Smart Grid Cooperative Communication with Smart Relay

Mohammad Helal Uddin Ahmed, Md. Golam Rabiul Alam, Rossi Kamal, Choong Seon Hong, and Sungwon Lee

Abstract: **Many studies have investigated the smart grid architecture and communication models in the past few years. However, the communication model and architecture for a smart grid still remain unclear. Today's electric power distribution is very complex and maladapted because of the lack of efficient and cost-effective energy generation, distribution, and consumption management systems. A wireless smart grid communication system can play an important role in achieving these goals. In this paper, we describe a smart grid communication architecture in which we merge customers and distributors into a single domain. In the proposed architecture, all the home area networks, neighborhood area networks, and local electrical equipment form a local wireless mesh network (LWMN). Each device or meter can act as a source, router, or relay. The data generated in any node (device/meter) reaches the** *data collector* **via other nodes. The data collector transmits this data via the access point of a wide area network (WAN). Finally, data is transferred to the service provider or to the control center of the smart grid. We propose a wireless cooperative communication model for the LWMN. We deploy a limited number of smart relays to improve the performance of the network. A novel relay selection mechanism is also proposed to reduce the relay selection overhead. Simulation results show that our cooperative smart grid (coopSG) communication model improves the end-to-end packet delivery latency, throughput, and energy efficiency over both the Wang** *et al.* **and Niyato** *et al.* **models.**

Index Terms: **Cooperative communication, end-to-end delay, smart grid.**

I. INTRODUCTION

The smart grid communication technology integrates advanced sensing technologies and control methods of power generation, distribution, and consumption. The smart grid is robust to load fluctuations, and the supply-demand balance can be properly maintained via intelligent real-time dispatching mechanisms [1] using close customer-grid interactions. Today's power distribution is very complex because of its heterogeneous generation and utilization systems. It requires collaboration, integration, and interoperability among the set of technologies and disciplines [2]. Two important examples are given of the increased complexity of controlling smart grid communication in the 21st century:

- Production of renewable energy (especially, solar energy) is increasing every day. This energy is either supplied to the national grid or consumed by home appliances. The problem is that the production of solar energy depends on the weather, such as whether it is a sunny or a rainy day. Weather changes frequently, and thus, the production of renewable energy fluctuates randomly and introduces uncertainties into the power system [3], [4].
- From the power consumption side, plug-in electric vehicles are increasing to reduce CO_2 emissions. These vehicles charge their storage batteries unpredictably, causing supply-demand fluctuation.

High fluctuation causes *blackouts* in the grid. Existing devices such as transformers and shunt capacitors need to communicate with each other in order to respond quickly to demand changes. A smart meter in a commercial building can request power from the distribution and generation system, which can then adjust the supply and demand accordingly.

From an economic point of view, frequent metering information is essential for customers in dynamic tariffing systems. Distributors set their tariffs based on the supply and demand in order to efficiently utilize resources. In a modern smart grid system, load management (LM) programs are introduced to control the demand and supply of power. Basically, LM programs depend on two types of programs [5]: Incentive-based programs (IBPs) and time-based rate (TBR) programs. Investigations of the paper [5] show that customers' power consumption expenditure decreases substantially if they consider the price elasticity in demand model. A smart grid communication system enables smart meters to transmit metering data, receive tariff information, and provide additional information to customers. As a result, industrial and commercial customers can optimize their utility costs (electricity, gas, and water) by adjusting their usage to off-peak periods.

Existing smart grid devices are equipped with 802.11-based sensor communication systems. The challenges with this wireless technology include reliability, electromagnetic interference, and interference from other wireless devices. The most critical issues are

- Low transmission range.
- Some smart devices remain in the basement.
- Nonuniform distribution of heterogeneous nodes such as smart devices, meters, and appliances for different purposes and from different vendors.

In the smart grid technology, data is transferred to an access point or a router (data collector) via intermediate nodes [1]. If the node density is low or if the neighbors lie at the maximum transmission range, then the transmission may fail. Residential and commercial buildings may not be adjacent, or obstacles may lie between them. Therefore, the transmission error increases

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because of nonuniform node distribution, longer distances, and obstacles between nodes. Obstacles decrease the transmission range, which increases the end-to-end hop numbers; obstacles also increase the packet error rate. Both situations increase the end-to-end delay. The node transmission range is a major factor for improving the packet error rate (PER) and the end-to-end delay in smart grid communication.

In contrast, modern grid distribution networks have almost negligible outage detection mechanisms, resulting low reliability [6]. The existing communication infrastructure for smart grid communication is inadequate owing to the speeds of response, adaptation, and control [7]. The roadmap technology for 2025 [3] will be able to identify fault locations and fault types using monitor and control centers. Creating a smart grid requires new communication protocol standardization and upgrades to existing communication infrastructure [2], [3].

In summary, network efficiency and stability must improve to support modern wireless smart grid communication systems. A quality of service (QoS) allied protocol is useful in a smart grid communication network. A QoS domain usually includes average delay, jitter, and outage probability [8], [9].

In this paper, we propose a smart grid architecture in which all the home area networks (HANs), neighborhood area networks (NANs), and local electric equipment form a local wireless mesh network (LWMN). Each LWMN has an access point called a data collector. Each data collector is connected to an existing wide area network (WAN) called the backhaul. In this study, we pay attention only to the LWMN. We use cooperative transmission [10] to increase the transmission range, reliability, overall network efficiency [11], and throughput [12]. Overall, our primary objective is to improve the end-to-end delay, throughput, and energy efficiency of smart grid communication systems.

In addition to the existing nodes, we deploy a limited number of relays in the network, equipped with smart antennas [13] and solar-powered systems. We call such relays smart relays (SRs). We use smart antennas because of their directional transmission property, which reduces the transmission region around it. Since SRs use solar power, energy cost is not a factor. We use geographic mesh routing because it has following advantages: (1) It is suitable for heterogeneous networks and devices [14] and (2) the cooperative technique increases the transmission range [15]. We use 802.11b technologies at the MAC layer because of their better obstacle penetration capabilities. The major contributions of this study are as follows

- We describe a smart grid architecture that tackles the issues of the 21st century.
- We propose an innovative cooperative network model for smart grid communication systems.
- We propose an efficient relay selection mechanism.

II. SMART GRID ARCHITECTURE

According to the national institute of standards and technology (NIST) roadmap [14], a smart grid should integrate smart metering technologies, hybrid plug-in electric vehicle (PEV) charging systems, and home appliances and customer devices. According to the roadmap, 1 million PEVs will appear in the United States by 2015 and will consume a great deal of energy. Their analysis shows that 70% of this energy can be supplied to recharge vehicles without adding generation and transmission capacity if customers recharge their vehicles during off-peak periods. To control the future smart grid system, the system is classified into seven interconnected domains [14]. In our proposed architecture, of the seven domains, we work only with the customer and distribution domains.

