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A Novel Scheme for Improving the Reliability in Smart Grid Neighborhood Area Networks

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ABSTRACT A smart grid, as its name implies, is an intelligent grid, which features two-way transmission for electricity and information. A smart grid can deliver various types of electrical services and streamlined, highly efficient energy consumption, but only if its communication systems are highly reliable. A smart grid can be based on wireless networks, which offer high speed and low cost, but problems with wireless technology can impair communications performance and destabilize the smart grid. Wireless local area network (LAN) mesh networks based on IEEE 802.11s can serve as the backbones of smart grids. IEEE 802.11s provides flexible, scalable, high-speed communications with low installation and management costs. In this paper, we first describe IEEE 802.11s, default routing protocol, Hybrid Wireless Mesh Protocol (HWMP); Even though HWMP has several shortcomings that destabilize smart grids, we propose a novel scheme to improve smart grid routing reliability. We present a simulation of our proposed scheme using ns-3 simulation software, and prove that our method can improve smart grid reliability.

INDEX TERMS Neighborhood area network, reliability, smart grid, wireless mesh networks, IEEE 802.11s.

I. INTRODUCTION

A smart grid includes several technologies related to electric power, communication, and control. Fig. 1 illustrates a typical smart grid, including smart houses, intelligent facilities, and renewable energy resources [1]. A smart grid can support transmission of power information and manage electrical services promptly [2]. A key characteristic of smart grid is bidirectional flows of electricity and information [3]. An optimized power transmission network can be constructed on the basis of bidirectional data flow.

Smart grid technology evolved from Automated Meter Reading (AMR), which is an unidirectional communication system, to Advanced Metering Infrastructure (AMI), which is a bidirectional communication system [4]. Fig. 2 illustrates the components of AMI. It consists of smart meters, sensors, a data transmission network, and a meter data management system (MDMS). The purpose of AMI is to collect data from sensors and share information between the electric power grid equipment and smart meters [5]. Furthermore, smart grids can manage electric devices using two-way information flows between AMI and smart meters. It can help consumers adjust electric power consumption; thus consumers can avoid using too much electricity and the power company can improve its allocation of resources resource allocation.

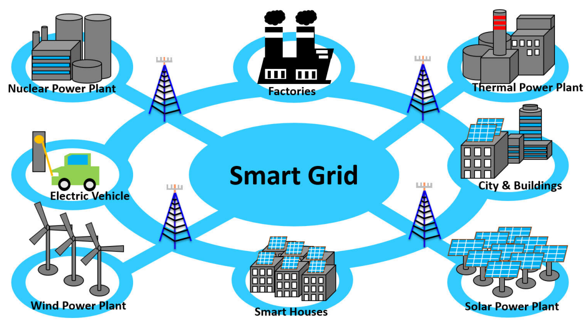

FIGURE 1. Relationships within a smart grid.

Smart grid communication infrastructure consists of three distinct categories of networks. As shown in Fig. 3, smart grid networks can be classified into home area networks (HANs), neighborhood area networks (NANs), and wide area networks (WANs). HANs concentrate on small-scale data communication between devices in smart houses. In a HAN, data may include metering data, on-demand electricity billing, and home energy displays For HANs, wireless sensor

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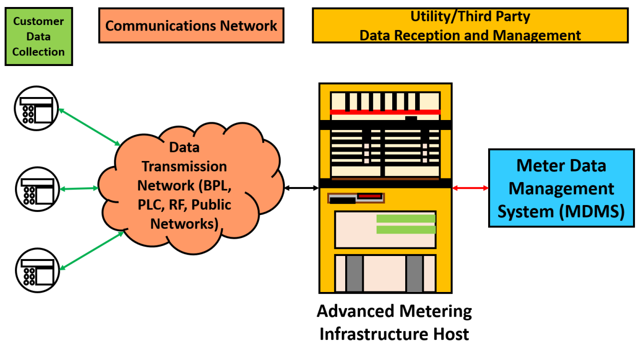

FIGURE 2. Advanced metering infrastructure.

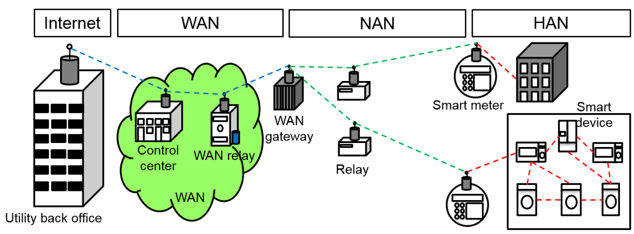

FIGURE 3. Smart grid communication infrastructure.

networks (WSNs), such as IEEE 802.15.4 ZigBee can be suitable for improving energy efficiency and prolonging network lifetime [6]–[9].

A WAN connects NAN data concentrators and smart grid control centers. WANs use high-speed data transfers to control operations over large areas. In addition, a WAN can serve as the backbone system combining HANs with NANs. For the aforementioned reasons, wireless technologies such as 3G, Ethernet, WiMax, and 3GPP are popular WAN building blocks.

The present paper focuses on NANs. NANs can provide a communication backbone between HANs and the substations of an electrical company. NANs can provide electric power substation surveillance and condition monitoring and management. Typically, HANs will volunteer information to the NAN periodically, but a server can send a request packet to demand information.

NANs have characteristics that differ from those of conventional wireless networks. To supply high quality of service (QoS) for time-critical data, a NAN must distinguish between numerous types of data. The commercial nature of a NAN also necessitates high reliability. Typically, servers are flooded with large numbers of data packets sent from NAN nodes. Wireless mesh networks can be easily deployed and can provide high-speed transmission of NAN packets to central servers.

Wireless mesh networks are reliable communications solutions for Internet service, disaster mitigation, military surveillance, and reconnaissance. For various green computing applications, wireless mesh networks can provide efficient backbone infrastructure for smart grid environments. IEEE 802.11s [10] is a promising solution to deliver high speed and reliable data transmission in NANs. IEEE 802.11s provides an efficient multi-hop routing protocol named Hybrid Wireless Mesh Protocol (HWMP), and also a method for unique topology formation. In smart grids, some of the functions of IEEE 802.11s can support numerous types of NAN requirements. The IEEE 802.11 [11] standard, defined the enhanced distribution channel access (EDCA) scheme, which uses priority methods and provides QoS for time-critical data. In HWMP, the airtime cost and hybrid transmission mechanism are considered suitable for static mesh networks; this is relevant because most NAN networks are static. In IEEE 802.11s, the root mesh station-to-mesh station integration with the mesh network can provide an appropriate topology for a NAN. For example, periodic upstream data produced by mesh stations can be continually transmitted to the root mesh station, which is wired to the gateway.

Taking account of the aforementioned characteristics of smart grid networks, IEEE 802.11s can be an appropriate mechanism, but implementation of a traditional IEEE 802.11s in a smart grid communication network tends to cause several problems. One principal problem is route instability. To apply different types of electrical applications and services, a smart grid environment requires highly reliable data transmission. Nevertheless, packet loss in a smart grid affects network reliability. Route instability is one of the causes of packet loss. The network routing instability problem [12] occurs when applying IEEE 802.11s HWMP; this problem impairs smart grid network reliability and throughput. To alleviate smart grid route instability and to improve the networks within smart grids, we propose a scheme to solve these problems. We evaluate the performance of our proposed scheme through ns-3 simulation [13] the results prove that it is useful for improving smart grid reliability and feasible to deploy.

