and subtrees are called as gates. In [14], the constraint of  $c$  was computed as  $2n_k - 1$ , where  $n_k$  is the maximum number of nodes on any branch in the tree. In this respect, finding the lowest cost spanning tree according to the  $c$  constraint by applying the log normal shadowing calculation in smart grid environments, is the purpose of our CMST algorithm.

In order to construct CMST we utilize the following variables: a graph is given  $G = V, E$  and number of nodes in  $G$  is  $n = |G|$ . Root  $r \in G$ .  $a_i$  represents other nodes in  $G$ . Edge cost is shown with  $c_{ij}$  between vertices  $a_i$  and  $a_j$ . In this way, a cost matrix is formed and shown with  $C = c_{ij}$ . According to these parameters, CMST algorithm's steps are listed below [40]:

- In the first step, all nodes that are 1-hop neighbors of the sink represent the root node of subtrees are connected to sink node ( $r$ ).
- Number of nodes in each subtree represents the cost of subtree and it is shown as  $\sum_n^{i=0} c_{ri}$ . Each of edge from root to subtree is a gate ( $g_i$ ).
- At each iteration, closest neighbor ( $a_j$ ) is selected for the connected nodes except the root node.
- Tradeoff function is computed for achieving potential savings by merging neighbor nodes instead of connecting them to the root node, directly with this equation:  $t(a_i) = g_i - c_{ij}$ .
- Greatest  $t(a_i)$  is searched for removing  $g_i$  gate that does not accord capacity constraint.
- These steps are repeated until better improvements cannot be achieved.

These steps are performed to construct the CMST by Capacitated Minimum Spanning Tree Algorithm. CMST algorithm's pseudocode [40] is explained in Algorithm 1

<sup>1</sup> RBCA can also work with other statistic routing topologies.

that is shown in Table 3. Pseudocode of the algorithm presents how the algorithm works to find the CMST [14].

#### 4.2. PRR-based routing protocol

PRR values of wireless links is important and widely-used to model the link quality. Packet Reception Rate (PRR) values of links except are calculated by using log normal shadowing model. According to this calculation, a PRR matrix is computed that includes each link's PRR value between a pair of nodes. This matrix is computed by using smart grid environments' parameters as shown in Table 2, i.e. 500 kV Substation, Underground Transformer Vault and Main Power Room. Therefore, different PRR matrices are obtained for different smart grid environments. PRR values show the link quality between nodes. If the link quality does not exceed some threshold, the link between the nodes is assumed to be bad (disconnected) and this edge in the graph is removed from the tree. Each node's signal level is identified by using log normal shadowing propagation model and Radio Received Signal Strength Indicator (RSSI) value, which is a measurement of power received from radio signal. These are computed by using the topology information and channel parameters. Then, signal to noise ratio (SNR) between the nodes is calculated as shown in Eq. (1) by using obtained RSSI values. According to SNR values, probability of bit errors are measured with respect to modulation type that is Non-Coherent Frequency Shift Keying (NCFSK). Then PRR matrix is formed in terms of Manchester encoding by using probability of error. As a result, PRR matrix is obtained to define link qualities of wireless links by using the channel parameters of smart grid environments.

This method constructs routing trees according to link quality and provides more reliable packet transmission between the nodes. PRR matrix is obtained as presented in Eq. (3).

$$PRR = \frac{(\text{Number of Received Packets})}{(\text{Number of Sent Packets})} \quad (3)$$

**Table 3**  
Capacitated minimum spanning tree algorithm for finding CMST.

Algorithm 1: CMST algorithm
1. <b>Input:</b> Capacity constraint ( $c$ ) of the tree, cost matrix $C$ and root node are given as inputs
2. <b>Compute:</b> Minimal cost spanning tree of a Graph, $G$ according to root node $r$ and $c$ (capacity constraint)
3. <b>Set:</b> $T = C_{1r}, C_{2r}, \dots, C_{nr}$
4. <b>while</b> no improvement to tree
5. <b>for each</b> node $a_i$
6. $a_i$ equals to closest node that is in different subtree
7. <b>Tradeoff function:</b> $t(a_i) = g_i - c_{ij}$
8. $t_{max}$ equals to maximum $t(a_i)$
9. $k$ equals to $i$
10. $t(a_i)$ equals to $t_{max}$
11. <b>when</b> cost of $i +$ cost of $j$ smaller than or equal $c$
12. $T$ equals to $T - g_k$
13. $T$ equals to $T \cup c_{ij}$
14. <b>Output:</b> GraphCMST = $T$

According to (3), PRR values of all links are computed between the nodes and a routing tree is constructed by utilizing these PRR values such that nodes select the neighbors as the parent with the maximum PRR value. The PRR-based routing algorithm is based on the MHST algorithm that is defined in Subsection 4.4. Edges are selected according to their outages vertexes' weights. However, in this algorithm weights are determined according to PRR values and the number of hops. The only difference is that PRR values are considered to build the tree. In this respect, PRR-based routing algorithm steps are listed as follows:

- List  $X$ , holds all edges and their vertices' weights,  $w$ , that is determined according to number of hops to sink and nodes' PRR values into graph,  $G$ .
- A flag array,  $F$  is used to store selected edges that are defined by dividing edge list,  $E$  into segments. If edge is selected, flag is set to 1 otherwise, 0. Selection is done according to weights of the edges.
- List  $X$ , is scanned to find minimum outgoing edge, that is hold in  $N$ , and successor of each vertex. Successors are stored in array,  $S$ .
- Cyclic edges are removed from  $N$  and remaining edges are marked to form tree.
- Successors in  $S$  are appended with their indexes and a list,  $L$  is formed.
- List  $C$ , is formed by splitting  $L$  to find new ids with a flag array that is 1 when new id is found with maximum PRR value and closest to sink.
- Subgraph's root node is found by using  $C$  list and if two subgraph has same root node, nodes in these subgraphs are removed from edge list,  $E$ .
- When these steps are performed, edge list, vertex list, weight list with max PRR value and least distance to sink are obtained.

As shown, the steps of creating a PRR-based routing protocol are similar to the MHST algorithm. Only difference is that PRR values of nodes are added to constraints while weights are identified. In this manner, pseudocode of PRR-based routing tree algorithm is described in Algorithm 2 that is shown in Table 4.

#### 4.3. CMST with PRR

CMST type topologies were shown to improve network performance with perfect link qualities [14]. However, the impact of variable link qualities were not considered. In our approach, we combine the CMST algorithm with PRR-based tree construction. Hence, we consider both link qualities and the constraint of  $c$  while constructing the tree.

In this routing protocol, CMST with PRR-based algorithm is implemented. According to this algorithm, nodes choose neighbors that are closest to sink and also have maximum PRR value. In this way, CMST algorithm becomes more reliable and suitable in real channel conditions. Nodes can transmit to the sink on a trusted path with minimum cost. In this case, steps in creating CMST with PRR are the same as in the CMST algorithm [14]. Only difference is that PRR check has been added to connect

**Table 4**  
PRR-based algorithm.

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Algorithm 2: PRR-based algorithm

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1. **Input:** Weighted Graph,  $G$
2. **Compute:** PRR-based Routing Tree,  $T$  for  $G$
3. **Set:**  $P$  is partition of vertices in  $G$
4. **Set:** PRR matrix that shows each node's PRR value in  $G$
5. **Set:**  $Q$  stores edges in  $G$  and their weights with maximum PRR value and minimum number of hops
6. **Set:**  $T \leftarrow \emptyset$
7. **while**  $Q \neq \emptyset$
8.  $(u, v) \leftarrow$  **remove edge according to minimum distance to sink and maximum PRR value from**  $Q$
9. **if**  $u$  in P-set  $\neq v$  in P-set
10. **edge**  $(u, v)$  is added to  $T$
11.  $P \cup (u, v)$
12. **Output:** GraphPRR =  $T$

---

nodes with their neighbors. These are shown in the following steps that are listed as follows:

- All subtrees are connected to root node  $r$ .
- $\sum_{n=0}^{i-1} c_{ri}$  indicates cost of each subtree.
- $PRR = prr_{ij}$  is a matrix that shows PRR values' of each node.
- $(g_i)$  is a gate from root to subtree that is removed from graph if PRR value cannot exceed threshold.
- Closest neighbor  $(a_j)$ , that has maximum PRR value, is searched for every node except root node.
- Tradeoff function is same with CMST. This is obtained with  $t(a_i) = g_i - c_{ij}$  equation.
- These steps are repeated until best tree is constructed.