We suggest a significant change to the proposed NIST domain systems. In our model, customers and distributors are included in a single domain because they are closely related to each other in terms of service and information [1]. We also consider a small-scale power generation (micro-level power generation) system in the proposed architecture. The motivation for this inclusion is as follows: Many commercial buildings and industries deploy their own in-house renewable or traditional energy generation system. This in-house generated energy can be supplied in the grid when the in-house generation systems have excess energy or they have off-peak utilization. The scenario of the new domain is as follows: (1) The domain includes heterogeneous energy sources such as solar cells and wind turbines in addition to traditional energy sources and (2) the domain includes heterogeneous energy consumption devices such as hybrid electric vehicles (EVs), hybrid home and industrial equipments, and home appliances. *Hybrid equipment and home appliances* use the traditional grid energy when renewable energy is unavailable.

Based on our proposed domain issue, we divide the smart grid wireless network into two major parts, the LWMN and the backhaul, as shown in Fig. 1.

LWMN: The LWMN integrates neighborhood area NAN, HAN, and all nearby intelligent electric devices into a single system. In terms of the geographic area, the LWMN covers a community of several buildings or a large commercial or industrial area that can extend up to 1 km^2.

Electric equipment includes transformers, circuit breakers, storage, smart inverters, solar cells, and EV charging systems. The *neighborhood network* [2] includes all the smart meters in households within the same neighborhood, and the HAN includes home appliances, sensors, and microcontrollers. An additional device called the SR is included in this architecture.

The SR is equipped with a solar panel and smart antenna with heterogeneous network capability. SRs are used as range extenders especially where there are no meters or only scarce populations of meters which would otherwise lack of mesh connectivity to a *data collector*. Some of the devices may lie in the basement and most of the meters and appliances will lie inside the congested building. Thus, the transmission range becomes shorter due to obstacles which increase the transmission error. Use of SR increases the transmission range and reduces transmission error.

Ismail and Zhuang [16] observes that the use of solar power in the base station reduces fossil fuel power consumption. In our model, we use a limited number of SRs and which are easier to control and manage [13]. Deployment of SRs with a solar power system may not be economically feasible. However, because of the gradual development of the renewable energy technology and in order to reduce CO_2 emissions some operators have already started to replace old and inefficient equip-

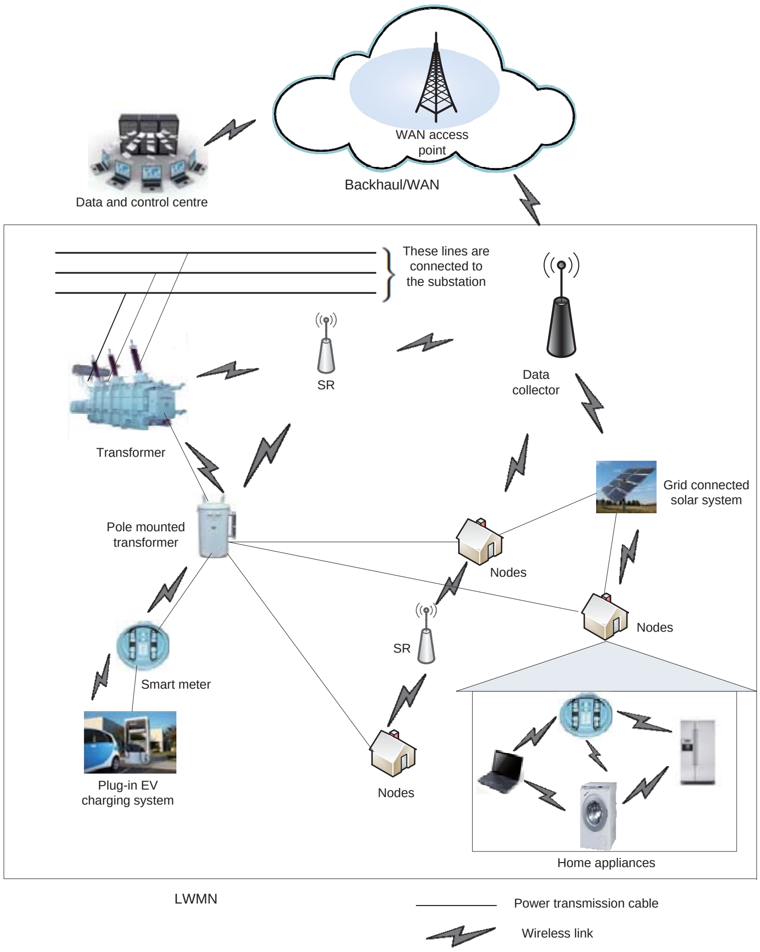

Fig. 1. Smart grid communication architecture based on an LWMN.

ment with energy-efficient equipment. For example, solar power based rural wireless local area network (WLAN) mesh network and green base tranceiver station (BTS) are deployed in different communities [17], [18]. One of the main philosophies of introducing this green technology is to save money over the product lifetime in addition to the reduction of CO_2 emissions. However, it is not mandatory that utility companies have to invest alone. Sometimes, the government provides grants for green technology. For example, the American recovery and reinvestment act of 2009 (ARRA) provided a huge fund as a grant to support manufacturing, purchasing, and installation of existing smart grid technologies. Similar smart grid efforts are also underway in other countries, including China, the EU, Japan, Korea, and Australia, among others.

Backhaul: A backhaul network is a WAN. It comprises high-capacity, low-latency broadband networks that extend the enterprise network to remote areas, bringing the data from the access networks back to the enterprise. Examples of backhaul networks include both wired and wireless point-to-point and point-to-multipoint broadband systems, fiber, and microwave systems. These backhaul networks form the backbone of all smart grid access networks. 3G and WiMAX are good examples of backhaul networks.

However, in this study, we are only concerned with the LWMN, which we deploy in our architecture. The major motivations of using the mesh architecture are as follows

- A smart grid consists of heterogeneous network devices [14] from different vendors and having different purposes.
- Different devices have different transmission ranges and duty cycles [1], [15].

Thus, the LWMN can easily connect heterogeneous network devices to fulfill different functions such as sensing, monitoring, and pricing [1]. All the electric devices, smart meters, and appliances are equipped with mesh-enabled communication modules, and each of them routes the data through nearby electric devices or meters. Each device or meter acts as a router until the data reaches the data collector, which has heterogeneous networking capability. Then, the collected data is transferred to the utility service provider or distributor or the control center via an established WAN called a backhaul network. Part of the backhaul network is shown in Fig. 1.

A smart grid uses wired or wireless media to transmit data. There are several mature wired and wireless technologies for smart grid communication such as power line communication (PLC), WLAN based on IEEE 802.11, WiMAX based on IEEE 802.16, 3G/4G cellular, ZigBee based on IEEE 802.15, and MobileFi based on IEEE 802.20 [6], [14]. In some instances, the wireless technology has some advantages over wired technologies in smart grids [1], [8]: (1) When many parameters in a substation need to be monitored, optical or PLC can result in an expensive and complicated system architecture; (2) PLC can not easily bypass transformers in a power distribution network; and (3) wired communication cannot provide peer-to-peer communication among electric devices in a flexible manner. Each wireless technology has some characteristic advantages and disadvantages. However, in the proposed LWMN, we use 802.11b for its optimal obstacle penetration capability.

In summary, the entire smart grid wireless communication network is divided into two parts: The LWMN and backhaul (WAN), as shown in Fig. 1. The data collector collects data from the LWMN and then transmits it to the access point or router of the backhaul. The backhaul transmits the data to the data center or control center or service providers. However, in this study, we do not work with the backhaul; rather, we propose a *smart grid communication architecture* only for the LWMN, as shown in Fig. 1.