The remainder of the paper is organized as follows: Section II introduces IEEE 802.11s HWMP and smart grid reliability. In Section III, a problem statement regarding smart grid reliability is defined. In Section IV, the processes of the proposed scheme are presented. Experimental results and performance of the proposed scheme as simulated by our ns-3 simulator are presented in Section V. Finally, the conclusion of our research is presented in Section VI.

II. RELATED WORKS

Several studies have proposed using mesh networks as smart grid infrastructure. Several manufacturers have proposed proprietary NAN solutions for smart grids. However, as smart grid designs grow in size and complexity, the requirement of high reliability grows in importance. The research in [14] introduced the concept of smart grid reliability and reported its importance. Arguments in [15] and [16] have proposed schemes to improve the reliability of IEEE 802.11s for use in smart grids.

A. IEEE 802.11s STANDARD OVERVIEW

For wireless local area networking, IEEE 802.11s is an 802.11 amendment. The protocol and architecture definition

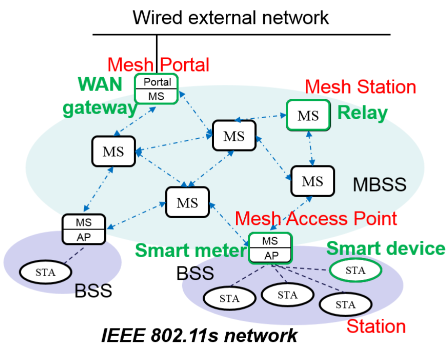

FIGURE 4. IEEE 802.11s networks.

of IEEE 802.11s are appropriate for wireless multi hop mesh networks [10]. The topology of IEEE 802.11s is built up from a root mesh station, which applies wireless connections to mesh stations. Fig. 4 demonstrates the relationships among IEEE 802.11s components. The mesh station (MS) is the basic entity of IEEE 802.11s [17]. Each MS not only has all the properties of a traditional IEEE 802.11s station but also relays data packets produced from the other MSs so that the data can arrive at the destination node using a multi hop path in the wireless distribution system. The Mesh Basic Service Set (MBSS) is the set of MSs and the connections between these nodes; this set is the wireless mesh network backbone. Similarly, the Basic Service Set (BSS) is the set of stations (STAs) that communicate with each other. Some MS also have extra characteristics. Any IEEE 802.11s network may include multiple mesh portals; each MS can forward to the wired external network through any mesh portal. An MS node can serve a nonmesh device by providing access to the wireless network. In the situation,that MS node can also become a mesh access point (MAP). The capabilities provided by an access point are specified by the IEEE 802.11s standards.

According to IEEE 802.11s architecture features, MSs supply various applications with multihop communications (which require cooperation with the root MS) and serve as terminals to client devices. Each multihop routing path is produced according to the HWMP. IEEE 802.11s standard, HWMP is the default route selection protocol. It includes two types of routing methods: The proactive tree-building mechanism and on-demand mechanism.

A brief introduction to the HWMP protocol elements is as follows: Root Announcement (RANN) is broadcast, which can tell MSs about the presence of and distance to the root MS. A Path Request (PREQ) can be broadcast or unicast; it asks destination MSs to create a reverse route to the MS, which sends the PREQ. Path Reply (PREP) is unicast; it creates a forward routing path to the source node and verifies the reverse route. Path Error (PERR) is broadcast; it reminds MSs that receive the PERR that the current route does not currently permit data transmission. Furthermore, by using a sequence number, it can not only differentiate the information of the current route from the out-of-data routing path but also keep can maintain a loop-free connection. Each MS possesses HWMP sequence number, and the information is disseminated to other MSs in these HWMP elements [17]. The design of the proactive tree-building mechanism is to operate with the PREQ or RANN created by the root MS. Both proactive tree-building and on-demand mechanisms use the same data messages and processing methods.

For IEEE 802.11s correlation instruments, airtime [18] cost is a default routing metric that is used by the IEEE 802.11s standard. The airtime cost formula calculates the consumption of the channel resource, which is similar to the ETT metric [19]. The airtime cost formula of the loss rate and link bandwidth is shown as below:

$$C_a = \left[O + \frac{B_t}{r} \right] \frac{1}{1 - e_f}. \tag{1}$$

In the airtime cost formula, O is the channel access and overhead O must be held constant and is measured in microseconds. B_t is the transmission frame size. It is also constant and its value is 8192 b. r is the data rate, which is in Mbps. e_f is the loss ratio when transmitting the frame with size B_t at data rate r. If the MS successfully transmits the data frame to the next-hop MS, then it returns an acknowledgement (ACK). However, if the MS does not receive an ACK, it attempts to retransmit the data frame until receiving an ACK or stops transmiting when the retry limit number is reached. Therefore, we select the media access control (MAC) retransmission count of each packet as our value for calculating the error rate of the network. The error rate is shown as follows:

$$e_f = \frac{\frac{1}{P} \sum_{i=1}^{P} M_i}{R_{max}}, \tag{2}$$

where M_i is the total number of MAC retransmissions of the frame i; P is the total number of successful and failed frame transmissions; R_{max} is the maximum allowed retransmissions. In general, the airtime cost stands for the latency and error rate of a particular multi-hop path when the data frames are transmitted through the route.

Both HWMP proactive tree-building and on-demand routing mechanisms use the airtime cost to estimate the path performance and select the most efficient path for the data packets. The routing path using the HWMP proactive tree-building mechanism can be set up in two ways: proactive PREQ and RANN [17].

The objective of the proactive PREQ method is to create and maintain routing paths towards the root from all MSs. PREQs are periodically broadcast from root to all MSs. The procedure of proactive PREQ is that the source MS broadcasts a PREQ that contains the destination MS MAC address when a source MS wants to transmit data packets to a destination MS. When MSs receive PREQ, they set up or update the route toward the source MS if it satisfies one of two situations: (1) The PREQ includes a larger sequence number than the current route. (2) The PREQ contains a better airtime cost when sequence numbers are the same.

Each MS must update the cumulative metric of the route to the source MS before re-broadcasting the PREQ. As soon as the destination MS obtains the PREQ, it must transmit a unicast PREP. If the destination MS receives more than one PREQs with a larger or the same sequence number and a better airtime cost, it must transmit another PREP following the new route which is updated. Then, intermediate MSs transmit PREPs along the best routing path, which is stored when the MSs received PREQ. When the PREP reaches the source MS, the routing path is established and can be used for bidirectional data transmission. However, if multiple PREPs are received,the system must choose the PREP that satisfies one of two situations as in the PREQ mechanism: (1) The sequence number of the PREP is the largest. (2) The PREP contains the lowest airtime cost if sequence numbers are the same.

The RANN mechanism disseminates metric information about the path to the root MS. The mechanism enables each MS to establish its own path. RANN frames are periodically broadcast by the root MS, and other MSs also rebroadcast these frames. When an MS must establish communication between it and the root MS, it transmits a unicast PREQ following the reverse path to the root MS, which is passed through RANN. As soon as the root MS receives PREQ, it sends a PREP to the source MS. Each MS calculates the airtime cost and accumulates inside the RANN frame. Each MS chooses the most efficient routing path to the root MS using the cumulative airtime cost in the RANN frame and the its own calculation.

