CR Based WSAN for Field Area Network in Smart Grid

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***Abstract*—Higher demand for good quality, more reliable and cleaner electrical power has driven the focus towards more robust generation, transmission and distribution framework. It has been envisioned that, a more intelligent grid capable of taking fast and reliable decisions is the need of the hour The Smart Grid. Through intercommunicating devices at every level, the smart grid is expected to take power management to a new level of sophistication and efficiency. The communication network for connecting all these devices is of paramount importance to enable two way information exchange, and reliable and fast automated control. It needs to comply with critical demands of throughput and delay. Use of wireless links is set to be handicapped by ever increasing spectrum scarcity. In order to build up the reliable network, use of Cognitive Radio (CR) provides a feasible solution, by accessing a wider range of spectra through Dynamic Spectrum Access (DSA). In this paper we present a CR based Wireless Sensor and Actuator Network (WSAN) model for distribution grid automation. Random appearances of Primary User (PU) have been modeled for DSA implementation. The performance of CR model is compared with legacy Wi-Fi model to evaluate its feasibility for adaptation to the demanding smart grid communication requirements.**

***Index Terms*—Smart Grid, Distribution Automation (DA), Field Area Network (FAN), Wireless Sensor and Actuator Network (WSAN), Cognitive Radio (CR), Dynamic Spectrum Access (DSA)**

I. Introduction

The present power grid infrastructure is aging and has not being renewed or updated for quite long period of time. It suffers from power deficiency, high transmission losses, poor power quality, and low reliability. To overcome these issues, the concept of Smart Grid was proposed. It is a technology that aims to infuse intelligence into generation, transmission and distribution systems of electrical power. The idea is, to collect data about the operation, condition and demands of the grid and automatically take required decision to best suit the situation. Evolution of smart real time decision making algorithms has helped to address the various problems associated with the power grid in a fast and reliable manner [1].

An efficient and reliable communication system is the backbone of smart power grid. This system is required to connect a vast number of sensing devices and actuators, and to relay status and control messages throughout the grid. There is no unique protocol or network that fulfills all the communication requirements for smart Grid. Hence various protocols have been proposed for different functionalities of smart Grid.

At a broader perspective, a Field Area Network (FAN) is required to automate the Distribution System of Smart Grid. FAN has a vast area of coverage both in terms of geography and functionality. These functionalities posses very srtingent bandwidth and latency requirements. For instance, a 5 Mbps bandwidth is required to support seamless transmission of data from Neighbour hood area Network (NAN) Aggregators to the substation whereas to support Distributed Energy Resource (DER) Islanding, FAN has to have a maximum of 100ms data latency[2]. Power Line communication could not be a viable solution owing to the issues discussed by authors in [3][4]. Hence a Wireless Sensor and Actuator Network (WSAN) is needed to realize the Field Area Network.

Application of WSAN in power grid requires high throughput and low end to end delay. Some of the viable communication protocols could be Cellular network, ZigBee, WiMAX or Wi-Fi protocols. However, the existing cellular network is not reliable. During peak network congestion, control messages may not meet delay requirements and hence may lead to failure of critical systems. Also, it does not reliably reach to all parts, especially rural areas[5][6]. The ZigBee protocol has very low throughput and cannot cater to the high data rate requirement of FANs for Distribution Automation (DA) [7]. Wimax could be best possible solution for FAN as proposed in the literature[2] [6] but the infrastructure for wimax is not fully installed and even it is fast loosing its popularity. Hence there is a need to explore for a better technology. The other available wireless solutions which is very neer to the requirement is wifi as it has low cost of installation and high data rates. But there are various issues associated with wifi like lower range and high interference from other protocols like zigbee and bluetooth which also works in same frequency band i.e., 2.4GHz. To overcome these issue one can think of mesh or multihop networks. Though these types of network helps in overcoming the range issues, they does not fully solve the problem. A Field Area Network needs to have a maximum latency of 100ms to support DER in distributin grid. If the number of hops are more in a mesh network then most probably this requirement may not be fulfilled.

On the other hand, spectrum sensing studies have indicated that, the UHF band, allocated to TV broadcasting, have a low duty cycle of operation and are not used for transmission in all geographical locations[8]. Such spectrum white spaces can be utilized by Cognitive Radio (CR) technology. A cognitive radio is a software defined radio with the ability to reconfigure its settings based on its own performance evaluation and channel characteristics [9]. CR technology can be used to enhance the effectiveness of Wi-Fi protocol in FANs for distribution grid. A comparative performance analysis of Wi-Fi operating in the 2.4GHz band and CR based Wi-Fi operating in 680MHz band, is presented in this paper. Through simulations and analyses, the advantages of CR protocol for WSANs in a FAN are presented.

