An Efficient ARP for Large-scale IEEE 802.11s-based Smart Grid Networks

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***Abstract*—Recently, wireless mesh networks (WMNs) have been touted as one of the suitable communication infrastructure for Smart Grid (SG) Advanced Metering Infrastructure (AMI) applications due to their ease of deployment and reasonable costs. These WMNs are typically based on the upcoming IEEE standard, namely IEEE 802.11s. However, 802.11s has performance related issues regarding scalability. One of the inefficiencies is related to the Address Resolution Protocol (ARP) when creating and maintaining the ARP cache and issuing path discovery within large-scale networks. In this paper, we propose an efficient ARP scheme for large-scale AMI networks. Specifically, we utilize the proactive Path Request (PREQ) message of 802.11s standard to perform the MAC address resolution during routing tree creation and maintenance and hence eliminate the broadcasting of ARP requests. Simulation results with the implementation of 802.11s in Network Simulator 3 (NS-3) show that compared to the original broadcast operations our approach improves the packet delivery ratio and throughput significantly.**

I. Introduction

Modernization of the current power grid to Smart Grid (SG) involves an enormous number of advanced electric power components and an extensive use of information and communication technology [1]. This new and advanced power grid will have bi-directional flow of information and flow of electric power among different devices in SG. Data reporting applications are expected to be the major applications in SG. For instance, Advanced Metering Infrastructure (AMI) is one of those data collection applications where utility companies can receive various information from the consumer's side via smart meters either on-demand or on pre-defined time schedules. Based on the collected information, the utility company can perform various actions such as bill processing, grid management, leakage detection, demand forecasting or dynamic pricing. The collected data in such applications must arrive within real time constraints and reliably to ensure precise analysis and usage. Therefore, the underlying data communication infrastructure plays a significant role to meet these constraints.

IEEE 802.11s-based Wireless Mesh Network (WMN) is one of the underlying data communication networks touted for Neighborhood Area Network (NAN) applications [1]. In this mesh network, mesh nodes communicate with each other via 802.11 protocol and hop the messages towards a gateway which can eventually relay it to the utility company [2]. The IEEE 802.11s standard operates at the MAC layer and uses Hybrid Wireless Routing Protocol (HWMP) [3] as its default routing protocol to find a multi-hop path towards the destination.

While 802.11s has been proposed as a suitable alternative for small-scale neighborhood area mesh networks [2], its performance for large-scale applications such as SG AMI has not been well investigated. For instance, IEEE 802.11s has a major drawback for IP-based applications in SG. As a MAC layer protocol, HWMP uses MAC addresses in all of its operations. Conversely, an IP-based application only knows the destination IP address. Each time the application layer of a node sends data, the corresponding MAC address of the destination IP address is searched in the Address Resolution Protocol (ARP) [4] table. If the IP address is not found in the ARP table, an ARP request message will be broadcast in a multi-hop fashion. On receiving an ARP request, only the destination node will issue a unicast ARP reply that contains its MAC address to the source node. Clearly, this will pose additional delay for HWMP path discovery operation since HWMP will have to wait until it receives the corresponding destination MAC address.

This additional delay becomes more apparent in a periodic data reporting operation such as SG AMI. Typically, a data collector gateway is set as the root of the WMN. Every smart meter sends its power consumption data periodically to the data collector at the same pre-defined time interval. As the root node, the data collector periodically broadcasts proactive path request (PREQ) or Root Announcement (RANNs) messages, as part of HWMP, towards all smart meters to create and update the path tree to the root. However, since the ARP table is empty at the beginning of data collection, all smart meters will broadcast an ARP request for the same destination IP address at the same pre-defined time interval. These broadcast ARP requests to the same destination are not efficient. This is because it may cause ARP flooding and consume a significant amount of bandwidth that may affect throughput and prevent the reported data to arrive in timely manner. The similar situation also occurs periodically when the ARP alive time out of an entry related to the sink node in the ARP table has expired. Each smart meter will broadcast an ARP request again toward the root node. The problem is compounded with the existence of WMN interference which is one of the major issues in WMN research when the network size grows [5].