By periodic transmission of RANN, each MS periodically updates the multihop routing path to the root MS to minimize airtime cost. As with the Ad hoc On-Demand Distance Vector (AODV) routing protocol [20], the IEEE 802.11s HWMP on-demand mechanism starts to send PREQs only when needed, particularly in cases of route time expiration or failure. MS broadcasts PREQ, which contains a destination MS MAC address, when it needs a path for transmitting data packets to a destination MS. The processes of PREQ in proactive tree-building and on-demand mechanisms are the same. As soon as the MS receives PREQ, it sends a unicast PREP to the source MS and re-broadcasts PREQ with the updated airtime cost. Another case related to the HWMP on-demand mechanism is the breaking of a connection link. PERR notifies the MS if the used link is broken. Once the MS detects the broken multi-hop route to the root MS, it originates the HWMP on-demand mechanism to discover a new path. This process also broadcasts PREQ messages from the source MS to the destination MS to establish a new multihop routing path. To select the most efficient route in all the available multiple paths, the mechanism chooses the path with the lowest airtime cost.

B. RELATED RESEARCHES

Several studies have investigated reliability improvements in smart grids. To reduce the influence about route instability, [21] proposes a reliability correction factor used by a multi-gateway backup routing mechanism to improve reliability. An algorithm presented in [22] dynamically selects one of the gateways in the smart grid network. This algorithm applies a probabilistic method to select gateways and prioritizes them with the most reliable path. Based on HWMP, [23] proposed a NAN load-balance and QoS-aware routing method. The present study aim to support multiple QoS requirements for various NAN applications and provide high-reliability data transmission to gateways in NANs. A method based on the hop-by-hop automatic repeat request (ARQ) proposed by [24] achieves the requirement of reliability when transmitting data in smart grid NANs. The method also satisfies the constraint of communication latency, which is another smart grid application requirement. To provide energy-efficient and reliable data transmission, [25] proposed a novel ad-hoc wireless sensor network routing protocol, named ETL-AODV. In an optimized link state routing (OLSR) optimal path selection mechanism, a QoS-aware wireless mesh network routing method using multiple metrics was proposed in [26] for smart grid AMI applications. The study solved reliability concerns by combining the pruning techniques and analytical hierarchy process (AHP) algorithm. Reference [27] addressed the selection of a source to a destination path with high throughput. It proposed a novel routing metric named the Hybrid Metric (HM) to provide smart grid NANs with more reliable data transmission.

Aside from HWMP, other protocols have been proposed for smart grid reliability. Greedy perimeter stateless routing (GPSR) is a representative geographic-based mechanism [28]. Present study investigated whether the routing protocol is feasible in smart grid NAN infrastructure and supports smart grid applications. To achieve the requirement of reliability, the results show that the packet delivery ratio can be a benchmark for smart grid reliability.

III. PROBLEM STATEMENT

Smart grids require reliable transmission of information about smart homes, quantity of energy consumption, and electricity prices. A packet delivery ratio can evaluate the reliability of a smart grid, and it can be a benchmark to determine smart grid reliability performance. The ratio of packets that are successfully received by the destination node to packets transmitted from all source nodes its the packet delivery ratio. The number of packets received by the root MS divided by the total number of packets transmitted from all source nodes yields the packet delivery ratio, as follows:

$$R_p = \frac{P_R \times 100}{\sum_{i=1}^{n} P_{G_i}}, \tag{3}$$

where R_p is the packet delivery ratio; P_R is the entire amount of packets received by the smart grid root MS; and P_{G_i} represents the total sum of packets sent from one of the MSs. We calculated the total sum of P_{G_i} to represent all packets sent from all of the MSs.

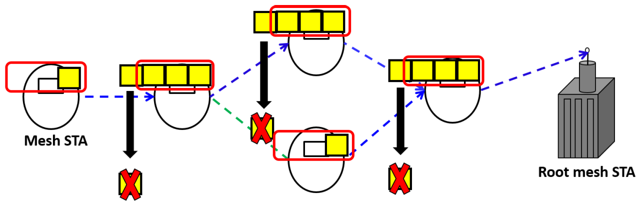

FIGURE 5. Network congestion.

Although IEEE 802.11s is thought to be appropriate to smart grid NANs, it still has some problems that may influence reliability and performance. Packet loss is among the critical problems that lower smart grid reliability IEEE 802.11s is the routing protocol. Packet loss occurs when one or more packets are sent through the network but fail to reach their destinations. This phenomenon causes a decrease of the packet delivery ratio and thus degrades the reliability of the smart grid. Two causes of packet loss are network congestion and network routing instability.

In smart grid, when we use the same routing path, smart meter will handle much more packets that occurs network congestion. Fig. 5 shows an example. Every MS has a routing path to transmit data packets to the root MS; the combination of these routing paths forms a tree topology in smart grid NAN infrastructure. One of the drawbacks of tree topology is that some connection links are used frequently and these overused links cause network congestion. Consequently, any path that produces network congestion causes packet loss, and degrades reliability. To avoid this situation, smart grid infrastructure uses IEEE 802.11s HWMP to periodically change the routing path; thus congested paths periodically become less congested. Although using IEEE 802.11s HWMP can reduce network congestion, it causes network routing instability problem, which can also degrade smart grid reliability.

Network routing instability has been documented as a potential problem for IEEE 802.11s HWMP [12], [17], [29]. The definition of routing instability is that network topology and reachability rapidly change. The main behavior of network route instability is the vanishing of a current routing path. If the route reappears quickly, we call it route flapping. In practice, route flapping is the main phenomenon of smart grid network routing instability.

In IEEE 802.11s HWMP, route flapping occurs because the airtime cost of the current route increases when packets are transmitted. By using IEEE 802.11s HWMP airtime cost formula (1) to choose the most efficient path, the airtime cost increases when retransmitting data packets. This occurs because the HWMP calculates the failure rate of the smart grid by selecting the total number of MAC retransmissions for each packet.

In smart a grid, the occurrence of routing flapping is particularly because of the IEEE 802.11s HWMP's proactive tree-building mechanism. RANN is one of the proactive tree-building schemes, that causes smart grid route flapping. Each smart grid MS calculates the airtime cost of the multi-hop route to the root MS when receiving a periodic RANN packet from the root MS; and it chooses the routing path that has the best metric. The, current used routing path airtime cost increases on rare occasions when packets are transmitted. Because other paths do not transmit frames, they appear to have lower costs than the path that has a high cost.Thus, when errors on the primary path raise the cost of that path, its primary status is revoked and a different path becomes the primary path.

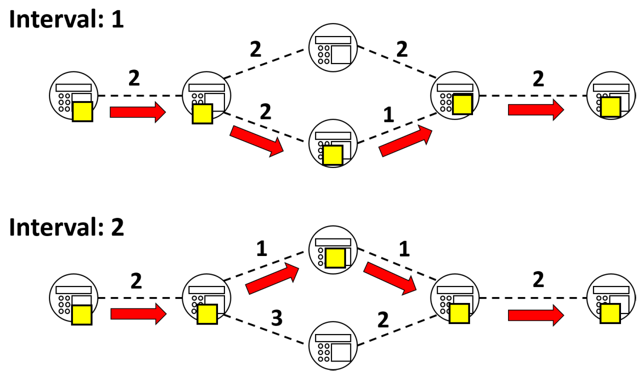

FIGURE 6. Route flapping.