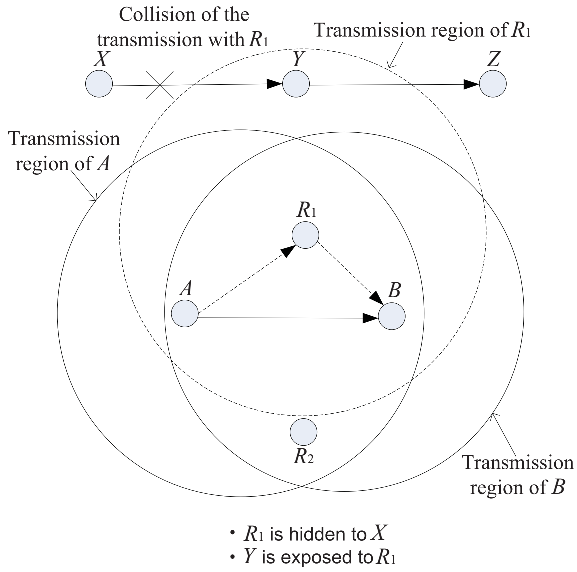

Fig. 2. Hidden and exposed terminal problems.

III. COOPERATIVE TECHNOLOGY

In wireless networks, the cooperative technology significantly increases the network performance because it provides alternate paths [19] when the defined link fails. In cooperative communication, when a sender transmits a data packet to a receiver, neighbors overhear the signal. This overheard signal is retransmitted by single/multiple neighbor(s) subsequently. The neighbor who retransmits the overheard signal is called a relay or helper. Cooperative communication increases the reliability and transmission rate and optimizes the transmission power [11].

A. Cooperative Technology in the Smart Grid

A recent study by Niyato and Wang [20] uses the cooperative technology to increase the reliability and throughput for smart grid communication. However, they use cooperation between the data collector and WAN infrastructures, that is, the backhaul in our study. Ultimately, there exist various reliable and high-speed WAN infrastructures such as WiMAX and 3G technology to cover the entire nation. In contrast, there is a lack of reliable network infrastructure for LANs for a smart grid. This is because smart devices have the following shortcomings, as mentioned earlier.

- These devices use 802.11-allied devices; thus, they have a lower transmission range.
- These devices are often deployed in the basement or inside congested buildings; thus, they are prone to unexpected transmission loss.
- These devices use the industrial, scientific, and medical (ISM) band and suffer from unexpected interference from various LAN devices, motors, and appliances.

Therefore, the use of the cooperative technology in smart grid LANs improves the reliability, transmission range, and performance of smart grid wireless networks. Thus, we propose cooperative transmission in the LWMN to improve the smart grid's communication performance. However, the existing cooperative protocols have some drawbacks.

B. Problems of Existing Cooperative Protocols

The cooperative technology increases the reliability and transmission rate and reduces the transmission power [10], [11]. However, this technology also poses new challenges because of the notorious hidden and exposed terminals in wireless networks. The major challenging issues are (1) the relay selection process and (2) the relay transmission process. Both these processes enlarge the transmission region relative to the expected transmission region of the sender/receiver. These issues introduce two problems in wireless networks:

- Collisions increase for the hidden terminals.
- Bandwidth wastage increases for the exposed terminals.

Collisions and bandwidth wastage degrade the throughput and overall network performance so that the expected network performance is not achieved.

In Fig. 2, node A transmits data packet to B where relay R_1 overhears the packet in the first phase. Subsequently, R_1 retransmits the packet to B in the second phase. The retransmission of R_1 enlarges the transmission region relative to that of the expected transmission region of A and B. In such situations, the following problems appear for the ongoing transmission of R_1.

- Collision occurs if node X transmits to node Y because R_1 is hidden next to X for the link XY.
- Node Y cannot transmit to Z if it has data to be transmitted because Y is exposed terminal for node R_1 for link YZ.
- Collisions also occur at R_1 if Y transmits to Z and A transmits to R_1 at the same time.

The relay selection process is an important part of a wireless cooperative network. Potential relays participate in relay selection process by sending [10] an *interested to help* indication message such as helper indication (HI) [11]. These messages or signals also enlarge the transmission region compared with the expected transmission region of A and B. This is because some relays remain near the periphery of the sender or the receiver transmission region, as shown in Fig. 3. If they transmit an *interested to help* message, then the transmission region is

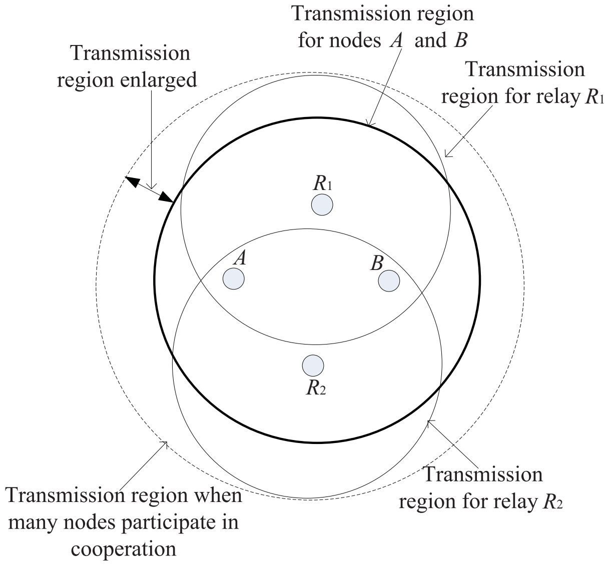

Fig. 3. Relay selection enlarges the transmission region.

enlarged. This enlarged transmission region is also responsible for increasing collisions and bandwidth wastage due to hidden and exposed terminal problems.

C. Solutions to the Problems

One of the most critical issues is to optimize the notorious hidden and exposed terminal problems from wireless networks. We propose the following innovative ideas to optimize the hidden and exposed terminal problems:

- We introduce a SR which listens omnidirectionally and transmits directionally [21], thus reducing the transmission region around it.
- We select a small circle zone; only relays in the circle zone can participate in cooperation.

We control the area and center of the circle zone as well as control the transmission power of the relay so that the transmission region of the relay does not increase the area of the expected transmission region of the sender and receiver.

IV. NETWORK MODEL AND OPERATION

According to our proposed smart grid architecture, each device, meter, and home appliance will form an LWMN. The device, meter, or home appliance can act as a source, router, and relay. Data from the source reaches the *data collector* via other nodes, where we consider all the meters, devices, and appliances to act as forwarding nodes. Since the cooperative technology increases the reliability and transmission rate as well as optimizes the transmission power, we use cooperative transmission in our smart grid architecture.

In our model, we consider that source S has data to send to destination D (*data collector*) where A and B are forwarders, as shown in Fig. 4. *We concentrate our discussion only on the hop AB of the path S-A-B-D because the same procedure is followed in the other hops*. The neighboring nodes of the sender and receiver can participate in cooperation as a relay. The neighbors of A and B, listening to request-to-send (RTS) and clear-to-send

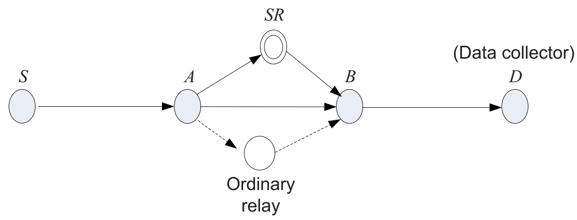

Fig. 4. Smart grid communication model.