The rest of the paper is organized as follows. Section II presents the features, requirements and challenges of Smart Grid Technology. The DSA model features and parameters are listed in section III. In section IV, the WSAN scenario, and comparative performance analyses and inferences are plotted. Section V concludes the paper.

II. OVERVIEW OF SMART GRID

The present power grid is losing out on good performance and quality power. Some of the key concerns are high fossil fuel consumption, increasing market demands, ageing infrastructure, and lack of innovation in this field. To overcome these drawbacks, the focus has shifted to develop more intelligent sensing and control mechanism for power grids, which is referred to as Smart Grids. The most important areas of development for smart grids are identified as digitalization, flexibility, intelligence, resilience, sustainability, and customization [11].

The smart grid is envisioned to incorporate the features like accommodating all generation and storage options, Demand side management by user participation, Time of use pricing, Providing better power quality, self-healing, optimized utilization of assets and enabling new services, products and market[13]. In order to actualize these features, a fast and reliable bidirectional data exchange mechanism need to be developed. This can be done by the use of multiple communication networks connecting every entity associated with generation, transmission and distribution of power.

A. Communication Networks

The data exchanged in a smart grid communication network could be monitoring, measurement, or control data, which have different criticality and need to be addressed accordingly. Various applications of smart grid have different constraints depending upon the priority of data exchange. To meet these varying requirements, literature has proposed a hierarchical communication model, as shown in Fig. 1, consisting of multiple, intercommunicating sensor networks having different set of quality of service requirements [1].

Communication networks like Home Area Network (HAN), Building Area Network (BAN), and Industry Area Network (IAN) are needed to enable features like demand side management, time of use pricing, and optimized use of power. In addition to home, building, or industry automation to save power, these networks, coordinated by smart meters, can enable remote controlling of appliances by the utility to minimize peak load demand [14].

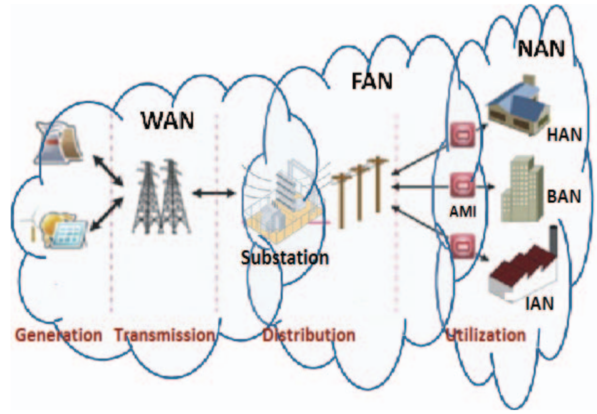

Figure 1. Communication networks for Smart Grid

The smart meters from different users form a local mesh network to ensure successful delivery of data to substation. This network is termed as Neighborhood Area Network (NAN). The coordinator of this network aggregates data from the locality, so as to minimize packet overheads and channel contention.

Multiple aggregators of NANs along with few other devices form the Field Area Network (FAN). This network reports the status of critical equipment of distribution system while acting as a bridge for meter data to the substation.

Many such substations are connected to the control centers or the utility office via a wide area network (WAN). This network helps in transferring real-time measurement data from electric devices to control centers and also different instructions as a response, from control centers to the devices[1]. As this network has to cover a large geographical area and also has to handle very large accumulated data, a very high speed, high data rate communication technology has to be considered. Normally, Fiber optic is considered to be the most suitable for such networks, as it has very low latency of about 5 μsec per kilometer[13].