An example of route flapping in a smart grid is shown in Fig. 6. In interval 1, the airtime cost of the current primary routing path is 7, and the cost of the other path is 8. By using the HWMP mechanism, data packets take the current routing path because it has a lower airtime cost than the other path. However, the airtime cost tends to increase as the system transmits packets over the primary path. In interval 2, the airtime cost of the current primary routing path increase to 9, and the other decreases to 6. Consequently, the other routing path is chosen as the current primary routing path, and data packets are sent over the other routing path. However, the airtime cost of the other path increases when it carries data packet, and the airtime cost of the first path decreases. The situation of interval 1 will appear, and we will similarly change the current routing path to the original primary routing path.

Route flapping degrades system efficiency. Because the IEEE 802.11s HWMP routing path selection process is used, the primary route frequently fluctuates in every RANN round. Thus, route flapping occurs when the MS chooses a route that happens to have a low airtime cost at the moment. However, the selection routing path suddenly becomes more loaded when transmitting the packets; thus as soon as the cheap path is used, it stops being cheap and other paths become cheap. This alternation of paths is known as route flapping.

Route flapping causes temporary connectivity loss in most sections of smart grid networks. Route flapping can cause out-of-order packet deliveries, dropped packets, and decreased packet delivery ratio. Thus, route flapping degrades the reliability of the network. In [15], the study determined that route flapping causes a severe decrease data transmission reliability in smart grid NANs. To increase the packet delivery ratio, our goal is to reduce route flapping without causing severe network congestion.

IV. PROPOSED SCHEME

In smart a grid environment, the route flapping problem usually lowers data transmission reliability. The proposed scheme uses a novel route selection algorithm to mitigate the route flapping problem. A version of, the route selection scheme suitable for use with HWMP is presented in Algorithm 1 [10]. The HWMP uses RANN to select the optimal routing path. In each RANN route selection round, each MS may receive numerous RANN messages, which contain cumulative airtime costs from multiple neighbor MSs. From these RANN packets, the MS selects the RANN that has the best airtime cost and establishes the route through the root MS by inquiring for the routing table on its own.

Algorithm 1 IEEE 802.11s HWMP Route Selection

Input: Airtime cost C_a of received RANN packet from the primary route, airtime cost $C_{other}(i)$ of received RANN packets from other routes, the primary route $path_{curr}(C_p)$, other routes $path_{other}(C_i)$

Output: The primary route $path_{curr}(C_p)$

if $C_a \leq min[C_{other}(i)]$ **then**
    return $path_{curr}(C_a)$;
else
    return $path_{other}(min[C_{other}(i)])$;

Algorithm 2 HWMP-RE Route Selection

Input: The routing metric $C_p(n)$ of the primary route in n round, the routing metric $C_p(n-1)$ of the primary route in $n-1$ round, the routing metric $C_i(n)$ of other route in n round, the routing metric $C_i(n-1)$ of other route in $n-1$ round, the current route $path_{curr}(C_p)$, and the reserved route $path_{other}(C_i)$

Output: The current route $path_{curr}(n)$

if $C_p(n) \leq C_i(n)$ **then**
    return $path_{curr}(C_p(n))$;
else
    if $(C_p(n) - C_p(n-1)) \leq (C_i(n) - C_i(n-1))$ **then**
        return $path_{curr}(C_p(n))$;
    else
        return $path_{other}(C_i(n))$;

Our proposed scheme is motivated by [15] and [16]. To mitigate the frequent occurrence of the route flapping problem in smart grid networks, a route selection algorithm modification of IEEE 802.11s HWMP is proposed. Although a MS may obtain numerous RANN messages from multiple neighbor MSs, the HWMP route selection scheme allows a MS to retain the most appropriate path to the root MS. The study modified HWMP route selection algorithm by using a routing table extension of the HWMP. Each MS stores copious information on routing paths of the current and previous RANN rounds. When receiving information from two successive RANN intervals, the previous and current rounds, every MS keeps and updates the airtime cost of the RANN packets. These RANN messages can be classified into four types: the calculation of the current route from RANN in the current round, calculations of reserved routes from RANN in the current round, the calculation of the current route from the previous RANN round, and calculations of reserved paths from the previous RANN round.

Procedures for stable route selection proposed from [15], [16] are presented as Algorithm 2. At the beginning, for all received RANN messages, the airtime cost is calculated by every MS. Then, each MS chooses a route to transmit data packets in the current RANN interval. Each MS, it also stores other routing paths that are less efficient than the primary routing path. In the next RANN round to select a new routing path, the primary and reserved paths airtime costs are saved as reserved information. Furthermore, the airtime cost is calculated for new RANN packets. Route flapping occurs because only the current metric can be selected as the primary routing path in the IEEE 802.11s HWMP. However, the route selection algorithm proposed by [15] and [16] uses both current and reserved airtime cost to select the new primary routing path. If the current route has a lower cost metric than reserved routes, it is maintained. We changed only the routing path if the reserved route cost is less than that of the current route and the airtime cost difference of the current route is higher than that of the reserved ones between the previous and the current RANN rounds. However, the current routing path is retained even though the reserved path has a lower airtime cost if the metric difference of the current path is lower than that of the reserved path.

Studies have proposed [15], [16] some route selection algorithms that have assumed that the performance of the primary routing path does not fluctuate too much, compared to other reserved paths; such algorithms propose to increase reliability by reducing route flapping. However, such algorithms compare the airtime cost variation of primary route to that of the reserved route, and the data transmission exists on the primary route, which causes the primary route to have more airtime cost variation than the reserved route because the reserved route has less data transmission than the primary route. Motivated by these considerations, we propose a novel approach as Algorithm 3.

To efficiently avoid route flapping, the proposed scheme focuses on the performance variety of the primary route. To successfully avoid route flapping, each MS keeps and updates metrics on primary route. Moreover, each MS calculates the fluctuation rate for the primary route as follows:

$$R_f = \frac{C_a - C_p}{C_p}, \tag{4}$$

where R_f is the routing path performance fluctuation rate of the primary route airtime cost, C_a is the airtime cost of the

Algorithm 3 Proposed Route Selection Algorithm

Input: Airtime cost C_a of received RANN packet from the primary route, airtime cost $C_{other}(i)$ of received RANN packets from other routes, the primary route $path_{curr}(C_p)$, other routes $path_{other}(C_i)$
Output: The primary route $path_{curr}(C_p)$

1 Airtime cost of the primary route C_p
2 Airtime cost fluctuation rate threshold of the primary route R_f
3 **if** $C_a \leq min[C_{other}(i)]$ **then**
4   **if** $C_a < C_p$ **then**
5         $C_p = C_a$;
6   return $path_{curr}(C_a)$;
7   **else**
8   return $path_{curr}(C_p)$;
9 **else**
10   **if** $C_a \leq C_p$ **then**
11         $C_p = C_a$;
12   return $path_{curr}(C_a)$;
13   **else if** $(C_a - C_p)/C_p \leq R_f$ **then**
14   return $path_{curr}(C_p)$;
15   **else**
16         $C_p = min[C_{other}(i)]$;
17   return $path_{other}(min[C_{other}(i)])$;