According to these steps, pseudocode of CMST with PRR algorithm is shown in Algorithm 3 that is shown in Table 5.

#### 4.4. Minimum Hop Spanning Tree – MHST

The simplest approach commonly used in WSNs is to minimize the number of hops to relay information towards the sink node. Using minimum number of hops minimizes the number of nodes participating in the relaying of information and hence considered to minimize the energy consumption. The reason why we also used the minimum hop spanning tree is that it is a simple approach and we are interested in showing the capacity improvements with other solutions compared to the simplest solution.

Connected graph,  $G$  is given and it includes a spanning tree which has subtrees. All vertices are connected by these subtrees. Different subtrees can be obtained from one graph. Minimum hop spanning tree is a spanning tree with number of hops less than or equal to the number of hops of every other spanning tree. There can be more than one minimum hop spanning trees of the same number of hops having a minimum number of edges. If all edges' number of hops are same in given graph, each spanning tree has minimum in this graph. In this respect, if graph has  $V$  vertices, each tree in this graph has  $V-1$  edges.

The steps in creating a MHST are listed as follows [41]:

**Table 5**  
CMST with PRR algorithm.

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Algorithm 3: CMST with PRR algorithm

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1. **Input:**  $c$ : Capacity constraint of the tree,  $C$ : cost matrix, PRR = prr matrix and  $r$ : root node are given as inputs
2. **Compute:** Minimal cost spanning tree of a Graph,  $G$  according to root node  $r$ , PRR matrix and  $c$  (capacity constraint)
3. **Set:**  $TPRR = C_{1r}, C_{2r}, \dots, C_{nr}$
4. **Set:**  $P = PRR_{1r}, PRR_{2r}, \dots, PRR_{nr}$
5. **while** no improvement to tree
6. **for each** node  $a_i$
7.  $a_i$  equals to closest node that is in different subtree and has maximum PRR value
8. **Tradeoff function:**  $t(a_i) = g_i - c_{ij}$
9.  $t_{max}$  equals to maximum  $t(a_i)$
10.  $k$  equals to  $i$
11.  $t(a_i)$  equals to  $t_{max}$
12. **when** cost of  $i +$  cost of  $j$  smaller than or equal  $c$
13.  $TPRR$  equals to  $TPRR - g_k$
14.  $P$  equals to  $P - g_k$
15.  $TPRR$  equals to  $TPRR \cup C_{kj}$
16. **Output:** GraphCMSTwithPRR =  $TPRR$

---

- All edges and their vertices' weights,  $w$ , that is determined according to number of hops to sink into graph,  $G$ , are put in a list,  $X$ .
- Segments are constructed by dividing edge list,  $E$ . A flag array,  $F$  is hold for storing each edge's selection information such as if edge is selected, flag of this edge becomes 1 otherwise, becomes 0.
- List  $X$ , is scanned to find minimum outgoing edge for each vertex and scanning values are stored in  $N$  that is used to find each vertex successor that is hold in  $S$  array.
- Edges, which form cycles, are deleted from  $N$  and remaining edges are marked.
- List  $L$ , is formed by subjoining each successor from  $S$  array with their indexes.
- $L$  list is split to find new ids by using a flag array,  $F$  such as if new id is found, flag becomes 1 otherwise, becomes 0. Vertices with flag value, 1 are added to  $C$  list.
- $C$  is used to find each subgraph's root node that is called as supervertex. Each edge is controlled to find they have same supervertex or not. If they have same supervertex, they are removed from  $E$  that is edge list.
- According to these steps, new edge list and weight list are formed and vertex list is created to find minimum hop spanning tree.

These steps show that how MHST is constructed according to minimum hop weights. In this respect, the pseudocode of this algorithms is described in Algorithm 4 that is shown in Table 6.

## 5. Performance evaluations

In this work, extensive simulations have been performed in Matlab, which is a numerical computing environment and a high level language that is used to simulate wireless sensor networks. The Matlab environment was utilized in the simulations since the models for

**Table 6**  
MHST algorithm.

Algorithm 4: MHST algorithm
1. <b>Input:</b> Weighted Graph, $G$
2. <b>Compute:</b> Minimum hop spanning tree $T$ for $G$
3. <b>Set:</b> $P$ is partition of vertices in $G$
4. <b>Set:</b> $Q$ stores edges in $G$ and their weights that is number of hops
5. <b>Set:</b> $T \leftarrow \emptyset$
6. <b>while</b> $Q \neq \emptyset$
7. $(u, v) \leftarrow$ remove minimum element from $Q$
8. <b>if</b> $u$ in $P$ -set $\neq v$ in $P$ -set
9.     edge $(u, v)$ is added to $T$
10. $P \cup (u, v)$
11. <b>Output:</b> GraphMHST = $T$

the CMST and MHST routing algorithms have been implemented in this environment before, in previous work [14]. To make the Matlab simulations realistic, we used a real physical layer model utilizing the Log-Normal Shadowing Model based on the measurements explained in Section 3.2 and summarized in Table 2. As indicated in [1], this model is used for large and small coverage systems, and additionally, it provides more accurate multipath channel models than other models for indoor wireless environments with obstructions. Additionally, the physical interference model [36] for creating a realistic wireless communication environment is utilized. Simulation parameters are presented in Table 7.

In the evaluations nodes are randomly deployed over a  $200 \times 200$  square meter terrain. Number of nodes are varied between 120 and 200 nodes.<sup>2</sup> For each simulation, we run multiple experiments with different seeds and take the average of the measured values. For the data collection scenario, we assumed a periodic data collection model such that all the nodes generate one packet periodically at the beginning of each scheduling frame (one frame is equal to a period where all the data packets from all sources have been delivered to the sink). Packets are delivered over multiple hops. In the first set of simulations, we assumed best effort delivery such that there are no retransmissions. Hence, if a packet is lost it is not scheduled for retransmissions. Impact of retransmissions is evaluated in Section 5.4.

In this study, performance of the RBCA protocol and the routing tree protocols, explained in Section 4, are evaluated for 500 kV Substation, Underground Transformer Vault and Main Power Room smart grid environments where experimentally determined the  $pathloss(\eta)$  and  $shadowingdeviation(\sigma)$  parameters for each smart grid environment have been obtained from [1], respectively. In the following, the network performance with each of the WSN routing tree algorithms, including Capacitated Minimum Spanning Trees (CMSTs), Capacitated Minimum Spanning Trees (CMSTs) with Packet Reception Rate (PRR), Minimum Hop Spanning Tree (MHST) that is named as Minhop in the graphs, Packet Reception Rate (PRR) – based routing algorithms, has been evaluated in terms of the following performance metrics:

**Table 7**  
Simulation parameters of the experiments.

Number of nodes	120–200
Size of the topology	$200 \times 200 \text{ m}^2$
Radio propagation model	Log-normal shadowing model
Number of frequencies	1, 8, and 16
Algorithms	CMST, CMST with PRR, MHST and PRR
Distance between the nodes	Randomly distributed
Modulation	Non-Coherent Frequency Shift Keying (NCFSK)
Encoding	Manchester
Output power	4.0 dBm
Noise floor	–93.0 dBm
Asymmetry	Symmetric links
Topology	Random

- **Throughput:** is the average data reception rate at the sink node for a frame period. It is simply the ratio of the delivered packets to the size of a frame (i.e., the number of timeslots required to complete the reception of the packets generated by all the source node at the sink node).
- **Delay:** is the time it takes for a data packet to travel across the network from a source node to the sink.

Simulations have been performed to show how the number of channels affects throughput and delay of routing protocols in three different smart grid environments and next the impact of number of retransmissions on throughput and delay has been addressed for 500 kV smart grid environment. Accordingly, in the following sections, simulation results are presented with respect to 500 kV Substation, Underground Transformer Vault (UTV) and Main Power Room (MPR) environments, respectively.

### 5.1. 500 kV Substation

The parameters of 500 kV Substation environment, which are shown in Table 2 have been used in this set of simulations. Four different routing algorithms are used to show which algorithm works better in which smart grid environment in terms of throughput and delay when the number of channels increases.

#### 5.1.1. Delay performance of multi-channel and routing algorithms in 500 kV Substation environment

Figs. 2 and 3 show the cumulative distribution and confidence interval of delay for different routing tree algorithms with varying number of nodes where the number of channels is also varied. 1, 8 and 16 channels are used to show the effect of using multiple channels in real channel conditions. We also explored how delay of routing algorithms change when the number of nodes increases, hence the density of the network changes.