(CTS) from the nodes A and B, respectively, calculate the data rate according to the following equation

$$B_{\text{coop}} = \frac{B_{AR}B_{RB}}{B_{AR} + B_{RB}} \tag{1}$$

where B_{coop} is the cooperative data rate, B_{AR} is the data rate between sender A and relay R, and B_{RB} is the data rate between relay R and receiver B. If $B_{\text{coop}} \geq B_{\text{dir}}$, then the relay participates in cooperation where B_{dir} is the data rate for direct transmission. In this work, we allow the two-hop cooperation [10] process. For example, the node A transmits to relay R in the first time slot and subsequently relay R transmits to receiver B in the second time slot. In this study, we consider the IEEE 802.11b PHY layer standards, which can support multiple data rates at 1, 2, 5.5, and 11 Mbps. All the control messages are sent by the sender and receiver at 1 Mbps. This study uses the 2.4 GHz ISM band.

We deploy a limited number (say x% of the total nodes; in our case $x = 10$) of SRs equipped with smart antennas and solar power systems. In our study, such a relay overhears omnidirectionally and transmits directionally [21]. Since SRs are equipped with solar power, they do not impact the network negatively by increasing power consumption in the network. A limited number of SRs are deployed in the network for (1) economic feasibility and (2) easier management of the SRs in the network.

Two categories of relays are available in this model: *SRs* and *ordinary nodes* (electric devices, meters, appliances, or mobile nodes). SRs have higher priority than ordinary nodes as potential relays. SRs that listen to both the RTS and CTS from A and B, respectively, participate in the relay selection phase. Since this model has two types of relays and each type may have more than one potential candidate, it is essential to have a relay selection phase to select an optimal relay. In order to select an optimal relay, our model allows a relay selection phase which starts after CTS. If SRs do not respond within the assigned time period then the potential *ordinary nodes* participate in the relay selection phase. The relay selection mechanism will be discussed in Section VI. Once the relay is selected, sender A transmits a data packet to the relay, and subsequently, the relay transmits to receiver B. If no relay is interested in helping sender A, sender A transmits directly to B.

SRs have two major benefits over ordinary nodes: (1) They reduce the interference region around them because of their *directional transmission* and (2) they save network energy because of their use of *green solar energy*. If a suitable SR is not found, ordinary nodes can participate in cooperation. However, only ordinary nodes lying in the dotted *circle zone* can participate in cooperation because of optimization of the hidden and exposed terminal problems, as shown in Fig. 5.

In this model, we prefer geographic routing because it avoids the high routing overhead of finding a route in a hop-by-hop search [22]. Thus, geographic routing achieves scalability, which is one of the most important requirements of protocol design for ad-hoc mesh networks [15]. Furthermore, the recent availability of small and inexpensive global positioning system (GPS) devices, together with emerging localization protocols, make geo-routing a preferable routing strategy [23], [24].

In geographic wireless mesh routing, a sender that currently holds the data packet knows the positions of its neighbors, that is, the nodes within its topology knowledge range (in our case, the transmission range is 100 m for 1 Mbps) and the position of the destination node. The sender can select any forwarder node within the transmission range to forward data to the next hop. The sender transmits packets directly to a next-hop node, which is selected among all the neighbors of the sender according to position-based forwarding rules [15].

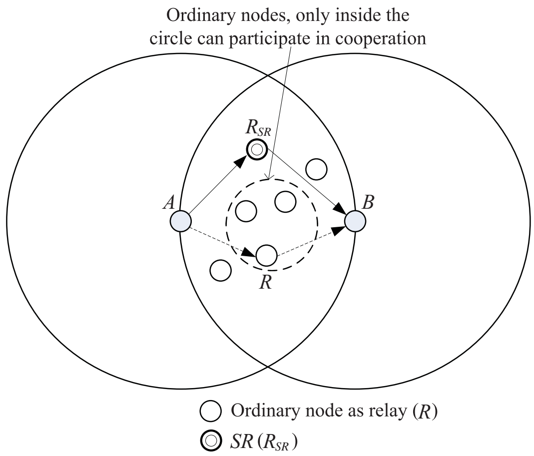

Fig. 5. Relay R from the dotted *circle zone* participates in cooperation if R_{SR} is not available.

V. MAJOR CHALLENGES OF OUR MODEL AND HOW TO OVERCOME THEM

The major challenge for SRs is that they increase the *directional transmission* range because the directional mode has higher gain than the omnidirectional mode. This higher gain causes of collisions for other nodes that lie behind the receiver. Therefore, we control the transmission power according to the distance between the relay and the receiver in order to limit the directional transmission range. The transmission power of the SR is as follows [21]

$$P_{TX_{SR}} = \frac{P_B d^{\alpha}_{(R_{SRB})}}{G_{SR} G_B} \quad (2)$$

where $d_{(R_{SRB})}$ is the distance between R_{SR} and B, P_B is the receiving power of B, G_{SR} and G_B are the gains of R_{SR} and B, respectively, as shown in Fig. 5.

As it was mentioned earlier, only ordinary nodes that lie inside the specified *circle zone* can participate in cooperation. Thus, to define the specific *circle zone* is the most critical issue. Here, we assume that the center of the circle is in the middle of AB. The relay transmission power (P_{TX_R}) is controlled in order to limit the transmission region. The transmission power of R is given by [25]

$$P_{TX_R} = d^{\alpha}_{RB}\left(\frac{2^r - 1}{p_{RB}}\right) \quad (3)$$

where α is the path loss factor, r is the given data rate in bits per second per hertz, and p_{RB} is the packet error rate for the link RB, and d_{RB} is the distance between R and B.

We consider an optimal value of the radius $\mathbb{r}_{\mathbb{c}}$ of the *circle zone*, shown in Fig. 5. The relay transmission power P_{TX_R} of (3) should be controlled in such a way that $T_{TX_R} = d_{RB}$, where T_{TX_R} is the transmission range of R and R is any relay within the *circle zone*. In this model, each node knows the locations of its neighbors. Therefore, a relay R can compute the distance $\mathbb{r}$ between its own location and the center of the *circle zone*. If the distance $\mathbb{r}$ is $\mathbb{r} \leq \mathbb{r}_{\mathbb{c}}$, then the relay is allowed to participate in cooperation. We control the radius $\mathbb{r}_{\mathbb{c}}$ and power P_{TX_R} so that the transmission region of R does not cross the border of the expected transmission region of A and B. Therefore, our proposed *cooperative model* does not enlarge the expected transmission region. Results, our model optimizes the effects of the hidden and exposed terminal problems.

VI. RELAY SELECTION MECHANISM

Each cooperative protocol has some overhead in addition to its hidden and exposed terminal problems, such as relay selection overhead and relay transmission overhead. Both types of overheads consume additional time and energy. Furthermore, if the selected relay is not the optimal relay, the performance of the network will be degraded from the expected performance. Therefore, a relay selection mechanism is important for selecting an optimal relay and to optimize the relay selection overhead. 2rcMAC [10] is an excellent relay selection mechanism for its cooperative protocol. However, the relay selection process has some significant drawbacks.