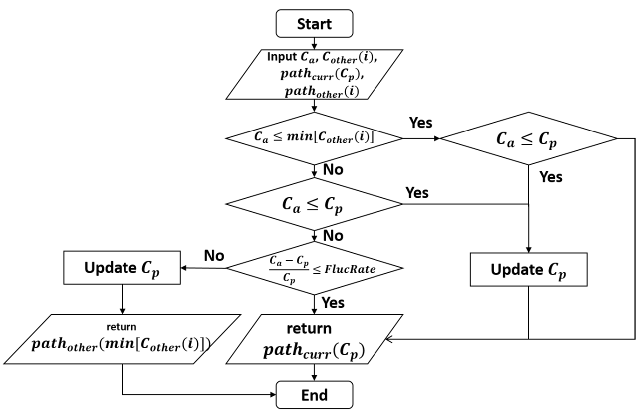

FIGURE 7. The flow of proposed route selection scheme.

received RANN packet from the selected route, and C_p is the airtime cost of the received RANN packets from the primary route. Aside from fluctuation rate, we also defined the airtime cost fluctuation rate threshold R_t, which is the criterion to used decide whether to change the routing path.

In Fig. 7, we illustrate of the proposed route selection. First, the primary route is maintained if it has been selected as the routing path in the RANN round because it has the lowest airtime cost compared with the other paths (Lines 7-8 of Algorithm 3), and if the cost from the received RANN is less

TABLE 1. Simulation environment.

Parameter	Value
PHY bit rate	54 Mb/s
Topology	3 by 3 $\sim$ 8 by 8
Rate adaption	Disabled
RTS/CTS	Disabled
HWMP RANN interval	5 seconds
Simulation time	600 seconds

TABLE 2. Application set of the smart grid.

Service Type	Transmission interval (s)	Application size (bytes)
AMI data	15	123
AMI management	300	4000
Power quality data	3	3000

than the airtime cost maintained in the MS, the airtime cost of the primary route is updated (Lines 4-6 of Algorithm 3).

Otherwise, if the primary route is not selected as the routing path in the RANN round, then we check the following cases to determine whether to change the routing path. Case 1. If the airtime cost from the received RANN of the primary route is less than or equal to the airtime cost maintained in the MS, then we maintain the primary route and update the primary route airtime cost (Line 10-12 of Algorithm 3). Case 2. If the cost from the received RANN of the primary route is greater than the airtime cost maintained in the MS, then each MS calculates the fluctuation rate for the airtime cost of the primary path. If the fluctuation rate is less than or equal to the threshold we set, then the primary route is maintained (Line 13-14 of Algorithm 3). Case 3. If the fluctuation rate is greater than the threshold, then the path that has the minimum airtime cost is selected the routing path in the current RANN round because we determine that the performance of the primary route would be decreased too much otherwise (Line 15-17 of Algorithm 3). By using the proposed route selection scheme, we reduce route flapping because the primary routing path is not frequently changed. Moreover, the algorithm allows the primary routing path to be changed only if its airtime cost has fluctuated excessively.

The difference on improving the reliability of the wireless mesh networks and NAN between our proposed scheme and [15], [16] is that efficiently avoiding route flapping. However, the goal of our proposed scheme and [15], [16] are both reducing route flapping to enhance the reliability. [15], [16] use not only the current airtime cost but also the previous one. [15], [16] determine the routing path with the less airtime cost just like the original mechanism. In addition, they decide to change the routing path only if have less variation from the current and previous airtime cost.

Our proposed scheme is motived by the variation from the current and previous airtime cost. [15], [16] determine whether to use other routing path by using less variation of current and previous airtime cost from all routing paths. However, our proposed scheme only focus on the variation of the airtime cost on the primary routing path. The difference between our proposed scheme and [15], [16] is that we decide to alter the routing path if the variation ratio of the primary path is over the threshold we set. The result of comparison of our proposed scheme and other ones will show in the next section.

V. EXPERIMENTAL RESULTS

The goal of the proposed routing selection scheme is to identify an optimized fluctuation rate threshold rate to have the highest packet delivery ratio and to provide the highest possible smart grid reliability. The proposed scheme compares the packet delivery ratio, total count of data packets that are successfully received, transmission delay and throughput; these comparisons are made relative to the route selection algorithm of the IEEE 802.11s HWMP and the route selection scheme proposed by [15], [16].

A. SETTING OF EXPERIMENTAL ENVIRONMENT PARAMETERS

The performance levels of the proposed routing selection algorithm and other schemes were evaluated through ns-3 simulation [13]. The ns-3 software can design different types of applications and network topologies. Under a smart grid environment, ns-3 is an ideal system for simulating the proposed scheme and the compared route selection schemes.

The proposed scheme was implemented using ns-3 802.11s modification codes. We compared IEEE 802.11s code with our proposed scheme. We also implemented the route selection algorithm proposed in [15], [16] and compared it with our proposed scheme. In Table 1, we show ns-3 experimental environment details. MSs were simulated as having 802.11a transmission devices, with maximum transmission of 54 MB/s. Every MS supported four kinds of transmission queues based on enhanced distribution channel access (EDCA) in 802.11e. EDCA can support that high-priority traffic has higher chance to be sent than low-priority one. A MS with high-priority traffic can waits less time than other MSs with low-priority traffic before sending packets. The priority levels are called access categories. Heavier traffic can be set wilder contention window which is need for access categories. There are four type of traffic including Background (AC_BK), Best Effort (AC_BE), Video (AC_VI) and Voice (AC_VO). In 802.11e, priority level from high to low of these four traffic types are AC_VO, AC_VI, AC_BE and AC_BK.

The smart grid application sets used by NAN MS transmission data are shown in Table 2. In the simulation, AMI data were transmitted from HAN MSs, and power quality data we sent from NAN applications. AMI data, AMI management data, and power quality data were transmitted to root MS for reporting at each distinct and specified time interval. All smart grid applications were transmitted to the root MS, which can be thought of as their destination.

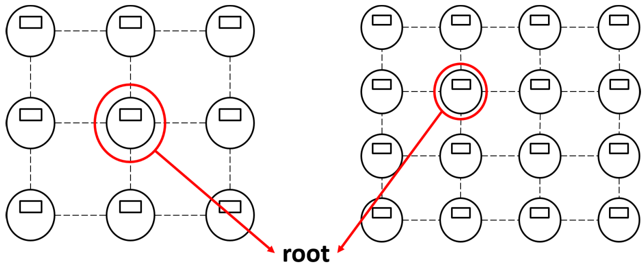

FIGURE 8. Center node of the topology.

TABLE 3. Proposed scheme comparison in 3 x 3 topology.

Thresholds (%)	Packet delivery ratio (%)	Delay (ms)
10	96.409574	18.906249
20	96.143617	18.902505
30	96.276595	18.850117
40	95.74468	18.988809
50	99.86413	18.184442
60	99.335106	16.753434
70	96.010638	19.271933
80	96.010638	19.271933
90	96.010638	19.271933

TABLE 4. Comparison of proposed scheme for 4 x 4 topology.