B. Field Area Network for Distribution Grid

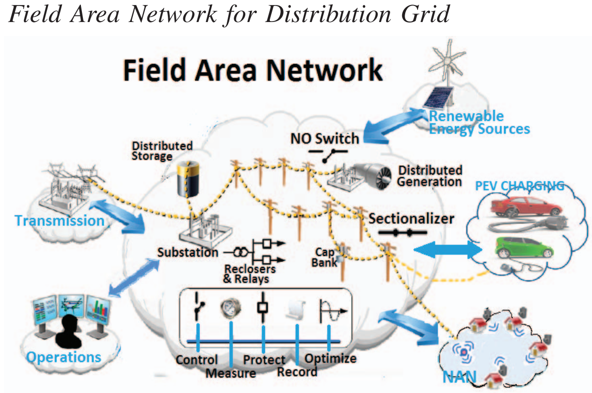

Figure 2. Field Area Network (FAN) components

Nodes other than NAN aggregators, which are part of the FAN are sensors/actuators termed as Intelligent Electronic Devices (IEDs) installed at critical points of distribution grid like transformers, lightning arrestors, circuit breakers, capacitor banks, junctions, etc. These IEDs are responsible for monitoring their health, report it to substation, and to take preliminary control actions in case of malfunction or failure. An envisioned FAN is shown in Fig. 2. FAN is expected to enable the following functionalities into the grid [1].

- Distribution Automation.
- Integration of distributed energy generation and storage options.
- To Relay smart meter data from NAN to substation.
- Integration of Plug-in Electric Vehicle (PEV) charging pumps.

The above functions of FAN, calls for a WSAN realization operating on critical equipment. Hence, it has tight constraints for delay and throughput. This paper attempts to evaluate the performance enhancement of CR technology over Wi-Fi for implementing WSAN and fulfill the requirements of FAN.

III. DSA MODEL FOR CR-WSN

Dynamic Spectrum Access (DSA) is one of the primary enabling features of CR technology. It is defined as the ability of a communication device (Secondary User or SU) to dynamically switch channels, enabling it to select channels with best propagation characteristics. However, utmost care must be taken so as not to interfere with transmission of the owner of the channel (Primary User or PU). The implementation of DSA requires spectrum sensing and frequency agility. Spectrum sensing refers to the monitoring of the current channel to detect the presence of PU. Frequency agility is the ability to switch to another channel if the PU starts transmitting in the current channel.

The non-interference with the PU is the most important concern for implementing DSA in CR. There are certain regulatory constraints that must be adhered to, in order to maintain signal integrity for the PU. Some DSA parameters are Incumbent Detection Threshold (IDT), Channel Detection Time (CDT), Probability of Detection (PD), Maximum Probability of False Alarm (PFA), Channel Move Time (CMT), Channel Closing Transmission Time (CCTT). They are described in greater detail in [17]. The value of these parameters shall depend on the channel we are using, the type of primary and secondary users networks. The IEEE 802.22 standard defines these parameters to facilitate DSA in TV broadcasting channels to be, IDT = -116dBm, CDT $\leq$ CMT = CCTT = 2s, PD = 90%, PFA = 10% [8].

Spectrum sensing is an important aspect of DSA model. Few of nodes are assigned this task, hence reducing overall power consumption for other nodes. Making the network coordinator responsible for spectrum sensing is a viable option, as it is a device with high computation power. The geographical area covered by FAN for distribution grid is small enough such that we may assume there wont be different primary users for different locations in that area.

In order to have reliable PU sensing, transmission from all nodes of the FAN needs to be suspended for a period of time termed as Quiet Period (QP). These network wide quite periods can be resembled as on-off model for data transmission in a way that the users can transmit data during non-QPs(on periods) whereas they have to shut their transmission during QPs(off period). This gives the advantage of detecting PU at very low IDT values and also helps in avoiding false alarms[19]. The QP repeats every QP_Interval and is of duration QP_Duration. The model employed in this paper assumes QP_Interval to be 2s, to meet 802.22 CDT and CMT specifications, and QP_Duration to be 50ms, the optimal sensing duration for reliable results [19]. The timing diagram of DSA model is shown in Fig. 3.

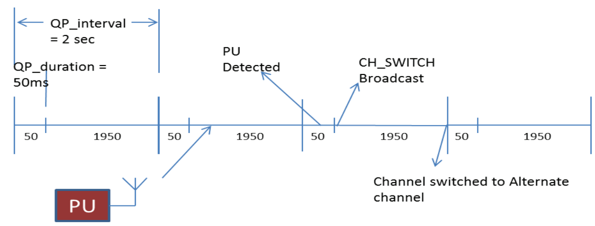

Figure 3. DSA model

PU can appear at any time on the operating channel, which is a random event. Hence it has been modeled by a suitable random variable. Once PU is detected by the coordinator in a QP, it broadcasts a Channel Switch command, which contains the information about the next selected channel. All nodes, then schedule shifting to new channel at the start of the following QP.