In Figs. 2 and 3, it is shown that as the number of channels increases, delay decreases for all the routing algorithms. This is because multiple channels eliminate interference, more simultaneous transmissions can take place and packets can be delivered to the sink in a shorter interval. In addition, it is shown that delay with these

<sup>2</sup> Less than 120 nodes resulted in unconnected graphs and more than 200 nodes resulted in very dense topologies.

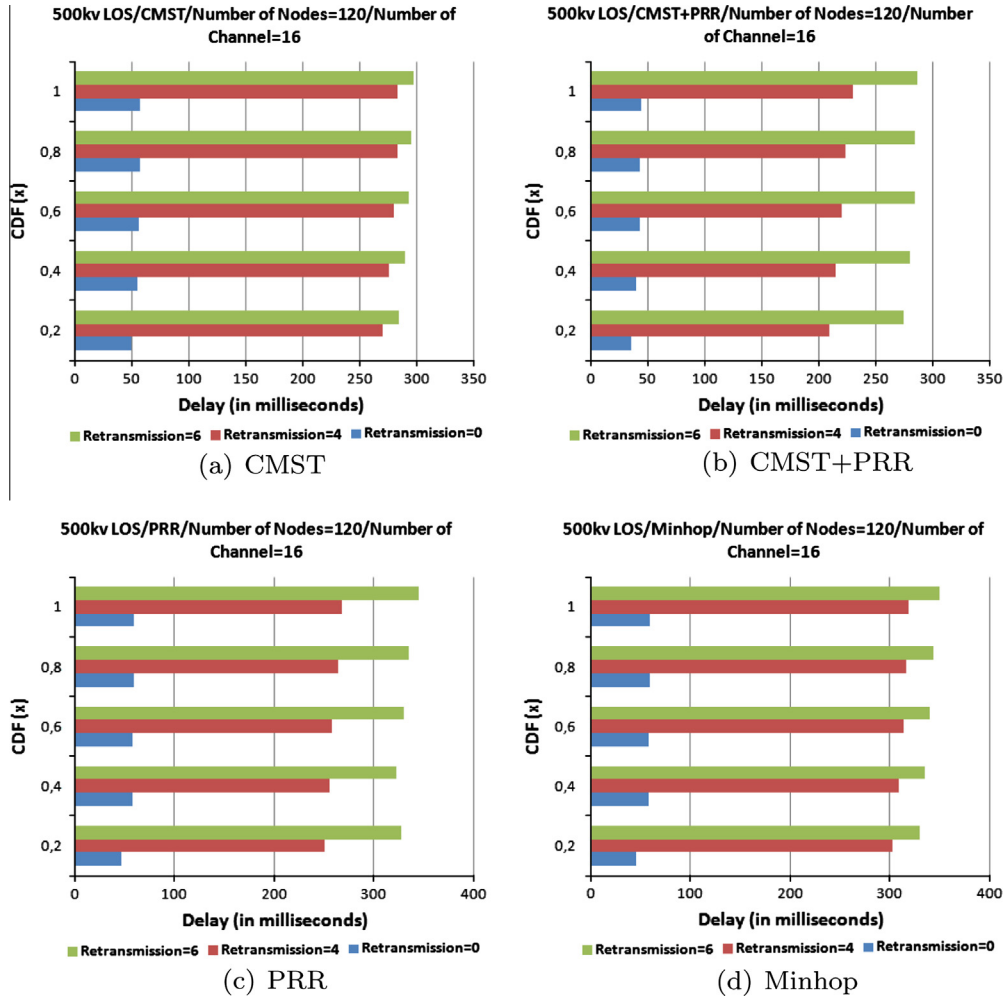


Fig. 1. Cumulative Distribution Function (CDF) of Delay for Routing Protocols when number of retransmission increases in 500 kV smart grid environment.

algorithms increases when number of nodes increases from 120 to 180 because the number of source nodes and the network density increases and more transmissions need to be scheduled. In Figs. 2 and 3, it is also observed that the CMST with PRR routing tree shows the best performance in terms of delay with 120 nodes and 16 channels. In addition, when the number of nodes and channels increase to 180 and 16, respectively, CMST with PRR routing algorithm performs again better than other routing tree algorithms. In general, the CMST type trees perform better than others in terms of delay. This is because CMST algorithm specifies routing trees minimizing the delay by considering the CMST constraint as also shown in the previous work.

### 5.1.2. Throughput performance of multi-channel and routing algorithms in 500 kV Substation environment

Throughput of the network with all the routing protocols increases when channels increase, as shown in Fig. 4, because the number of lost packets decreases around 45%. Routing protocols send packets through multiple

channels and therefore, packets are transmitted to the sink node concurrently over multiple channels. Fig. 4 shows the network throughput with 95% confidence intervals with different routing trees according to different number of nodes where the number of channel increases from 1 to 16 in 500 kV Substation environment. Since the delay is decreased with multiple channels the throughput of the network increases for each routing tree. In Fig. 4, generally it is observed that the CMST with PRR routing tree shows the highest performance in terms of network throughput. On the other hand, in general MHST routing tree algorithm shows the lowest performance in terms of network throughput under the same conditions since it neither considers the link qualities nor the capacity limitation.

### 5.2. UTV

In this section, the results of the simulations for the Underground Transformer Vault (UTV) environment are presented.

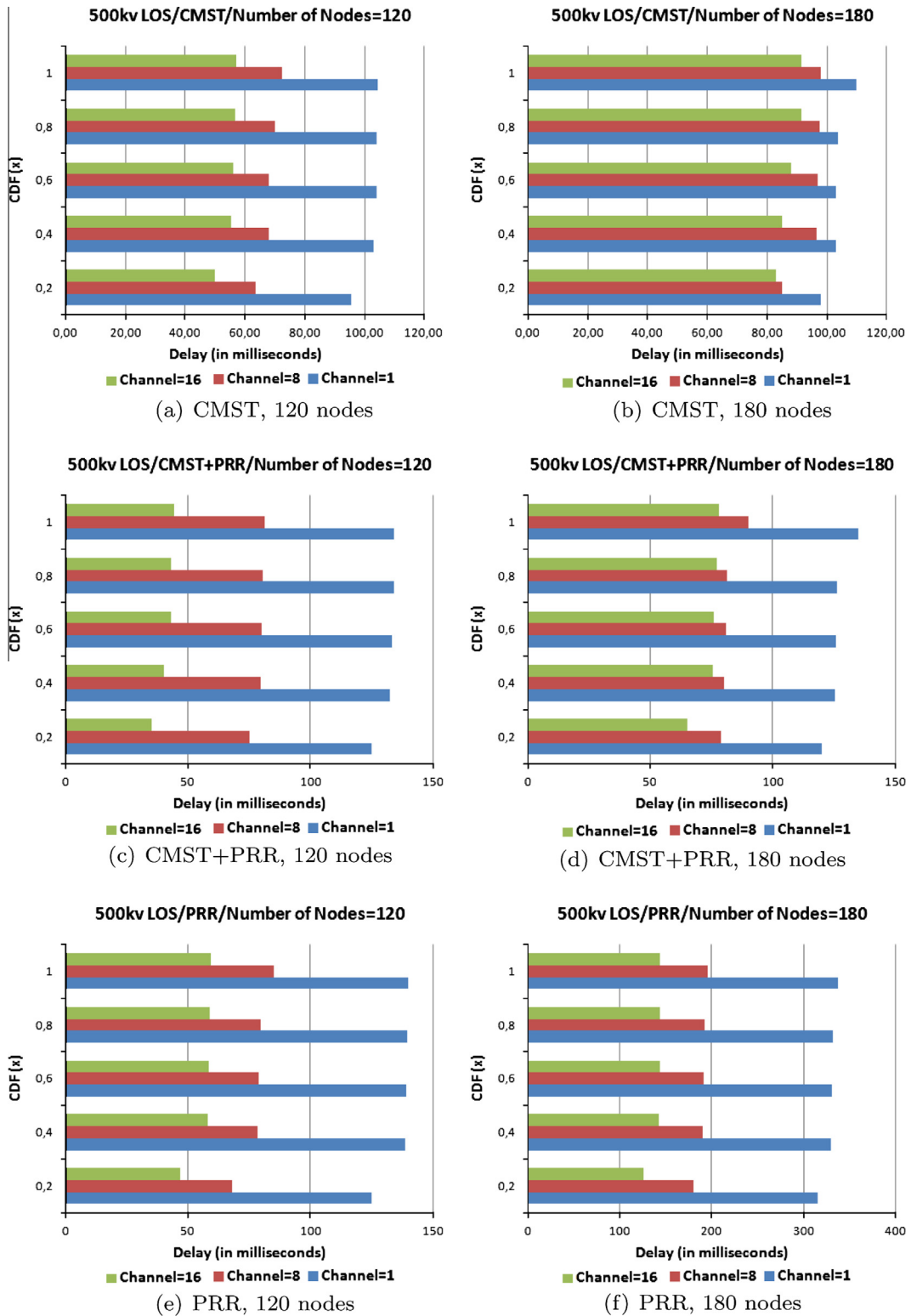


Fig. 2. Cumulative Distribution Function (CDF) of Delay for Routing Protocols when the number of channel increases in 500 kV Substation smart grid environment.