Thresholds (%)	Packet delivery ratio (%)	Delay (ms)
50	90.76923	24.615839
55	79.0909	22.709812
60	83.426573	27.718433
65	83.986013	23.405562
70	84.755244	23.164053

In the simulation scenario, each node represents a smart grid NAN MS. They are spread out in the smart grid network with a grid topology. We ran the simulation with 9, 16, 25, 36, 49, and 64 MSs, respectively. We set the data collection node as the center node of the grid topology, which was also the destination of each smart grid application. In Fig. 8, we show an example of choosing the root MS in the simulation. If the node number of one side in the topology is odd, then the center node of the grid will be the root MS. However, when the number of nodes of one side is even, four nodes exist in the center, and we set the upper left corner node as the root MS.

When the number of nodes was increased, the data traffic generated caused network congestion in the simulation environment. Various results are compared and analyzed to evaluate the performance of the proposed scheme.

TABLE 5. Comparison of proposed scheme for 5 × 5 topology.

Thresholds (%)	Packet delivery ratio (%)	Delay (ms)
50	86.504424	42.016651
55	75.663716	39.457433
60	74.059734	37.905884
65	75.497787	39.969652
70	74.83407	41.191422

TABLE 6. Comparison of proposed scheme for 6 × 6 topology.

Thresholds (%)	Packet delivery ratio (%)	Delay (ms)
50	75.205992	43.301234
55	68.089887	40.936022
60	64.644194	40.082753
65	64.232209	40.23866
70	64.307116	45.074321

B. SIMULATION RESULTS

The count of data packets successfully transmitted to the root MS divided by the total count of data packets that are sent from NAN MSs can be considered the calculation of the average packet delivery ratio. The packet delivery ratio can be considered the paramount criterion for satisfy the reliability of smart grid networks. End-to-end delay indicates the average time required to successfully transmit a packet to the root MS from the source MS. The throughput represents data received in 1s by a root MS. The proposed scheme compares the original HWMP with the route fluctuation prevention algorithm presented in [15], [16].

To guarantee fair evaluation, all schemes were implemented in ns-3. First, to find the most appropriate airtime fluctuation rate threshold, we implemented the proposed scheme with different thresholds from 10% to 90% to compare the packet delivery ratios when the number of MSs were 9. In Table 3, we find that when the proposed scheme thresholds ware 50% and 60%, the scheme exhibited efficient performance, with packet delivery ratios exceeding 99%. We also observe that when the threshold was greater than 70%, the packet delivery ratio was approximately the same. By examining the different thresholds from 10% to 90%, we can conclude that the best performance resulted from thresholds between 50% and 70%.

In the next step, we simulated the performance of the proposed scheme using thresholds of 50%, 55%, 60%, 65%, and 70% when the number of MSs was 16, 25, and 36. The results of the simulations are listed in Tables 4 to 6. From these simulation results, we observe that the highest packet delivery ratio arose with a threshold of 50%. Therefore, the proposed scheme has the most efficient performance with a high probability when the threshold is 50%. With different fluctuation rate thresholds, the simulation indicated that the threshold of 50% had the best packet delivery ratio. Therefore, we set the fluctuation rate threshold to 50%.

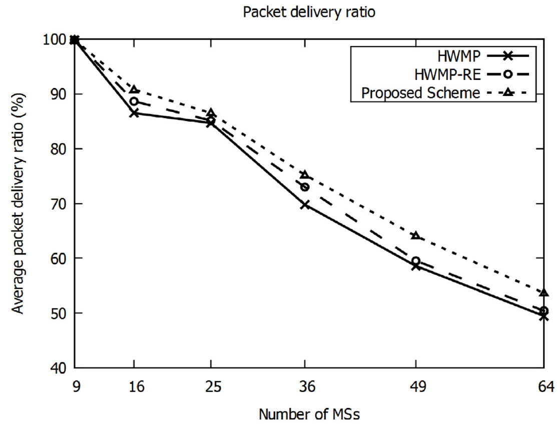

FIGURE 9. Packet delivery ratios.

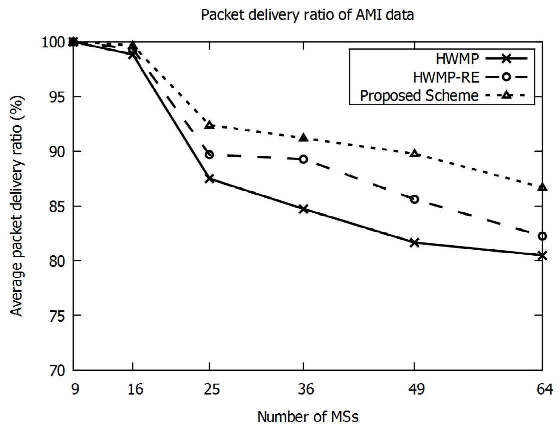

FIGURE 10. AMI data packet delivery ratio comparison.

Fig. 9 illustrates the measurement of the average packet delivery ratio of the three route selection schemes, which can represent the reliability of the smart grid. All three schemes ensured almost 100% packet delivery ratio when nine MSs were deployed in the smart grid network. If more MSs are deployed in the network, then the packet delivery ratio decreases and the influence on route flapping will be diminished.

According to the result of Fig. 9, the proposed scheme has a higher packet delivery ratio than the HWMP or route selection scheme proposed by [15], [16] even when the number of MSs is as high as 64. Our proposed scheme has a better packet delivery ratio of up to 6% than HWMP when the number of MSs is 36 and 49. Furthermore, the proposed scheme has a 6% higher packet delivery ratio than the route selection scheme proposed by [15], [16]. Consequently, it can ensure that the proposed scheme has a higher reliability than other route selection schemes in a smart grid environment.

The result shown in Fig. 9 contains three types of data packets, including AMI data, AMI management, and power quality data. We also analyzed the packet delivery ratio of these three types of packets. Fig. 10 represents the packet delivery ratio of AMI data. Each MS transmits AMI data every 15 s, and the packet size of AMI data is 123 B.

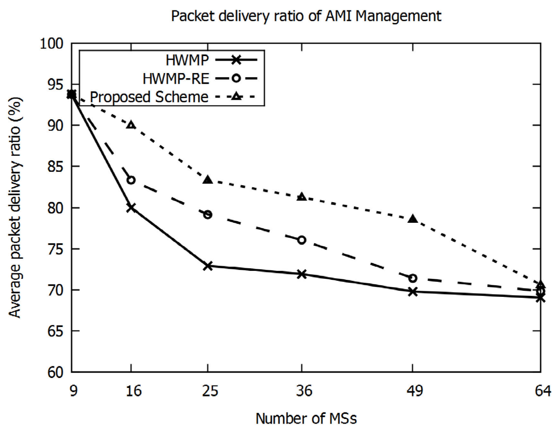

FIGURE 11. AMI management packet delivery ratio comparison.