IV. SIMULATION, ANALYSIS AND COMPARISON

This section presents a comparative performance analysis of legacy Wi-Fi and CR enabled Wi-Fi protocols for realizing WSAN implementation of FANs in distribution grid. Simulations were carried out in NS-3, which has a built in IEEE 802.11 model. We have implemented CR features and paradigms to implement QPs and channel switching as per 802.22 specs described in section III. Various experiments were carried out with both models and results are compared. Different topologies were evaluated to see its effect on the performance of the network.

A. Range Test

The communication range for 2.4GHz channel and a CR channel centered at 680MHz are compared at same transmission power. The transmitter and receiver antennae gains are

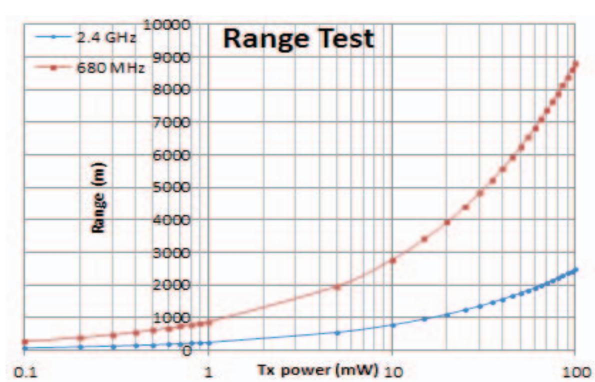

Figure 4. Range test semilog plot

kept fixed at unity, receiver sensitivity at -86dB, and free spacepath loss model is adopted. This model calculates quadratic path loss as presented by author in [18]. The transmission power is varied in steps and the range of transmission for both channels are noted, are plotted in Fig. 4. Here the range is taken to as a point at which the receiver completely stop receiving any packet from transmitter.

As seen from Fig. 4, for same transmitter power, the range of 680MHz channel is more than thrice that of 2.4GHz channel. This can be explained by the higher propagation loss at higher frequencies. The improvement gained in terms of communication range can help in reducing transmitter power or deploy fewer number of sensor nodes to cover a given area.

B. Distribution Grids Field Area Network Scenario

For distribution grid automation, two types of topologies were evaluated. The first is a planned topology as shown in Fig. 5 whereas the other one is a uniformly distributed topology as shown in Fig. 6. Each topology is designed with 36 sensor nodes and one coordinator.

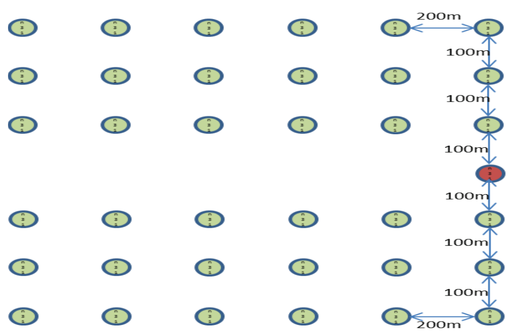

Figure 5. Planned Topology

The expected traffics in a FAN are:

- Smart meter aggregated data from NAN.
- To and Fro data for DER Coordination.
- Critical equipment's health monitoring data.
- Measurement data from IEDs for power quality management.
- Control information from substation or Utility to IEDs.

These data traffic scenario are modeled as two different types of packets in our simulations. The sensor nodes send status packets of size 256 bytes to the coordinator every 0.25 seconds. The choice for this packet size is from [19] with an assumption of 8-bit Analog-to-digital conversion resolution instead of 16-bit resolution. The coordinator broadcasts a control packet of size 256 bytes to all nodes every 2 second. For CR simulations, there is a third category of packets, the Channel Switch command. It is broadcasted from the coordinator to all nodes, every time PU is detected in any QP.

The three types of packets are assigned priorities. The Channel Switch command packet has the highest priority, followed by control packet, and finally status packet.

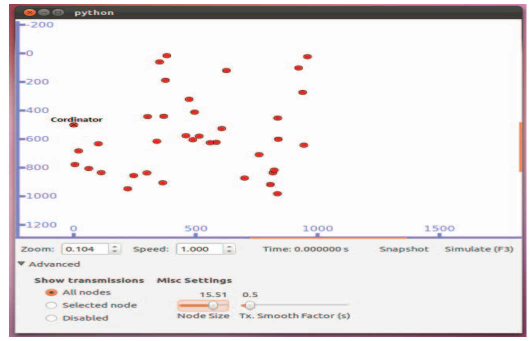

Figure 6. Random Topology

The Wi-Fi protocol transmits at the 2400MHz channel. For the implementation of CR model, we considered availability of two channels with center frequency 680MHz and 702MHz respectively and a bandwidth of 20MHz, which can be opportunistically used for data transmission. We also consider that once PU starts transmitting in one channel, the other one gets freed for use by SU. Spectrum sensing is assumed to be at coordinator only. These assumptions are similar those considered in [20], but PU appears only once throughout the simulation, which is a much relaxed condition. In our simulations, we model the PU appearance as a Bernoulli random variable having 30% success probability (SP). We also consider the absolute worst case scenario of SP = 100%, i.e., PU appears in the operating channel in every quiet period.