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Configuring a static ARP in each node may alleviate this problem. Nevertheless, this is not an efficient approach considering the number of smart meters involved when trying to keep them up to date in case of hardware changes at the root node. Therefore, we propose an extended proactive PREQ message of HWMP to accommodate a dynamic MAC address mapping. On receiving this extended proactive PREQ message, each receiving node will add or update its ARP table. In this way, every node will have the address mapping of the root node and can send its data to the root node without any possible delay caused by ARP requests.

We conducted an extensive performance evaluation of the proposed technique in large-scale WMNs using NS-3 simulator which has a built-in draft implementation of IEEE802.11s. Simulation results revealed that the proposed technique can significantly improve the packet delivery performance when the network scales.

This paper is organized as follows. Section 2 discusses the related works. Section 3 describes our proposed method. Section 4 presents the performance evaluation of our proposed method. Section 5 summarizes our results and concludes the paper.

II. Related Work

In IEEE 802.11s WMN, at least two types of broadcast messages occurred: (1) during MAC address resolution and (2) during path discovery. Broadcast messages in shared wireless medium such as in WMN, may lead to frequent contention and collision in transmission among neighboring nodes. The experiments reveal that WMNs may experience up to 50% loss of throughput at each hop when a real world environment is considered [5]. This is still the case even when the new IEEE 802.11n standard is used as the underlying MAC layer [6]. To alleviate this issue, one proposed solution is to use multiple radios and communicate via different channels [7]. However, this requires additional hardware and introduces issues such as inter-flow interference that need to be addressed. Our work in this paper is focusing on single radio WMNs.

Based on the availability of a root portal, two different multi-hop ARP (MARP) schemes for MAC address resolution in Wireless LAN based mesh networks are proposed in [8]. A proxy ARP at the root portal is proposed when a root portal is available and tree routing is enabled. An integration of route discovery information into ARP request/reply frame is proposed when a root portal is not available. In the first approach, to build the proxy ARP, when a node receives a RANN message, it sends a unicast gratuitous ARP to the root portal in order to notify the root of its own IP and MAC addresses. In this way, the root node knows MAC and IP addresses of every node in the network. In the second approach, PREQ message is inserted at the end of ARP request and PREP message is inserted at the end of ARP reply message. However, none of these approaches are suitable for data reporting applications such as SG AMI. This type of data reporting requires no interaction among the nodes that need the MAC address resolution since all the nodes report to the sink node and hence every node only needs to know the IP and MAC addresses of the sink node. These approaches are different than our approach. Our approach incorporates the MAC address resolution message into the PREQ and is geared for 802.11s while theirs incorporates PREQ and PREP messages into the ARP request and ARP reply message respectively.

III. Proposed ARP Method

A. Background on HWMP

In the basic proactive path selection operation of HWMP, root node broadcasts a proactive PREQ message periodically with an increasing sequence number. Each node may receive multiple copies of PREQ, each traversing different path from the root node to the receiving node. The receiving node creates or updates its current route to the root node if the PREQ contain newer information (i.e., greater sequence number), or if the sequence number is the same as the current route but it offers a better metric. Each receiving node then updates hop-count of PREQ, retransmits the updated PREQ, and sends a unicast Path Reply (PREP) to the root.

B. Approach Details

The basic idea of our proposed method is that during the proactive routing formation and maintenance of HWMP in which the root node broadcasts a PREQ message, a MAC address resolution message that contains the root node address is piggybacked with the proactive PREQ message. Every node (e.g., SM) that receives this extended proactive PREQ message, in addition to its basic PREQ receiving process, will create or update its ARP table. The decision to create or update the ARP table is also based on the freshness of the PREQ message (i.e., based on the PREQ sequence number).