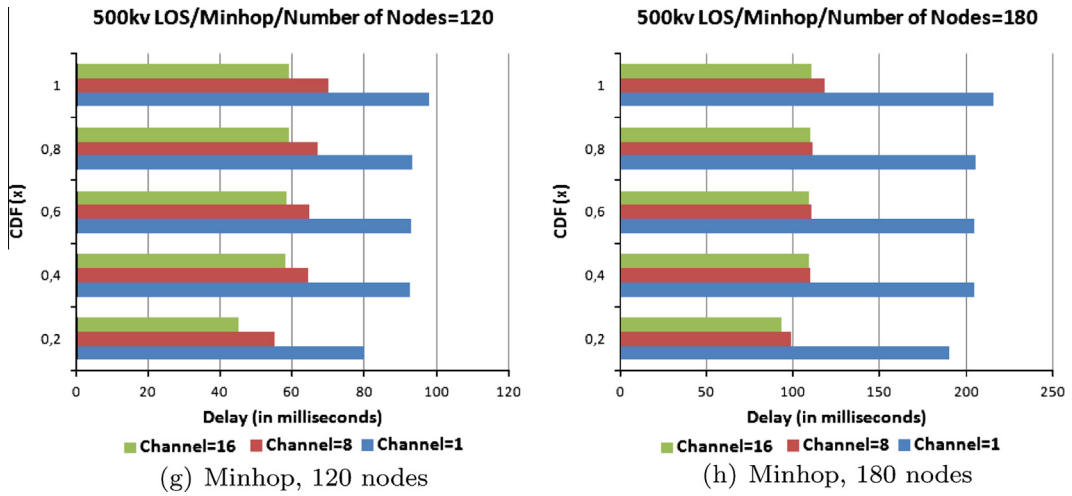


Fig. 2 (continued)

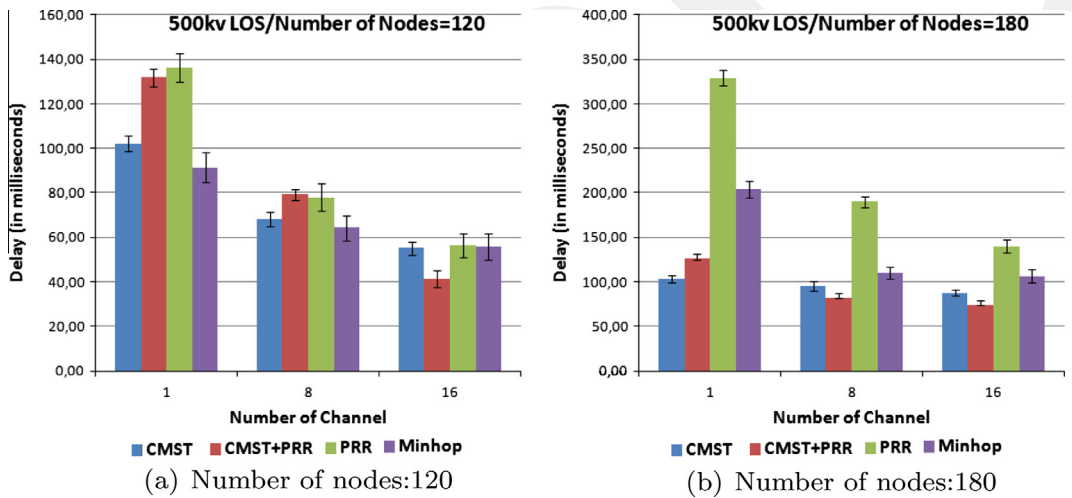


Fig. 3. Average delay with 95% Confidence Interval for Routing Protocols when number of channel increases in 500 kV Substation smart grid environment.

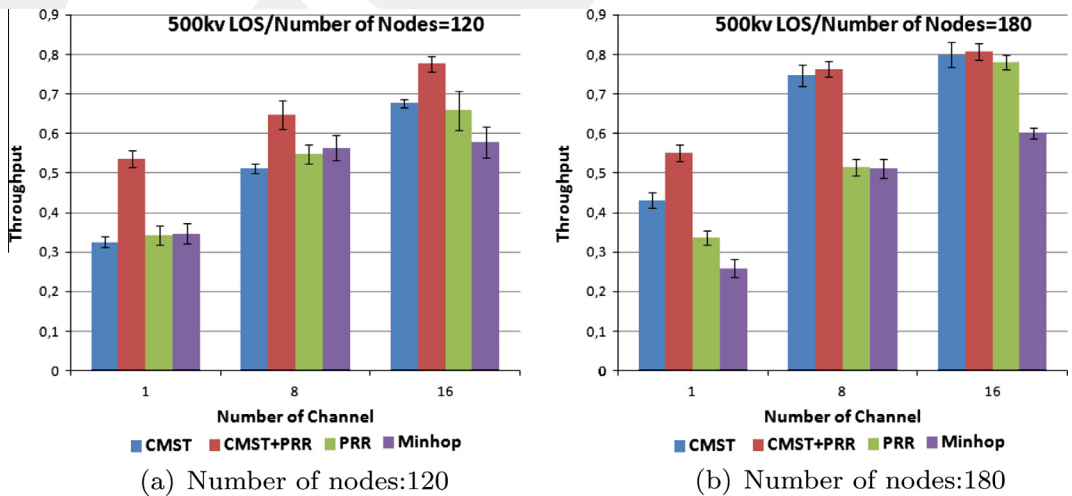


Fig. 4. Average throughput with 95% Confidence Interval for Routing Protocols when number of channel increases in 500 kV Substation smart grid environment.