The transmission power for both protocols is set at 1mW (0dBm). This value is adopted with an idea of low power consumption at the nodes. To enable multihop transmission, OLSR protocol is used. Since, OLSR protocol does not support mulihop broadcasting, which is needed for transmitting control and channel switch command packets to all nodes, we have implemented a flooding based protocol to serve the purpose.

C. Hop Count Analysis

The number of hops for each data packet is logged and a hop count analysis is presented. By hop count, we means the number of hops taken by a packet transmitted from each sensor node to reach the coordinator. Fig. 7 and Fig. 8 shows the hop count statistics for planned and random topologies respectively. As can be seen from Figures, the CR protocol

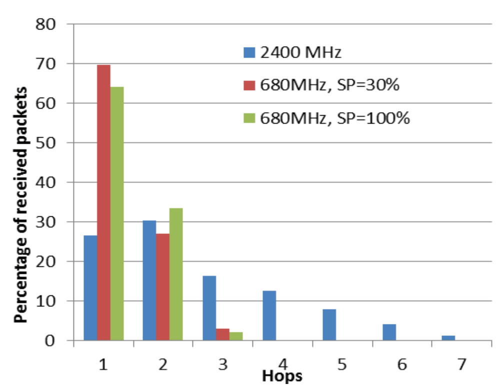

Figure 7. Hop count analysis for planned topology

implemented on the Wi-Fi model significantly reduces the number of hops for all packets, owing to its higher communication range. Also, the packet dropping rate is significantly reduced.

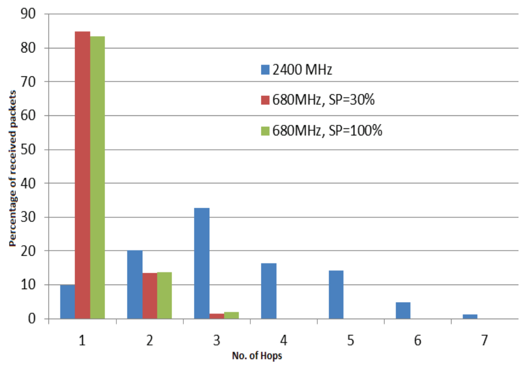

Figure 8. Hop count analysis for random topology

D. Packet Delay Analysis

Delay is an important performance criterion for a WSAN network. Critical sensor data and high priority control action need to be relayed within stipulated time bounds to realize a real time monitoring and control systems for smart distribution grid. The possible causes of data latency in a communication network could be data acquisition and processing, bad channel condition, low data rate and bandwidth, channel contention by higher number of nodes in a broadcast channel, and multi-hopping.

The end-to-end delay of each received packet was logged and a statistical analysis of the collected data was done. The maximum and average delay performance for the three scenarios simulated is shown in Table I.

Table 1. End-to-end delay performance statistics

	Maximum (ms)		Average (ms)	
	Planned Topology	Random Topology	Planned Topology	Random Topology
2400MHz	934.1	236.9	70.0	49.2
680MHz, SP=30%	380.4	581.4	18.2	10.7
680MHz, SP=100%	1615.5	2305.6	40.3	26.45

From Table I, it can be observed that the average delay performance for CR model with 30% SP is better than that for legacy Wi-Fi model even after having QP and channel switching overheads. Even for the worst case scenario where PU appears in the operating channel in every QP, the average delay performance is still better than legacy Wi-Fi. The reason for having higher maximum delay is because of channel switching. Whenever network switches to newer channel, the old network information like routing table becomes void and hence these things has to be established again which consumes time. Anyhow we don't consider that even a channel with 30% SP (on an average free for 3 sec) will be used for cognitive radio communication. Rather a channel which will be free for couple of minutes (say 10 mins, leading to 0.33% SP) will be considered for CR applications. Hence, we expect that even the maximum delay will be in limits of application requirement.