Their protocol declares a relay response (RR) frame. The RR frame is divided into 8 slots (time slots) and each slot is further divided into 7 mini-slots. According to 802.11b, the data rates in the sender-to-relay and relay-to-receiver for each slot are (2,5.5), (5.5,2), (2,11), (11,2), (5.5,5.5), (5.5,11), (11,5.5), and (11,11). Each pair of data rates is found according to the distance between the sender-to-relay and relay-to-receiver, respectively. Each potential relay can sense the data rate after overhearing the RTS and CTS and then computes its own cooperative data rate using (1). Each relay falls into one of the eight slots according to its cooperative data rate. Then, the relay further picks one of the 7 mini-slots randomly and sends a one-bit RR signal in that mini-slot. There are 56 mini-slots in 8 slots ordered from the lowest to the highest data rate. Therefore, the sender has to wait until the 56th mini-slot to listen for the responses from the relays. Then it picks the two highest data rate relays for its protocol. As an example, RR is found in the 4th, 18th, 36th, and 54th mini-slots. The protocol selects two relays at the end of the RR frame. Thus, the sender picks the respondents of the 54th and 36th mini-slots as optimal relays. This relay selection mechanism has the following disadvantages

- A sender has to wait for the entire RR frame, which prolongs

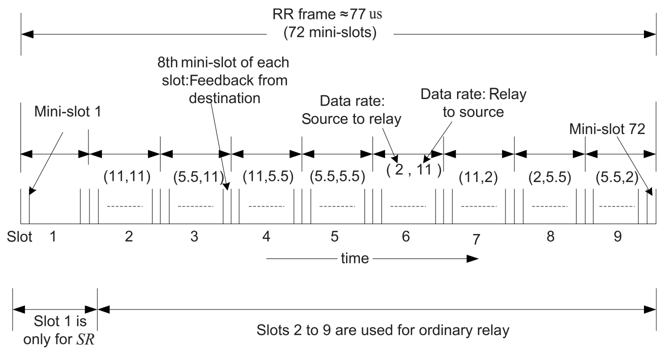

Fig. 6. Relay response frame.

the relay selection time.

- If two relays send a response in the same mini-slot, say at the 54th mini-slot then the protocol allows both the relays to transmit the same packet at the same time, which may result in a collision at the receiver because of the fading effect.

In our protocol, we modify their strategies to overcome the aforementioned drawbacks and to obtain some additional benefits. Our model needs only one relay, and this relay is selected by the receiver rather than by the sender. In our mechanism, the 8th mini-slot in each slot is used for the feedback from the receiver. Therefore, there are a total of 9 slots and 72 mini-slots. The entire RR frame is shown in Fig. 6. In this relay response frame, the 1st slot is reserved only for SRs because SRs have higher priority than the ordinary relays. If the receiver does not receive any response in the 1st slot, then the ordinary relays send their response in the following slots. The potential ordinary relays send their *RR* bits in the order of the highest to the lowest data rate. If the receiver can recognize a success response (only one response in a single mini-slot), the receiver sends feedback at the 8th mini-slot of the respective slot. Thus, each potential relay waits in the listening mode in the 8th mini-slot of each slot. If two relays send responses in a single mini-slot, the receiver ignores the response.

We can explain the relay response mechanism with examples. Suppose as shown in Fig. 6, a relay sends a one bit response in the 6th mini-slot of the 1st slot. Then, the receiver sends one-bit feedback in 8th mini-slot of the same slot. The rest of the potential relays stop their participation after listening to the feedback from the receiver. Finally, the receiver sends a message including the bit location, that is, the 6th mini-slot. From this message, a potential relay can understand that a respondent of the 6th mini-slot was selected as a relay. Another example is this: Suppose two relays send responses in 9th mini-slot, and one relay sends a response in the 18th mini-slot. Then, the receiver sends feedback at the 24th mini-slot. Here, there is no response from the mini-slots of the 1st slot; the response of the 9th mini-slot of the 2nd slot is ignored because it is considered as a collision. Once the relay is selected, the sender transmits data packet to the relay and subsequently, the relay transmits to the receiver. However, the RR time and mini-slot position counting must be highly synchronized between the relay and the receiver; otherwise, the mini-slot position may be different for them. The main advantages of our relay selection mechanisms as follows

- The receiver does not need to wait for the entire RR frame as in 2rcMAC; thus, it requires less than the average number of slots.
- The two relays are not allowed to send the same data packet at the same time, thus avoiding collisions among the relays.

In contrast, 2rcMAC always requires 56 mini-slots to select the relays.

VII. Analysis

The PER affects the end-to-end delay and energy consumption of transmissions. Thus, we need to determine the PER in order to evaluate the end-to-end delay and energy efficiency. The PER for the two-hop cooperative transmission is given by [26]

$$p_{\text{coop}} = 1-(1-p_{AR})(1-p_{RB}) \tag{4}$$

where p_{AR} is the PER for link AR and p_{RB} is the PER for link RB. According to [27], PER is given by

$$p(d,\text{SNR}) = 1-e^{-\frac{d^{\alpha}}{\text{SNR}}} \tag{5}$$

where d is the distance between the sender and the receiver and α is the path loss factor. Thus, the PER for direct transmission is as follows

$$p_{\text{dir}} = p_{AB} = 1-e^{-\frac{d_{AB}^{\alpha}}{\text{SNR}_{AB}}}. \tag{6}$$

Similarly, we can calculate p_{AR} and p_{RB} as was done for p_{AB}. For simplicity, (5) can be written as

$$p \approx \frac{d_{AB}^{\alpha}}{\text{SNR}_{AB}}. \tag{7}$$

Therefore, p_{AR} and p_{RB} can be written as follows

$$p_{AR} \approx \frac{d_{AR}^{\alpha}}{\text{SNR}_{AR}} \tag{8}$$

and

$$p_{RB} \approx \frac{d_{RB}^{\alpha}}{\text{SNR}_{RB}}. \tag{9}$$

Now, substituting the values of (8) and (9) into (4), we can calculate p_{coop}. Both (8) and (9) show that the PER increases with increasing distance and decreases with increasing signal-to-noise ratio (SNR).

A. End-to-End Delay

The end-to-end delay of a single packet is measured as the time difference between when the packet was received at the sink or the *data collector* and when it was generated at the source [28]. Delays experienced by individual data packets are averaged over all packets received by the sink. The lower the delay is, the better the performance is. If there are H hops in the path, then the end-to-end delay for the path is defined as

$$E2ED = \sum_{i=1}^{H} E2ED_i. \tag{10}$$

We assume that there are M_i packets in the queue of node n_i when a new packet arrives. Thus, according to the paper [29], $E2ED_i$ can be defined as

$$E2ED_i = (M_i+1)E[T_i] \tag{11}$$

where $E[T_i]$ is the service time, defined as the duration of keeping the packet in the MAC layer until successful transmission or until it is dropped after the maximum retry limit is reached. Thus, the meaning of $E2ED_i$ is that the total delay passing through hop i equals the MAC service time of those packets queuing ahead of the new packet plus the MAC service time of the new packet itself. The MAC service time is given by [29]

$$E[T_i] = \frac{L}{B_{\text{coop}}}\left[\frac{1-p_{\text{coop},i}^{K}}{1-p_{\text{coop},i}}\right] + E[\text{backoff time}] \quad (12)$$

and

$$E[\text{backoff time}] = \frac{W_{\min}[1-(2p_{\text{coop},i})^{K+1}]}{2(1-2p_{\text{coop},i})} - \frac{1-p_{\text{coop},i}^{K}}{2(1-p_{\text{coop},i})}. \quad (13)$$

Here, $W_{\min}$ is the minimum contention window, K is the maximum number of retransmissions, and L is the packet length. In this study, we find the simplified end-to-end delay only for cooperative transmission. According to our cooperative communication model, in some hops, senders may transmit in the direct mode when the data rate is higher in the direct mode than in the cooperative mode. However, it is very complex to determine the specific number of hops for the direct mode and the cooperative mode. However, the end-to-end delay given by (10) is the upper bound, because the sender transmits in the direct mode when it requires a lower transmission time than in the cooperative mode.