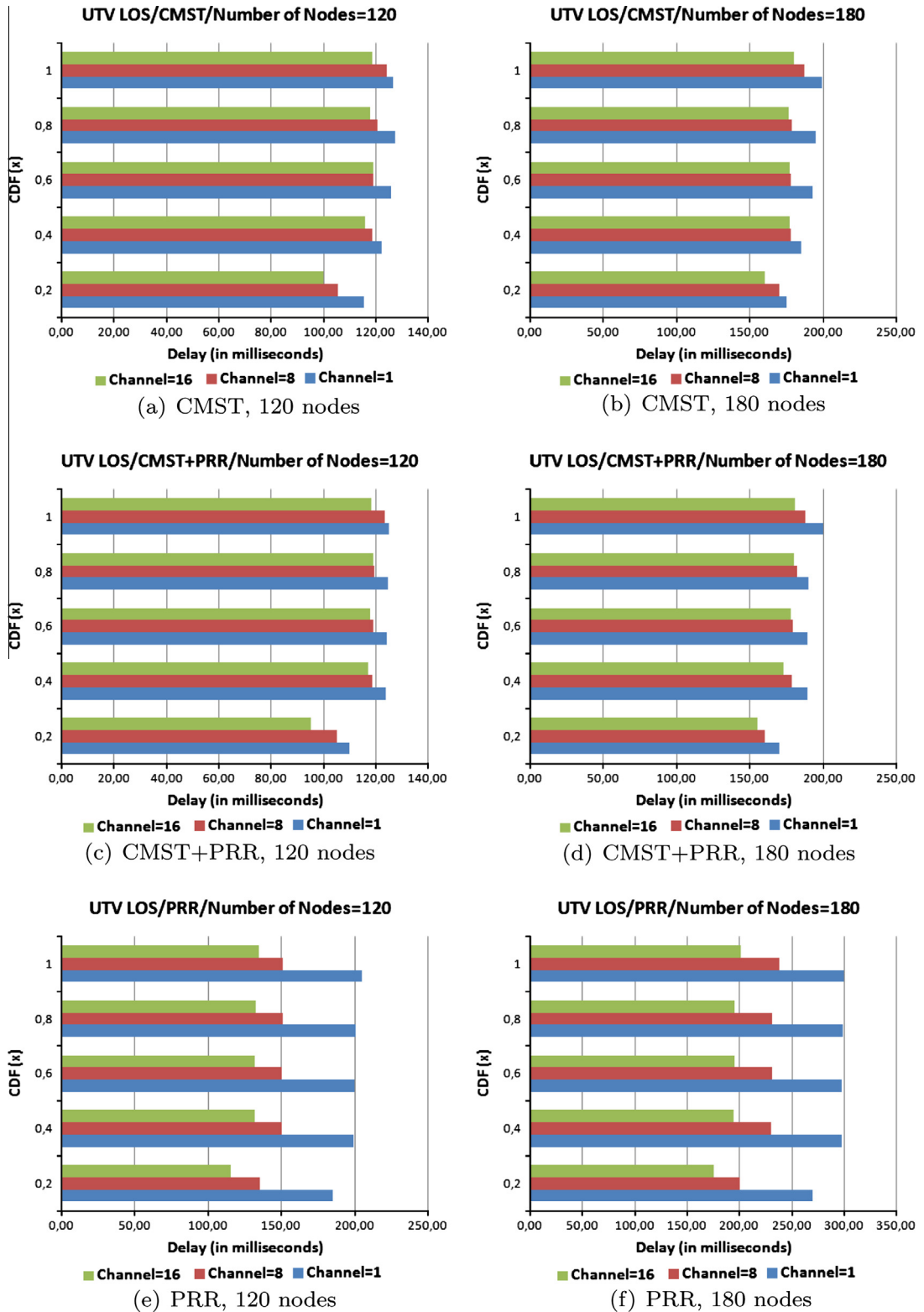


Fig. 5. Cumulative Distribution Function (CDF) of Delay for Routing Protocols when number of channel increases in UTV smart grid environment.

5.2.1. Delay performance of multi-channel and routing algorithms in UTV environment

In this part, effect of using multiple channels is investigated. PRR values are obtained by applying log normal shadowing propagation model in UTV environment. Environment parameters are shown in Table 2. In this regard, Figs. 5 and 6 show the cumulative distribution of delay and average delay with 95% confidence interval for different routing tree algorithms where the number of channels and the number of nodes increase from 1 to 16 and from 120 to 180, respectively.

In Figs. 5 and 6, generally it is observed that delay of PRR-based and Minhop routing algorithms decreases when the number of channels increases. However, the delay with CMST and CMST with PRR-based are not affected with the increase in the number of channels, but they give better results than PRR and Minhop algorithms. First of all, compared to the 500 kV Substation environment, the UTV

environment is less harsh, link qualities are better and links are less affected by interference due to simultaneous transmissions. Since the impact of interference is not visible in this set, the impact of routing trees becomes more visible. The performance with only a single channel is already good with CMST and CMST with PRR trees. However, Minhop trees and PRR-based trees cannot perform well with a smaller number of channels. Increasing the number of nodes to 180 nodes does not change the situation, either. CMST and CMST with PRR based trees perform the best. Since we do not consider the impact of retransmissions in this set, both algorithms perform similar.

5.2.2. Throughput performance of multi-channel and routing algorithms in UTV environment

Fig. 7, shows the throughput with all the evaluated routing tree algorithms with different number of nodes, where number of channel increases from 1 to 16. Similar

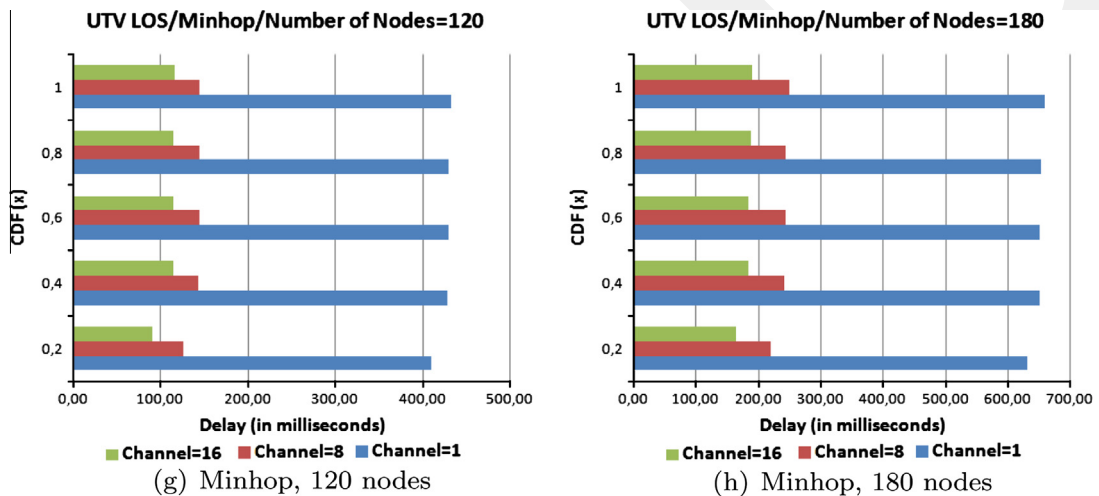


Fig. 5 (continued)

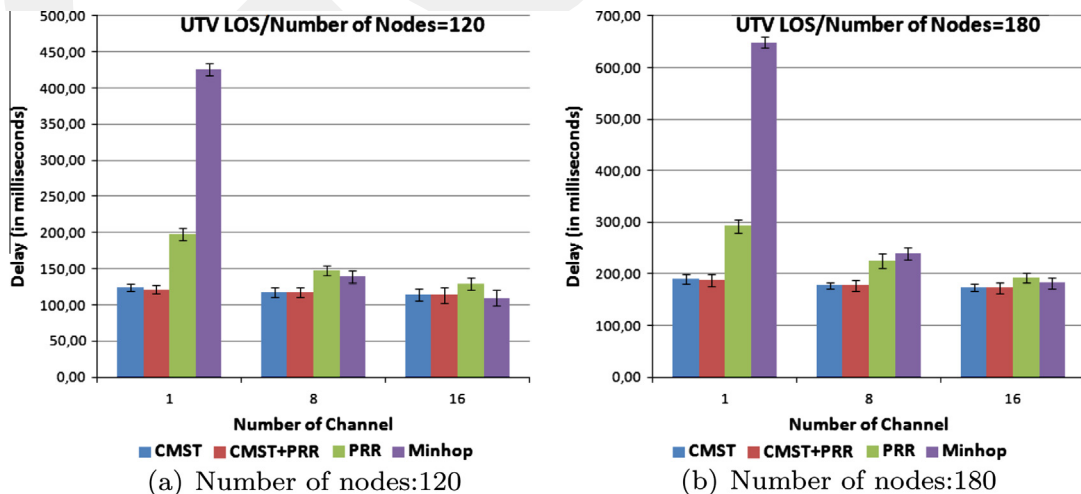


Fig. 6. Average delay with 95% Confidence Interval for Routing Protocols when number of channel increases in UTV smart grid environment.

to the delay results, it is observed that the throughput with CMST and CMST + PRR based trees do not change much with the increasing number of channels whereas Minhop trees and PRR-based trees perform better. It is also shown that throughput performance with CMST, CMST with PRR and PRR-based routing tree algorithms are close to each other when the number of channels is 16 for both 120 and 180 nodes. The throughput performance with CMST with PRR routing tree algorithm is a little better than the other evaluated routing tree algorithms because more reliable links are constructed by considering each link's PRR value and therefore, packets are sent over reliable links and the number of lost packets decreases in CMST with PRR routing tree algorithm.

### 5.3. MPR

In this section, performance of the routing algorithms are evaluated in Main Power Room smart grid environment. We run our simulations by using MPR parameters that is shown in Table 2. As a result of simulations, we obtained throughput and delay performance of each routing tree in MPR environment by increasing the number of channels and the number of nodes.