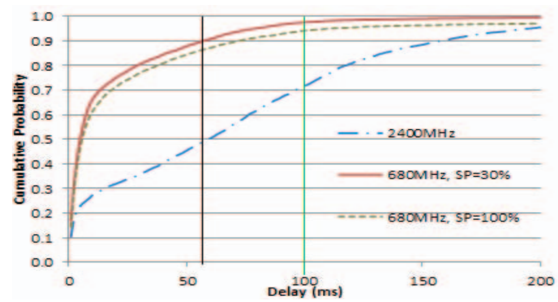

Figure 9. Packet delay CDF for planned topology.

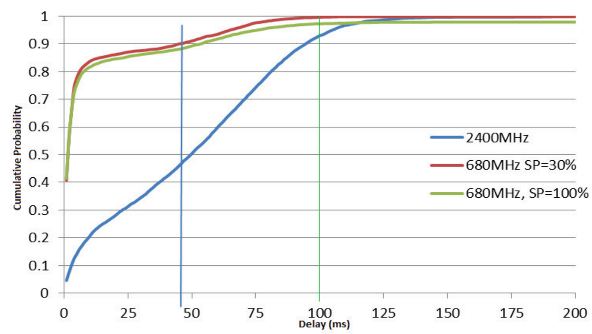

Figure 10. Packet delay CDF for random topology.

Fig. 9 and Fig.10 shows the Cumulative Distribution Function (CDF) of the packet delay statistics for planned and random topologies respectively. It can be seen that, the CR protocol shows very less delay for majority of packets. For instance, almost 100% of packets have delay less than 100ms for CR model, whereas for legacy Wi-Fi, only 70% of the packets reach their destination with 60ms delay in planned topology and less than 95% in random topology. Hence we can conclude that cognitive radio based WSAN best serves the requirements of FAN in smart grid by providing a latency less than 100ms for 100% of packets.

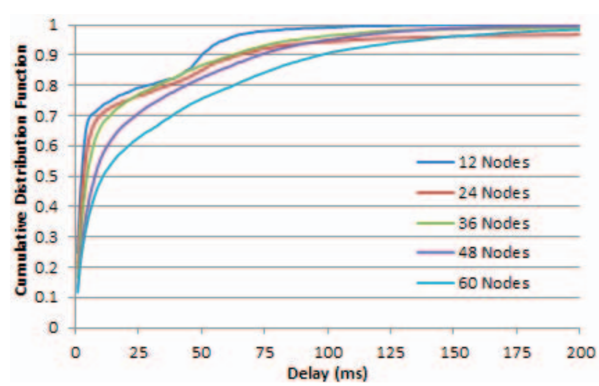

Figure 11. Packet delay CDF plot for varying number of sensor nodes in planned topology.

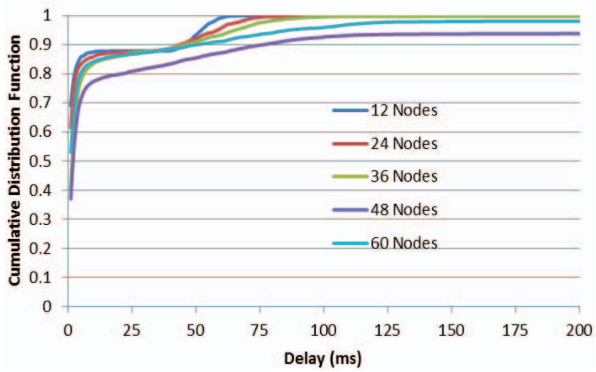

Figure 12. Packet delay CDF plot for varying number of sensor nodes in random topology.

We have also tested the scalability of the network in terms of delay performance. The number of sensor nodes is varied and the packet delays are logged in each case. The CDF of packet delays for different number of sensor nodes is shown in Fig. 11 & 12. The results shows that there is no much degradation in the latency performance with the incremental sensor node density.

V. CONCLUSION

Owing to tight delay and throughput criteria, the FAN is the most crucial network of a smart grid communication infrastructure. From the above analyses, we conclude that CR model is better than legacy Wi-Fi in terms of latency, power efficiency and network simplicity due to higher range and hence less number of hops. The packet loss rate is also substantially better. We also observed that there is no much change in performance with the variation of network topology. We presume CR model can perform still better if a more deterministic MAC protocol is employed instead of random CSMA. To reduce the overhead of QP, dynamic QP duration can be employed. This could be a topic of considerable research interest. The other important advantage of CR is that it can perform better in urban scenario with multipath fading, due to transmission at lower frequency. Our further research shall focus on exploiting this characteristic in realizing FANs in urban areas.

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