B. Power Cost

Any cooperative communication approach requires additional relay retransmission power to retransmit the data packet. However, the probability of successful transmission in the cooperative mode is much higher than in the direct transmission mode [26]. Therefore, successful transmission requires fewer retransmissions in the cooperative mode than in the direct mode. Thus, in reality, less power is required in cooperative transmission than in direct transmission. The power cost of two-hop transmission includes the transmission cost of A, $P_{TX,A}$, the transmission cost of relay R, $P_{TX,R}$, and the receiving cost of each relay and receiver P_{RX}. Thus, the total power cost for cooperative transmission is given by [26]

$$P_{\text{coop}} = P_{TX,A} + P_{RX,R} + (1-p_{AR})(P_{TX,R} + P_{RX,B}) \quad (14)$$

where $1-p_{AR}$ is the probability that the packet is actually relayed by R. If the relay fails to decode and transmit the packet, then sender A transmits directly to B. The power cost for direct transmission is given as follows

$$P_{\text{dir}} = P_{TX,A} + P_{RX,B}. \quad (15)$$

The required transmission energy for cooperative transmission is $E_{\text{coop}} = LP_{\text{coop}}/B_{\text{coop}}$ and for direct transmission is $E_{\text{dir}} = LP_{\text{dir}}/B_{\text{dir}}$, where L is the packet length.

The expected number of retransmissions [30] for hop AB is given by $ETX = 1/(1-p)$, where p is the PER. Thus, the expected energy for successful transmission can be written as $E_{\text{coop}}^{\text{expected}} = E_{\text{coop}}/(1-p_{\text{coop}})$ for cooperative transmission and $E_{\text{dir}}^{\text{expected}} = E_{\text{dir}}/(1-p_{\text{dir}})$ for direct transmission. From (7), PER is found to be $p \propto d^{\alpha}$, where $2 \leq \alpha \leq 4$. Here, d is the distance between any sender and receiver. If the distance between the sender and the receiver for direct transmission is much higher than the sender-relay or relay-receiver distance, the PER in direct transmission may be higher than that for the two-hop cooperative transmission. This is because the PER is proportional to the distance raised to the power of α.

VIII. PERFORMANCE EVALUATION

A. Simulation Environment

In this section, we evaluate the performance of our proposed coopSG model and compare it with the models of Wang *et al.* [1], Niyato *et al.* [20], CoopMAC [31], and the noncooperative transmission model. We compare the performance with the model of the Wang *et al*. because their model has some similarities in some extent with our model. Although their proposed model deals with the security issue, uses the 802.11 MAC protocol. We also compare our results with the results of Niyato *et al.* because their proposed NAN architecture is similar to that used in our model. Their NAN also uses 802.11 technologies at the MAC layer. However, neither of the models uses cooperative transmission at NAN, and so we further compare our results with the well-known cooperative MAC protocol CoopMAC, although it was not proposed for smart grids. The Wang *et al.* propose two levels of hierarchies in their architecture: A lower-level mesh network and a higher-level mesh network.

A.0.a Lower-level mesh network. At the lower level of the hierarchy, the HAN, building area network, and factory area network are merged into a single system. The lower-level mesh network interconnects appliances, smart meters, grid-tied inverters, etc.

A.0.b Higher-level mesh network. The higher-level mesh network interconnects all the lower-level mesh networks through a router.

Therefore, our proposed LWMN part is similar to the lower level of the hierarchy. Our model uses a *data collector* that collects data from the LWMN and transmits it to the control center through a backhaul. In contrast, in Wang *et al.*'s model, the router of the higher-level mesh collects data from the lower-level mesh and transmits it to another higher-level router. Since our study only pertains to the lower-level hierarchy, we evaluate the performance for the LWMN and compare it with the performance of Wang *et al.*

On the other hand, Niyato *et al*. propose a model in which the data collector collects data from end devices such as smart meters or home appliances in the community. Here, a community corresponds to groups of houses (e.g., a village). All the devices transmit data through a NAN (e.g., single-hop or multi-hop WiFi) to the data collector. The data collector transmits data to meter data management systems (MDMSs). The MDMS performs demand estimation and power allocation for the community. Thus, our proposed model has architectural similarities with the model of Niyato *et al.*, so we compare our results with the results of their model.

We evaluate the performance using simulation experiments conducted on NS-2. We deploy 1000 nodes within an area of

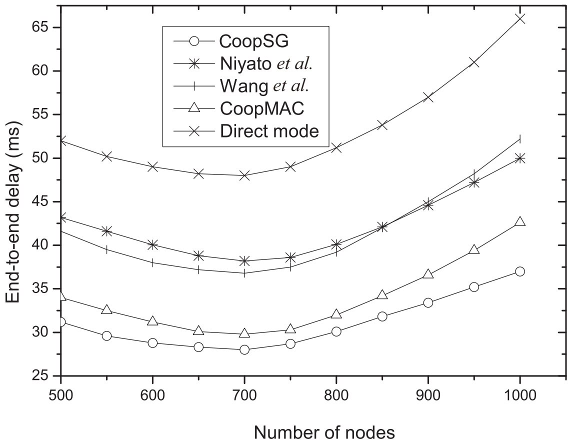

Fig. 7. End-to-end delay vs. number of nodes.

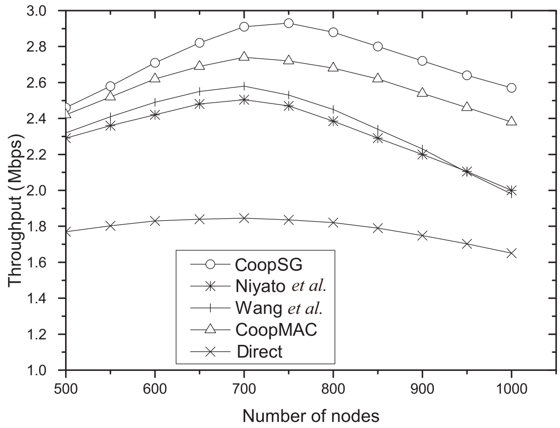

Fig. 8. Throughput vs. number of nodes.

1000×1000 m^2, where the node distribution was random uniform. All the mesh nodes follow the 802.11b MAC protocol. The sink or data collector is placed in the middle of the area. We consider the transmission range to be 100 m. We consider that application to be event driven, and the packet size is 1024 bits. We find the results for varying node densities, and the simulation was run for 200 s.