#### 5.3.1. Delay performance of multi-channel and routing algorithms in MPR environment

Figs. 8 and 9 show the cumulative distribution and average delay performance with 95% confidence interval for different routing algorithms in MPR environment, where the number of channels increases from 1 to 16 and the number of nodes increases from 120 to 180. It is observed that delay with Minhop and PRR-based routing trees decreases when the number of channel increases. However, the delay performance with CMST and CMST with PRR only slightly decrease with the increasing number of channels and their delay performances are close to each other. Results are very similar to the results obtained

in Section 5.2. It is also shown that delay of routing trees increases when the number of nodes increase from 120 to 180. This is an expected result just because when the number of nodes increases, the number of source nodes and the network density increases and more time is required to complete the receptions at the sink node. In Fig. 8 and in Fig. 9, generally it is observed that the delay performance with CMST and CMST with PRR routing trees are similar with each other and show the best performance in terms of network delay.

#### 5.3.2. Throughput performance of multi-channel and routing algorithms in MPR environment

Main Power Room (MPR) environment has better channel quality than the other smart grid environments in terms of path loss and shadowing deviation parameters that are shown in Table 2. Therefore, the throughput of our routing algorithms increase better than other evaluated smart grid environments. Fig. 10 shows the confidence interval of throughput performance for different routing tree algorithms in Main Power Room environment, where the number of channels and number of nodes increase from 1 to 16 and from 120 to 180, respectively.

In Fig. 10, generally it is observed that the throughput of all routing trees increases when the number of channel increases from 1 to 16, more increase is observed with Minhop and PRR based routing trees and a slight increase with CMST and CMST with PRR based trees. It is also shown that the number of nodes does not affect the throughput performance. This is because both the number of packets to be delivered and the delay increase, hence the throughput does not change and stays similar. Overall, CMST with PRR routing tree algorithm shows the highest performance in terms of network throughput, since this routing tree is specifically designed for minimizing schedule length and minimizing network delay for achieving maximum efficient operation of the WSN.

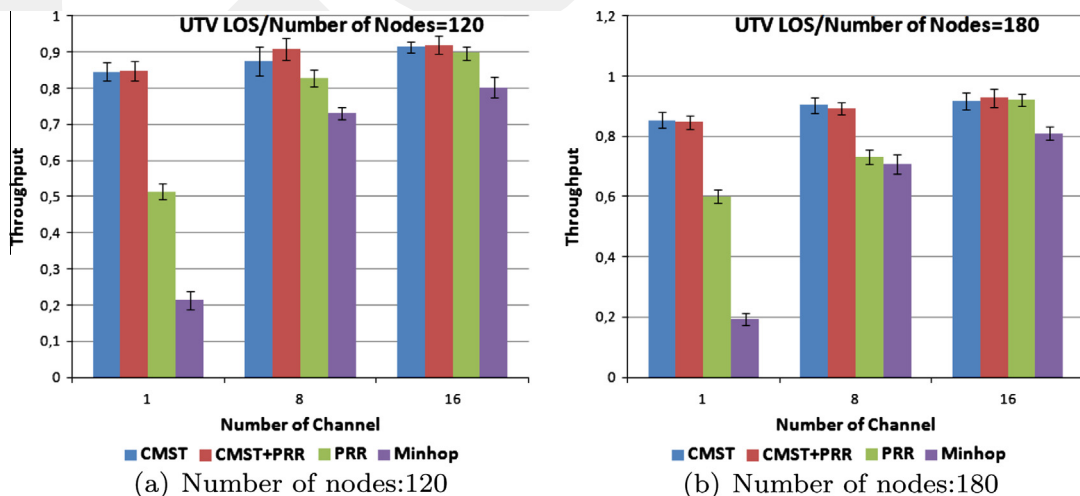


Fig. 7. Average throughput with 95% Confidence Interval (CI) for Routing Protocols when the number of channels increases in UTV smart grid environment.

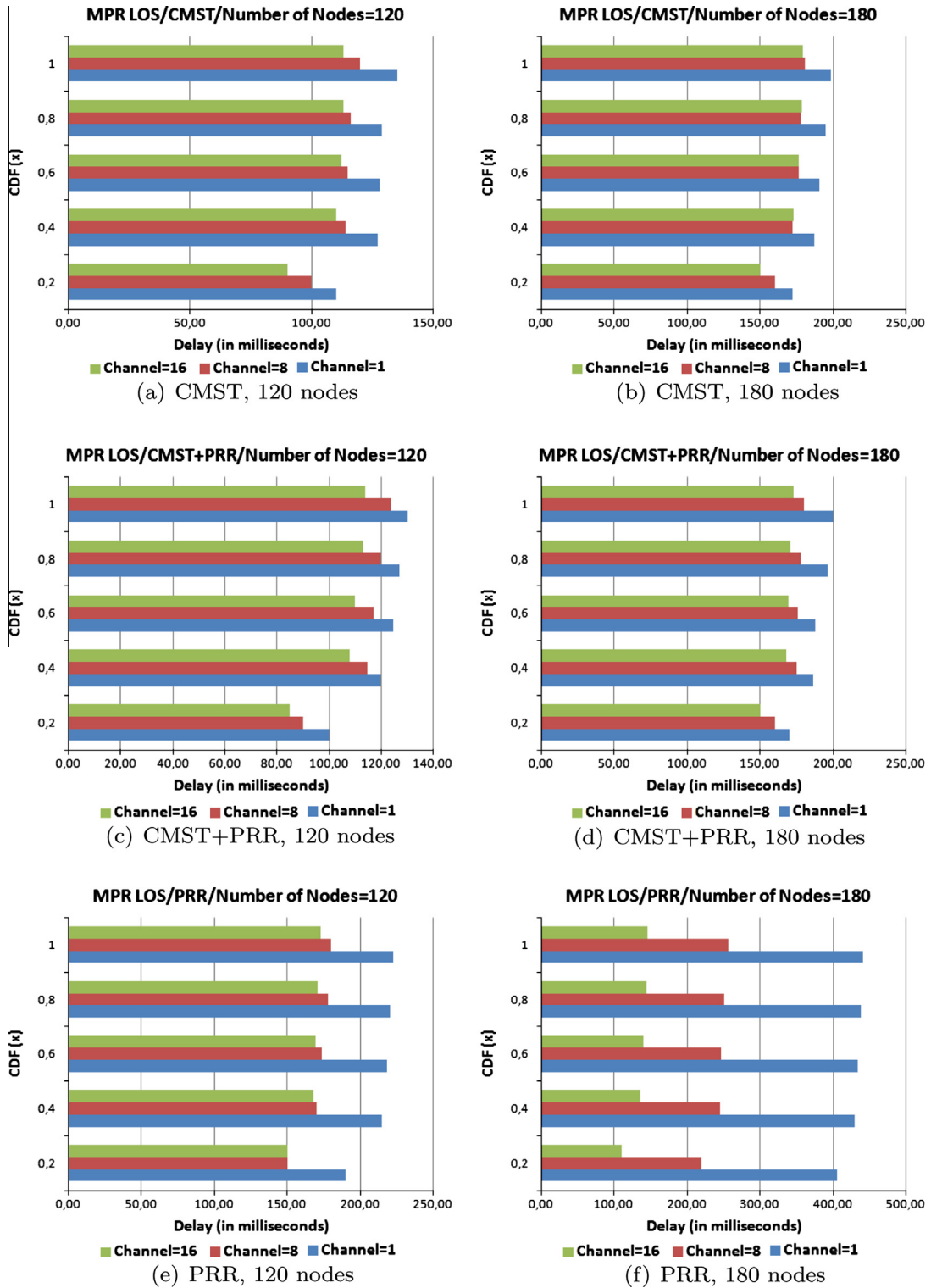


Fig. 8. Cumulative Distribution Function (CDF) of Delay for Routing Protocols when number of channel increases in MPR smart grid environment.