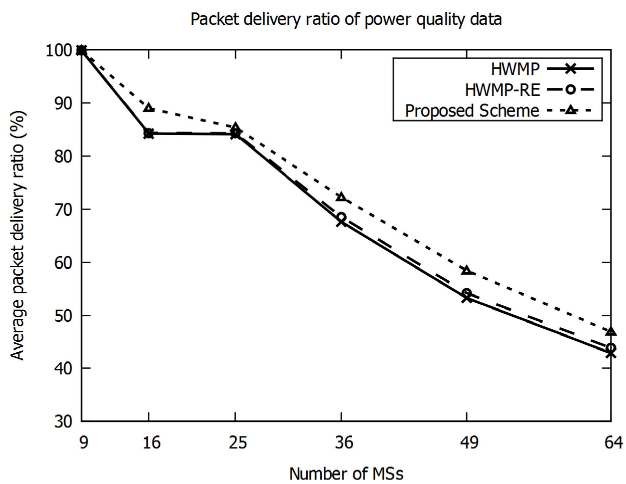

FIGURE 12. Power quality data packet delivery ratio comparison.

Compare with the AMI management and power quality data, the AMI data packet size is small.

Fig. 10 shows that the AMI data has a high packet delivery ratio. When the number of MSs is 9, the packet delivery ratio is almost 100%. Furthermore, the AMI data packet delivery ratio is over 80% even when there are 64 MSs. From these experiments, we observe that small packets do not impair reliability drastically.

As Fig. 11 shows, the packet delivery ratio of AMI management traffic is lower than that of AMI data traffic. Nevertheless, the AMI management time interval is 300 s, which is much longer than power the intervals for quality data and AMI data. Because the total amount of AMI management data is not excessive the packet delivery ratio of AMI management still exceeds 70%.

Fig. 12 represents the power quality packet delivery ratio. The transmission interval of power quality data is 3 s and the application size is 3000 B. With a short transmission interval and large data size, the power quality data packet delivery ratio has inefficient performance. The number of power quality data packets dropped over half of the transmission power quality data when the number of MSs was 64.

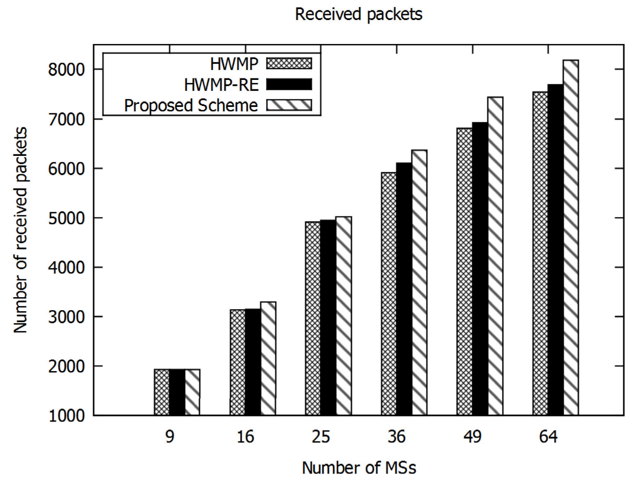

FIGURE 13. Comparison of total received packets.

Because the statistics of Fig. 9 and Fig. 12 are similar, we knew that the packet delivery ratio was influenced mostly by power quality data packets in the smart grid system. We also observe from Figs. 10 to 12 that the proposed scheme provides high reliability even if various smart grid applications are used.

To compare the reliability of three different route selection schemes, Fig. 13 shows the total sum of received packets from the root MS. When the number of nodes is 9, the counts of received packets are the same, but the distinction between the three schemes appears when the number of MSs is increases.

Although our proposed scheme has a packet delivery ratio only 2% to 6% more than HWMP and 1% to 5% more than the proposed route selection scheme proposed by [15], [16], the difference in sum of received packets is notable when the number of MSs is high. Our proposed scheme has approximately 100 packets more than HWMP when the number of MSs is 16 or 25, and has more than approximately 400 packets when the number of MSs is 36. Moreover, when the amount of MSs up to 49 and 64, the proposed scheme outperforms the number of received packets than HWMP about 600 because the number of transmission data is getting more and more when the number of MSs is increasing.

Consequently, the proposed route selection algorithms highly efficient for receiving packets from a root MS; that the proposed scheme can provide excellent reliability in a smart grid environment.

In Fig. 13, the statistics on the total number of data packets received from root the MS include AMI data, AMI management, and power quality data. Our analysis also calculated the number of received packets on these three types of smart grid applications separately.

Fig. 14 illustrates the total received packets of AMI data. Because the transmission interval of AMI data is 15 s, the total number of received packets of AMI data is 16% to 25%. The difference in the total amount of received AMI data packets is not evident when the number of MSs is 9 or 16. However, when the number of MSs is 25, the total number of

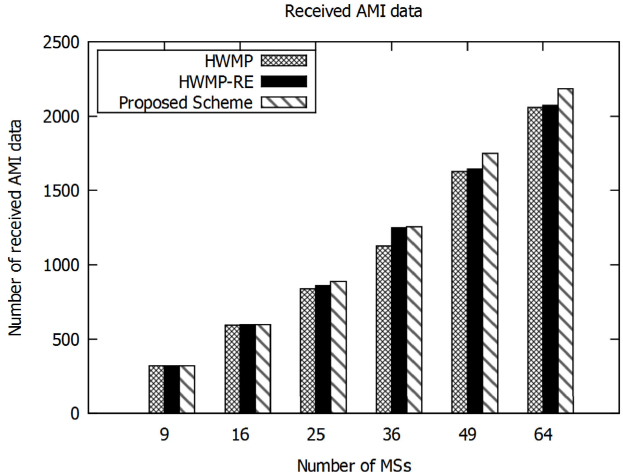

FIGURE 14. **Comparison of total number of of received AMI data packets.**

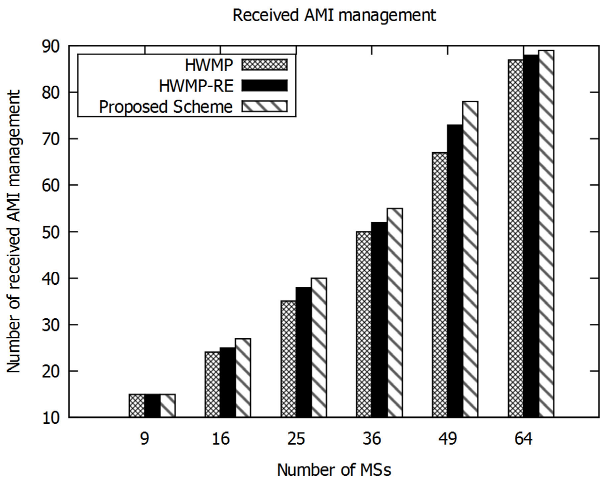

FIGURE 15. **Comparison of total number of received AMI management packets.**

AMI data packets in the proposed scheme is approximately 40 more than the HWMP, and also approximately 20 AMI data packets greater than that for the scheme proposed in [15], [16]. When the number of MSs is greater than 25, the total number of received AMI data packets in the proposed scheme is approximately 120 AMI data packets more than that for HWMP and outperforms the scheme in [15], [16] by more than 100 AMI data packets.

The total number of AMI management packets is shown in Fig. 15. Because the MS transmits AMI management every 300 s, the total number of AMI management packets is not over 100. The total number of AMI management accounts for only 4% of the total received packets when the network has 9 MSs. Moreover, when the number of MS is greater than 9, the total number of AMI management packets is less than 1% of the total number of received packets. Although AMI management data packets are not the majority of all received data packets, our proposed scheme still processes more received AMI management packets than do HWMP and the route fluctuation prevention algorithm proposed in [15], [16].