B. Simulation Results for Different Models

In this subsection, we show the impacts of node density on the performance and compare it with the models of Wang *et al.* [1], Niyato *et al.* [20], and CoopMAC [31].

The graphs shown in Fig. 7 show that the average end-to-end delay of coopSG significantly improves over Wang *et al.*, Niyato *et al.*, CoopMAC, and the noncooperative mode. Initially, the end-to-end delay decreases with the node density. This is because a suitable relay becomes available for our coopSG model. In the case of the Wang *et al.*, Niyato *et al.*, and noncooperative models, suitable neighbors become available to forward the packet in the next hop. In the case of CoopMAC, a suitable relay becomes available to retransmit the packet to the receiver. Thus, the transmission rate increases and the PER decreases, and hence, the end-to-end delay decreases in all cases. The figure shows that the end-to-end delay increases with further increase in the node density. This is because packet generation increases with the node density, which increases the number of collisions and thus increases the end-to-end delay. The model of Wang *et al.* shows better performance than the model of Niyato *et al.* This is because Niyato *et al.* use a security firewall that reduces attacks from malicious nodes.

Throughput is defined as the number of bits delivered to the destination per unit time. Fig. 8 compares the throughput as a function of the node densities. Our proposed coopSG increases throughput significantly over those of Wang *et al.*, Niyato *et al.*, CoopMAC, and the noncooperative mode. This is because we use two-hop cooperative transmission in our model, but Wang *et al.* and Niyato *et al.* use the direct transmission mode. In two-hop cooperative transmission, the data rate for each link will be higher. This is because the lower the distance between two communicating nodes, the higher the data rate [32]. For example, a sender transmits data using direct mode, with a data rate of 2 Mbps. In contrast, data rates for sender-relay and relay-sender are, for example, 5.5 Mbps. Therefore, the throughput of two-hop cooperative transmission will be better than that of direct transmission. Although CoopMAC uses cooperative transmission, it does not use two-hop cooperative transmission, and thus, the throughput of CoopMAC is lower than that of our proposed model. Fig. 8 shows that the throughput of the noncooperative model is much lower than that with coopSG. This is because we use geographic routing, which searches for a data forwarder at a maximum distance (in our model), and thus, the noncooperative model shows poor performance.

Fig. 9 shows that our coopSG is more energy efficient than the models of Wang *et al.*, Niyato *et al.*, and CoopMAC. This is because the number of successful transmissions of data packets in the simulation period is higher in coopSG than in other models. Therefore, the per-packet energy consumption is lower in coopSG. The per-packet energy consumption is higher with noncooperative transmission because of the lower number of successful packet transmissions and the greater distance. The energy efficiency increases as the node density increases because it increases the probability of getting a better relay node. In the case of the noncooperative model, the sender has a suitable neighbor to forward data to, and thus, the energy efficiency increases with the node density. However, after a certain node density, collisions increase, which increases retransmissions and thus decreases the energy efficiency.

C. Simulation Results with Unfavorable Weather

In this model, we use SRs equipped with a solar panel, and so clouds, fog, and other meteorological phenomena affect network performance. Weather is a great challenge for solar-powered network systems. Therefore, we perform simulations with different light intensities to evaluate robustness with different types of weather, where we consider the duration of day and night to be equal (i.e., 12 hours each). To evaluate the robustness of the model against weather, we measure the network performance at the 1st hour, 2nd hour, 3rd hour, and so on, during the night, based on the average light intensities during the day.

Some papers propose increasing the solar panel size based on load and weather to avoid the vulnerability of the network to

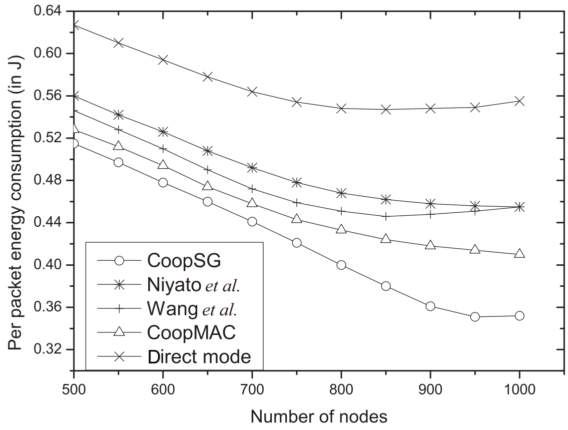

Fig. 9. Per packet energy consumption vs. number of nodes.

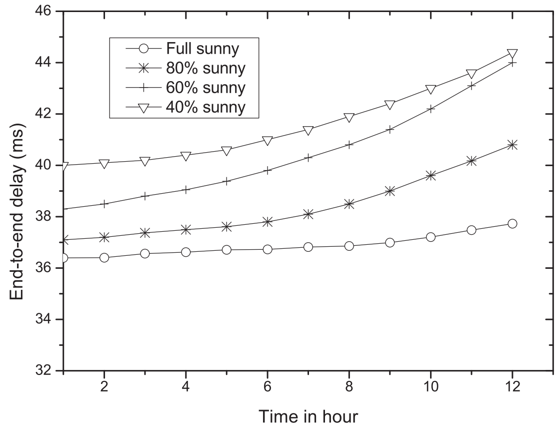

Fig. 11. End-to-end delay vs. time at different light intensities.

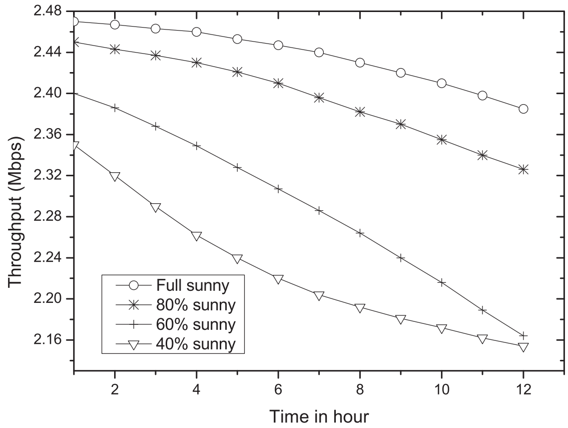

Fig. 10. Throughput vs. time at different light intensities.

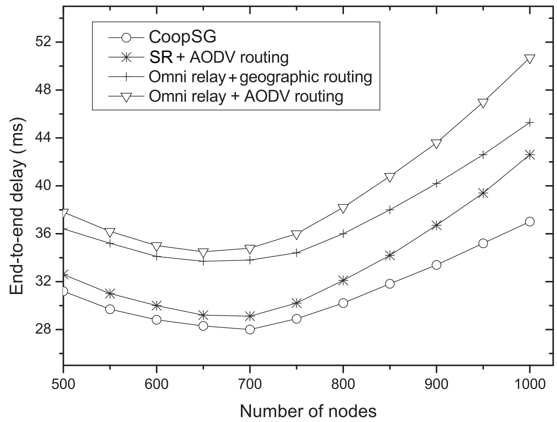

Fig. 12. End-to-end delay vs. number of nodes for the different types of antenna and routing.

the weather. However, this will increase the cost of the systems. According to the data of [33], we consider the average light intensity to be 36,000 flux for a full sunny day, where the peak light intensity is 80,000 flux. We perform our simulation for such a scenario, where the SRs work properly on a full sunny day. This means that during a full sunny day with an average light intensity of 36,000 flux, the SRs work properly at night.