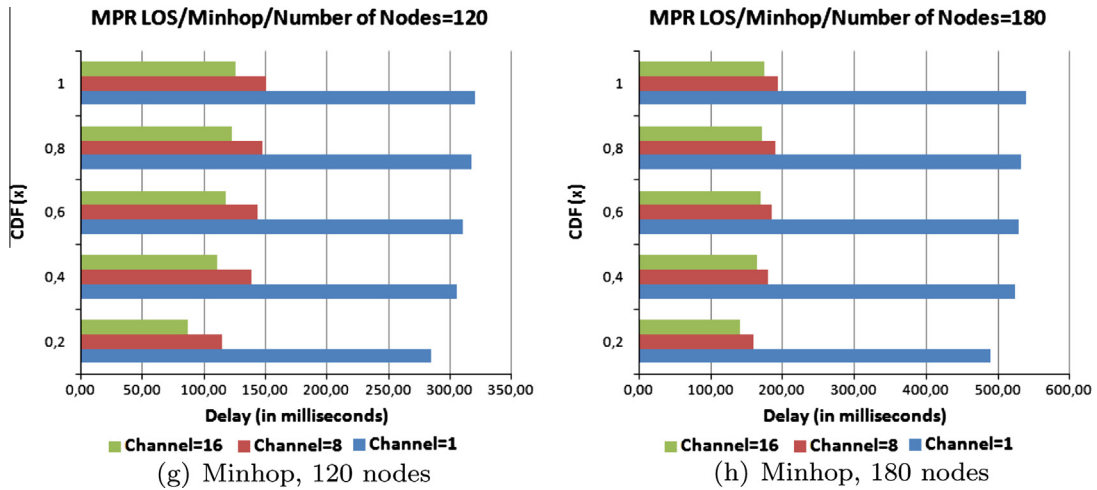


Fig. 8 (continued)

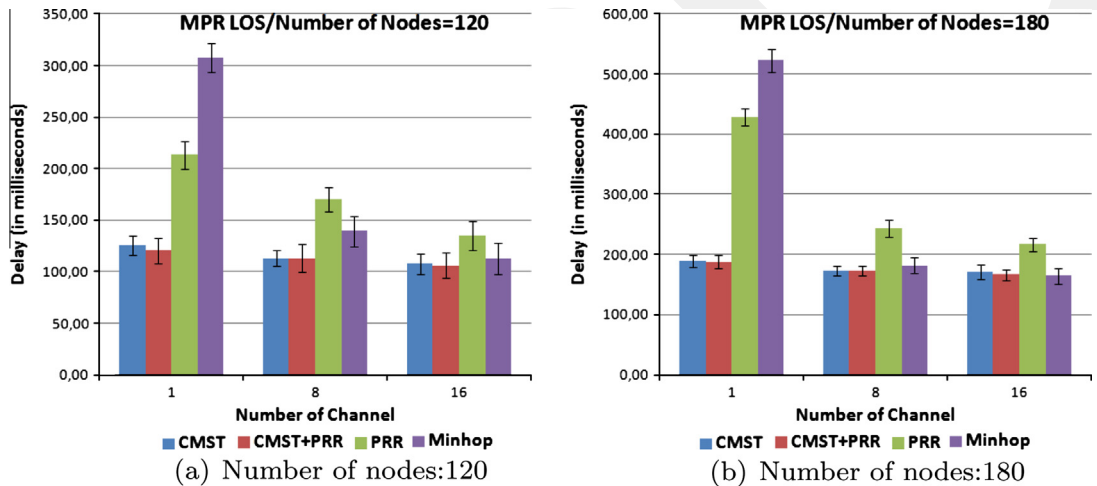


Fig. 9. Average delay with 95% Confidence Interval (CI) for Routing Protocols when number of channel increases in MPR smart grid environment.

#### 5.4. Impact of the number of retransmissions with different routing trees in smart grid environment

In this section, effect of retransmissions is analyzed for 500 kV Substation smart grid environment to see how the throughput and delay of the routing trees change with the number of retransmissions. Simulations are performed with 120 nodes and for 16 channels.

##### 5.4.1. Impact of number of retransmissions on the delay in 500 kV environment

Figs. 1 and 11 show the cumulative distribution of delay and average delay with 95% confidence intervals with different routing tree algorithms in different network conditions, where the number of retransmissions in case of lost packets due to link unreliability increases from 0 to 6. Delay with routing algorithms increases when the number of retransmissions increases. Delay occurs with retransmissions because each node tries to send multiple

times if a packet is not sent at the first try and hence more packets need to be scheduled for each frame period. We measure the delay with routing trees according to number of retransmissions such as 0, 4 and 6 and the delay with each routing tree is observed with respect to these number of retransmissions.

In Fig. 1, it is observed that the CMST with PRR routing tree algorithms show the best performance in terms of network delay. This is because CMST with PRR both balances the number of nodes on the subtrees and considers the links with better qualities at tree construction phase, hence it experiences less packet losses.

##### 5.4.2. Impact of number of retransmissions on the throughput in 500 kV environment

Fig. 12 shows the average throughput with 95% confidence interval with different routing tree algorithms in Main Power Room environment, where the number of retransmission increases from 0 to 6. Number of retransmissions affects

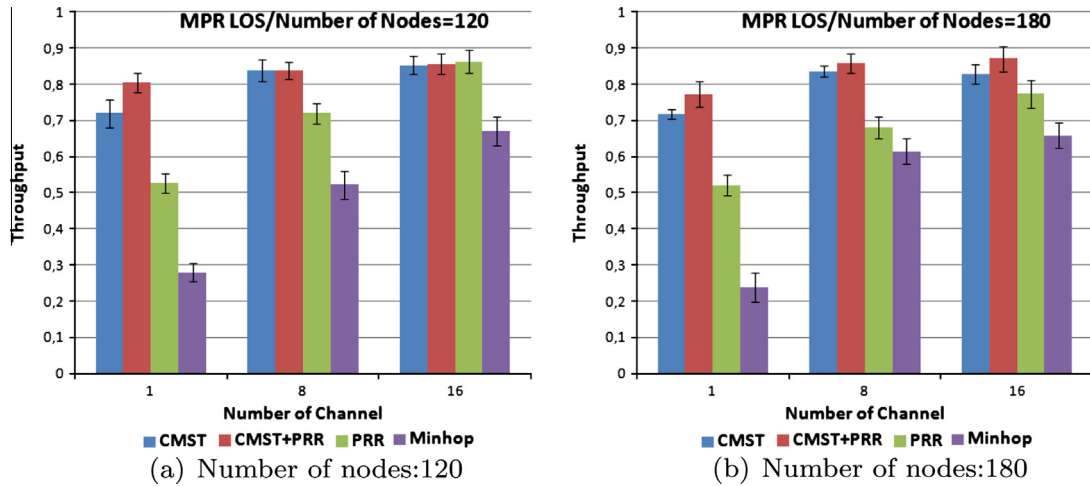


Fig. 10. Average throughput with 95% Confidence Interval (CI) with Routing Protocols when the number of channels increases in MPR smart grid environment.

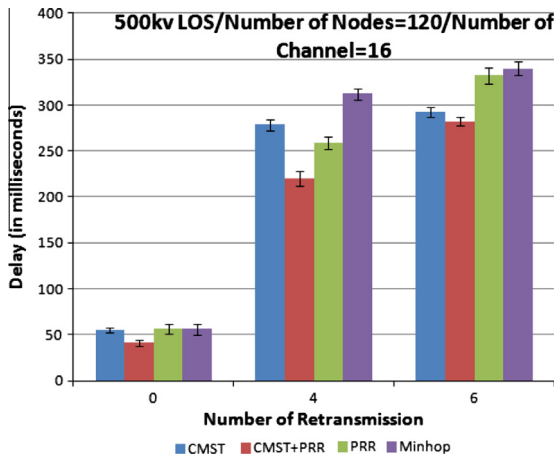


Fig. 11. Average delay with 95% Confidence Interval (CI) for Routing Protocols when number of retransmission increases in 500 kV smart grid environment.

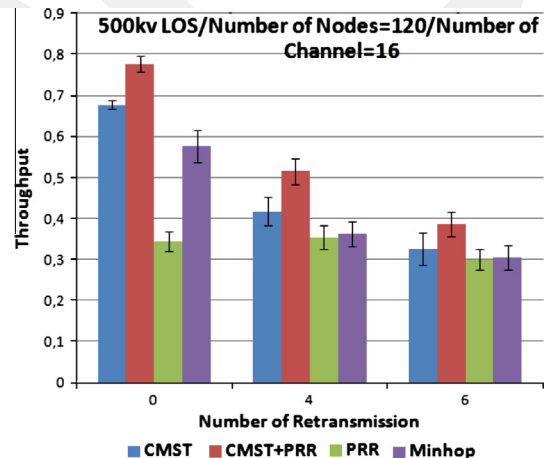


Fig. 12. Average throughput with 95% Confidence Interval (CI) for Routing Protocols when number of retransmission increases in 500 kV smart grid environment.

the throughput of our proposed routing algorithms because of the delay performance. As seen in Section 5.4, delay increases for all the tree types with respect to number of retransmissions. Therefore, throughput of routing trees decrease every time in this condition considering that the number of delivered packets to the sink increase little. Accordingly, trees with less delay provide more throughput than other trees if the number of retransmissions increases. In this context, CMST + PRR provides better throughput as shown in Fig. 12 than others because as already stated in Section 5.4, it results in less delay than the other trees when the number of retransmissions increases and it delivers more packets than the other routing trees since it considers transmissions over reliable links.