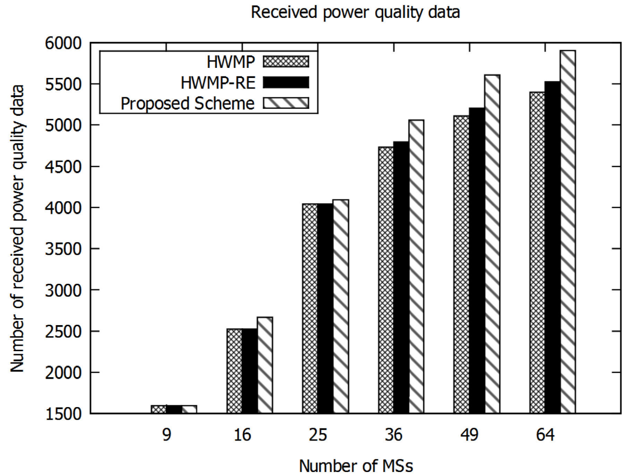

FIGURE 16. **Comparison of total number of received power quality data packets.**

Because the transmission interval is only 3 s, power quality data are the majority of the total received data packets from the root MSs in a smart grid. In Fig. 16, the power quality data packets account for up to 70% to 80% of the total received packets. Consequently, power quality data plays a key role in smart grid reliability. Compared with the received packets of AMI data and AMI management packets, the difference in received power quality data is more obvious in smart grid applications. When the number of MSs is 36, the proposed scheme processes approximately 300 more received packets than the other schemes. Furthermore, the proposed scheme processes approximately 500 more power quality data packets than the route selection scheme using the HWMP. Our proposed scheme processes approximately 400 more power quality data packets than the route selection scheme proposed in [15], [16].

According to the statistics in Fig. 13, 16, the proposed route selection algorithm outperforms the other schemes in the total number of received packets, which indicates that our proposed scheme provides higher reliability for smart grid applications.

Although the proposed route selection scheme can provide a high packet delivery ratio to guarantee high reliability, it must trade off an undesirable transmission delay for achieving high reliability. An end-to-end delay comparison of the three route selection schemes is shown in Fig. 17. When there exists a better routing path with lower airtime cost, the proposed route selection scheme is not certain to use it if thefluctuation rate of the airtime cost of the primary route exceeds the threshold we set. The proposed scheme sacrifices data transmission time to realize reliability.

In Fig. 17, we find that the HWMP end-to-end delay uses less time to transmit data packet than the proposed scheme and the scheme proposed in [15], [16]. The proposed route selection scheme and the scheme in [15], [16] have approximately equal transmission times when the number of MSs are 9, 16, 25, or 36. However, when the number

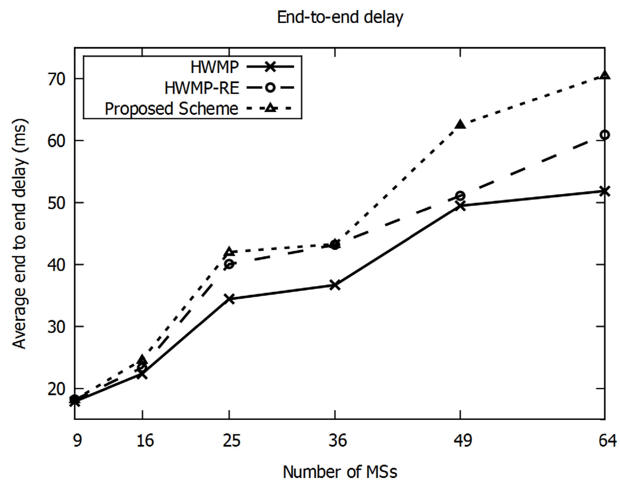

FIGURE 17. **End-to-end delay comparison.**

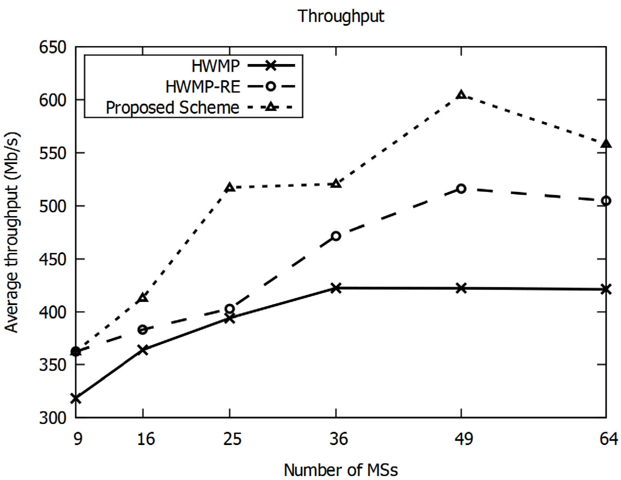

FIGURE 18. **Comparison of throughput (Mb/s).**

is 49 or 64, the data transmission time using our proposed scheme is 10 ms greater than that of the system proposed in [15], [16].

Although the fact that our proposed scheme requires a longer data transmission time, it causes a delay of an acceptable data transmission time range because it is only several millisecond, and the purpose of the research is to deliver an excellent packet delivery ratio to provide high smart grid reliability. Furthermore, we promise that the proposed scheme delivers excellent performance even though it suffers from undesirable end-to-end delay.

We compared the average throughput of the three route selection methods and present the results in Fig. 18. The throughput of the HWMP decreased when the number of MSs is 36, but the throughputs of our proposed scheme and the route selection scheme proposed in [15], [16] decrease when the system has more than 49 MSs. Although the proposed scheme has a relatively long data transmission interval, we can provide better throughput than can the other schemes. Consequently, our proposeds scheme provide not only relatively desirable reliability but smart grid performance.

Regarding the simulation results, the proposed route selection scheme can provide high reliability of data transmission in a smart grid environment. With the route fluctuation threshold of 50%, although the end-to-end delays of data transmission interval increase, the system can guarantee high reliability and throughput for various smart grid applications, which is the most important requirement for smart grid transmission systems.

VI. CONCLUSION

In this paper, we propose a novel route selection algorithm that utilizes the IEEE 802.11s HWMP. Our proposed method improves smart grid reliability by increasing the packet delivery ratio. The main contribution of the proposed route selection scheme is that it solves network congestion and the route flapping problems, which are the main problems that degrade smart grid reliability. Sometimes, such problems can be caused by using the original version of HWMP. We solved the problems using an airtime cost fluctuation rate threshold to determine whether to change the primary route. The results of an ns-3 simulation proved that our proposed system has a high packet delivery ratio and better throughput than other protocol route selection schemes when the threshold is 50%. The statistics of the simulation demonstrate that the proposed route selection scheme can achieve high reliability.

In the future, to provide further highly reliable smart grids, we can use the proposed scheme modified with the IEEE 802.11s HWMP and add some other methods to improve smart grid performance, including modification of the calculation of airtime cost and a novel scheme to provide route recovery, which are crucial factors to increase smart grid reliability. It is also an important issue that how to keep high reliability in heavy load traffic. Furthermore, the subject of quality of service (QoS) is also the target that we can work hard on it in smart grid environment.

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