Fig. 10 shows the changes in throughput at night, with the average light intensities being measured during the day. The graphs of the figure depict throughput changes that are negligible at 80% light intensity but change sharply at 60% light intensity. In the case of 40% light intensity, the throughput decreases sharply initially. However, the rate of decrease declines with time. This is because we deploy a limited number of SRs in the network. If the SRs are inactive, then ordinary nodes work as a relay. Although the network performance declines because of the bad weather, it is acceptable during most types of weather.

Fig. 11 shows the changes in the end-to-end delay at night with the average light intensities during the day. The graphs shown in the figure indicate that the end-to-end delay changes are negligible at 80% light intensity, but change sharply at 60% light intensity. Initially, the end-to-end delay increases sharply at 40% light intensity but the rate of increase declines with time because we deploy a limited number of SRs in the network. If the SRs are inactive owing to unfavorable weather, then the ordinary nodes work as relays. Although the network performance declines during bad weather, it is acceptable during most types of weather.

D. Simulation Results without Smart Antennas

In our proposed scheme, we use smart antennas and geographic routing, where the smart antennas transmit directionally. The results of our proposed scheme are compared with the performance of other approaches such as smart antennas with ad hoc on demand distance vector (AODV) routing [34], an omnidirectional antenna with geographic routing, and an omnidirectional antenna with AODV routing.

The graphs of Fig. 12 reveal that coopSG provides better end-to-end delay than the other scenarios. Our coopSG model provides better results than the smart antennas along with AODV routing model; this is because our model uses geographic routing, which has a lower routing overhead and a minimum hop distance. On the other hand, smart antennas along with AODV routing provide significantly better results than omnidirectional antennas along with AODV routing. This is because the smart antenna has higher directional gain and transmission range than the omnidirectional antenna, which has a low transmission error.

The graphs shown in Fig. 13 reveal that coopSG provides higher throughput compared to other scenarios such as a smart

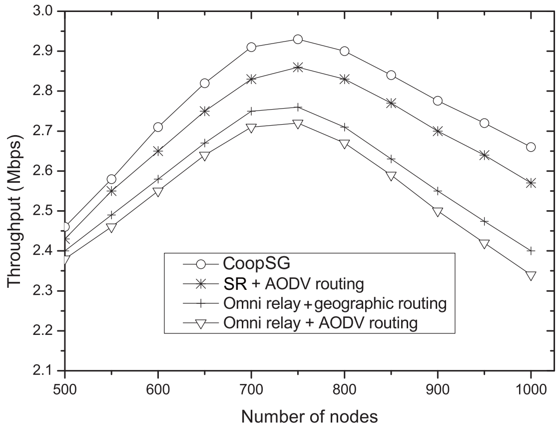

Fig. 13. Throughput vs. number of nodes for different types of antenna and routing.

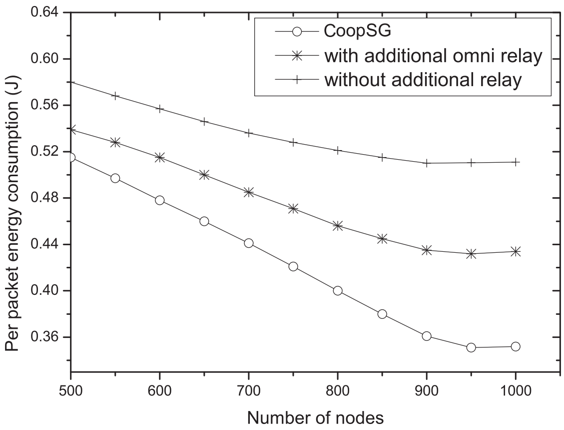

Fig. 14. Per-packet energy consumption vs. number of nodes (using an additional omni-directional relay and without an additional relay).

antenna along with AODV routing, an omnidirectional antenna along with geographic routing, and an omnidirectional antenna along with AODV routing. The coopSG model provides better results than the smart antenna along with AODV routing model; this is because coopSG uses geographic routing, which has a lower routing overhead and a minimum hop distance, which reduces the packet delivery time and increases the throughput. On the other hand, the smart antenna along with AODV routing model provides significantly better results than the omnidirectional antenna along with the AODV routing model. This is because the smart antenna has a higher transmission rate, higher directional gain, and higher transmission range than the omnidirectional antenna, which has a lower transmission error and a higher throughput.

We also compare the results of energy consumption of our proposed model considering cooperative transmission with an additional omnidirectional relay (instead of an SR) and without deploying additional relays. The graphs shown in Fig. 14 indicate that our proposed coopSG model outperforms the schemes of cooperative transmission with an additional omnidirectional relay and without deploying an additional relay. The SR uses directional transmission, which consumes less transmission power than an omnidirectional antenna. On the other hand, the scheme

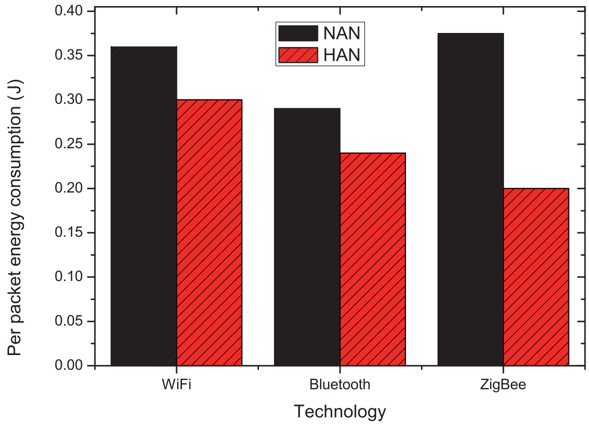

Fig. 15. Per-packet energy consumption for different technologies.

without deploying an additional relay uses only home appliances or smart meters as relays. In this scheme, the network suffers from a lack of suitable relays in suitable places and thus experiences a higher transmission error [35]. It also causes higher energy consumptions.

E. Simulation Results for Different Technologies

We also compare the energy consumption of different technologies such as WiFi, Bluetooth, and ZigBee for scenarios HAN and NAN.

The graphs shown in Fig. 15 illustrate that the per-packet energy consumption is far lower in ZigBee compared to WiFi for the HAN environment. This is because ZigBee uses low energy transmission. In contrast, the per-packet energy consumption is better in WiFi compared with ZigBee for the NAN environment. This is because ZigBee uses low energy transmission, which has a poor obstacle (wall) penetration capability and a lower transmission range. Thus, ZigBee needs more retransmissions and larger hop distances, which increase energy consumption. However, ZigBee is far better in terms of energy consumption in HAN, where the distance is shorter and obstacles are rare.

IX. CONCLUSION

Smart grids are becoming complex owing to increased generation of renewable energy and dynamic power consumption. If industries and residences can use their utilities during off-peak times, the entire community will benefit. In this paper, we propose a wireless cooperative communication model for the future smart grid technology. In our model, we optimize the end-to-end delay, throughput, and energy consumption. We also optimize the relay selection overhead and hidden and exposed terminal problems of cooperative communication. Our proposed system outperforms traditional non-cooperative smart grid communication systems.

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