In Fig. 12, it is observed that the throughput performance of all the routing tree algorithms decreases when the number of retransmissions increases. This is because the delay increases while trying to transmit all the packets

multiple times. In addition, it is also shown that CMST with PRR routing tree again carries out more reliable and more effective communication with retransmission than the other trees because it has less delay than others as shown in Fig. 1. All of these results show that CMST + PRR routing tree is more efficient in smart grid environments when multi channel communication and retransmission are applied.

### 5.5. Overview of simulation results

The extensive simulations have been performed considering real field tests performed in 500 kV Substation, Underground Transformer Vault (UTV) and Main Power Room smart grid environments to measure network and throughput performance of different routing tree algorithms, such as Capacitated Minimum Spanning Trees (CMSTs), Capacitated Minimum Spanning Trees (CMSTs)

**Table 8**  
Comparison of simulation results in smart grid environments.

Propagation environment	Multi channel	Number of nodes augmentation	Best routing tree
500 kV Substation – Delay	Decrease	Increase	CMST and CMST + PRR
500 kV Substation – Throughput	Increase	Increase	CMST and CMST + PRR
Underground Transformer Vault – Delay	Decrease	Increase	CMST and CMST + PRR
Underground Transformer Vault – Throughput	Increase	Increase	CMST and CMST + PRR
Main Power Room – Delay	Decrease	Increase	CMST and CMST + PRR
Main Power Room – Throughput	Increase	Increase	CMST and CMST + PRR

with Packet Reception Rate (PRR), Minimum Hop Spanning Tree (MHST), Packet Reception Rate (PRR) – based routing algorithms in various network conditions where the number of channels, number of nodes are increased from 1 to 16 and from 120 to 180, respectively. We also investigated the impact of the number of retransmissions on the throughput and delay for 500 kV Substation smart grid environment. Through these simulations, the wireless channel has been modeled using log-normal shadowing path loss model. As a result, the results of our performance evaluations can be summarized as follows:

- Impact of multi channel communication on the delay metric is examined for different routing trees in smart grid environments and CMST with PRR routing tree is found to perform better than others when the number of channels increases. This is because it minimizes the schedule length by constructing balanced trees according to each node's PRR value that must exceed certain threshold to build reliable paths.
- Throughput of all tree types are measured by applying multiple channels in smart grid environments and their performance is compared with each other. We observe that CMST with PRR shows the best performance because it delivers the same amount of packets in a shorter interval compared to other routing trees. On the other hand, other trees construct paths without taking into consideration PRR values or balanced subtrees and therefore, their performance is lower than CMST with PRR routing tree algorithm.
- Impact of the number of nodes is also investigated to assess the performance of different routing trees with changing density. We again observe that, CMST with PRR routing tree performs better in delay and throughput performance than the other routing tree algorithms. Despite in some cases, CMST and CMST with PRR routing tree algorithms have similar results, in general, CMST with PRR performs better than CMST. This is because it constructs the paths also considering the PRR values of the links which is not implemented by CMST.
- Impact of the number of retransmissions is considered to evaluate its effect on throughput and delay performance of different routing tree algorithms in smart grid environments. Number of retransmissions increases the reliability of the network, however, it decreases the throughput of the routing algorithms because it increases the delay by making multiple transmissions, as expected. Therefore, it must be applied carefully according to application's requirements in smart grid

environments. Our simulations show that none of the evaluated routing tree algorithms perform very well when the number of retransmissions has been increased. Therefore, before applying retransmission, application requirements and network capabilities should be considered together to improve the overall network performance. However, if retransmissions has been applied for the application, according to our simulations CMST with PRR routing tree can be preferred because its throughput and delay performance is better than other routing algorithms with balanced subtrees and PRR threshold.

Based on the simulations above, it is observed that the performance of the routing tree algorithms differ in terms of network throughput and network delay in different network conditions. Before making a decision for network design in smart grid environments, WSN-based smart grid applications requirements as well as network abilities must be considered together to improve network performance. In summary, evaluated routing tree algorithms have been compared in Table 8 in terms of multi channel condition, number of nodes augmentation and best routing tree algorithm. While the performance evaluations in this work provide valuable insights about the performance of routing tree algorithms in smart grid environments, we expect that this paper will motivate the research community to further explore this promising research area.

## 6. Conclusion

In this paper, delay and throughput of CMST, CMST with PRR, PRR-based and MHST routing trees in three smart grid environments are presented by considering different parameters extracted from real field tests. Simulations are performed to evaluate the impact of the number of channels, the number of nodes and retransmissions on delay and throughput in different smart grid environments. The comparative performance evaluations have been done to determine quantitatively how much communication delay and throughput of the network will change in real channel conditions, when frequency and retransmission increases. In the future, we will implement TSCH mechanism in our approach to see how this mechanism changes performance of routing trees. Consequently, simulation results provide a guideline for the design of new algorithms for the smart grid applications. In summary, the main contributions and findings of this paper have been listed as follows:

- Impact of real channel characteristics on the CMST, CMST with PRR, MHST and PRR-based routing algorithms are revealed by implementing the log normal shadowing model for different smart grid environments. Path loss and shadowing deviation parameters of different smart grid environments [1] are used in order to compute log normal shadowing model equation for measuring proposed routing algorithms' throughput and delay performance.
- The throughput and delay performance of different routing algorithms, such as CMST, CMST with PRR, MHST and PRR-based routing algorithms, have been compared in three different smart grid environments to determine which routing algorithm is more reliable when log normal shadowing model is applied. It is shown that the CMST with PRR-based routing tree shows the highest performance in terms of delay, since this routing protocol is specifically designed for minimizing delay and increasing the network capacity. It is also shown that the throughput performance of the CMST with PRR algorithm is better than other proposed algorithms for different smart grid environments.
- When the number of channel increases, we show that throughput increases for all smart grid environments, including 500 kV Substation, Underground Transformer Vault and Main Power Room. Retransmissions also impact the delay and throughput of the network for smart grid environments. It is observed that CMST with PRR shows the best performance in terms of network throughput and delay because it constructs reliable communication channels by considering PRR values of the links at the tree construction stage. In this way, it decreases delay of transmission by avoiding multiple transmission.

## Acknowledgement

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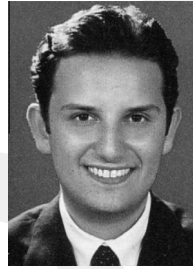


**Melike Yigit** received her B.S. and M.S. degrees in Computer Engineering from Bahcesehir University, Istanbul, Turkey, in 2010 and 2012, respectively. Currently, she is a Ph.D. student in Bahcesehir University, Istanbul, Turkey and works at Turkish Airlines (THY), which is an international airlines in Turkey, as a Business Analyst. Before starting THY, she worked in Huawei Technologies Co. Ltd. and Alcatel-Lucent Teletas as a software developer and San-Tez Project student, respectively. Her current research interests

are smart grid communications, power line communications and wireless ad hoc and sensor networks.



**Ozlem Durmaz Incel** received her Ph.D. in Computer Science from the University of Twente, Netherlands, in March 2009. She was a visiting student in the Autonomous Networks Research Group of the University of Southern California as part of her Ph.D. studies in 2007–2008 and worked as a postdoctoral researcher and a lecturer at Bogazici University in 2009–2012. She received both her M.Sc. and B.Sc. degrees in Computer Engineering from the Yeditepe University, Turkey, in 2005 and 2002 respectively. Currently, she is an assistant professor in the Computer Engineering Department of Galatasaray University. Her research interests are in the design and analysis of algorithms/protocols for wireless networks, particularly for sensor networks, and in the embedded networked sensing systems especially on participatory sensing.



**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, reviewer and program committee member to numerous journals and conferences in these areas. He is also the recipient of the IEEE Trans. on Industrial Informatics Best Paper Award in 2012, IEEE ISCN Best Paper Award in 2006, the European Union FP7 Marie Curie RG 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.