To implement this idea, we extended the structure of proactive PREQ message and add additional communication interface between HWMP protocol and Address Resolution Protocol for creating or updating the ARP cache based on the MAC address resolution message in this extended proactive PREQ message. HWMP protocol will check the presence of this extended field and verify its freshness and pass the MAC address resolution message to ARP protocol. On receiving this message, ARP protocol will do the update. In Network Simulator 3 (NS3), ARP protocol is implemented in ArpL3Protocol class while HWMP protocol is implemented in HwmpProtocol class.

To determine the length of the MAC address resolution message, we have two choices: (1) put only an IP address; or (2) put both IP and MAC addresses. The first choice comes from the fact that the MAC address of the PREQ originator has been included in the PREQ message. As shown in Fig. 1, PREQ message has the MAC address of the root node in the *Originator Mesh STA Address* field. Hence, it reduces the overhead. On the other hand, putting both IP and MAC addresses in the MAC address resolution message is more flexible at the expense of an additional overhead of at least 48-bits (i.e., the length of MAC address). For our purpose,

Element ID	Length	Flags	Hop Count	Element TTL	Path Discovery ID	Originator MESH STA Address	Originator HWMP Sequence Number	Originator External Address	Lifetime
Octets: 1	1	1	1	1	4	6	4	0 or 6	4

Metric	Target Count	Per Target Flags #1	Target Address #1	Target HWMP Sequence Number #1	......	Per Target Flags #N	Target Address #N	Target Sequence Number #N
4	1	1	6	4	.....	1	6	4

Fig. 1: PREQ message format in HWMP of 802.11s standard.

B0	B1	B2	B3 ... B5	B6	B7
Gate Announcement	Addressing Mode	Proactive PREP	Reserved	AE	Reserved
Bits: 1	1	1	3	1	1

Fig. 2: Flag Fields format in PREQ message of HWMP.

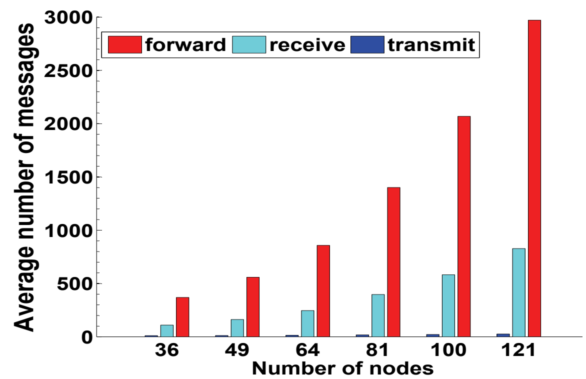

Fig. 3: Average number of broadcast messages per node.

we choose the flexibility offered by the second choice in our design. Therefore, we add two additional fields into the PREQ message to store the MAC address mapping. The first field is for MAC address and the second field is for IP address of the root node respectively.

To distinguish between the original proactive PREQ message and the extended proactive PREQ message, we use the reserved bit in the *Flags* field of PREQ message as the identifier of these two additional fields. As shown in Fig. 2, there are several reserved bits in the *Flags* field. We use the last bit of the *Flags* field as the *ARPTag* subfield. These two additional fields are present when $ARPTag = 1$.

IV. Performance Evaluation

A. Experiment Setup

We use NS-3 and flow monitor module [9] to collect a set of network performance metrics for performance evaluation of our proposed approach. We consider an **N** by **N** mesh grid of smart meters using 802.11g to represent the SG AMI network. One node in the grid acts as the data collector (e.g., root) while (**N**×**N** - 1) nodes act as smart meters. The data collector is located at the top left corner of the grid mesh network for each network size considered. Every smart meter sends a periodic message (i.e., power report) to the data collector every 0.5s. All smart meters send their report at the same pre-defined time schedules. The transmission range is set to 120 meter and the distance between nodes is set to 100 meter. In this way, each node can communicate with maximum four neighbors by the grid cell sides. We varied the number of nodes in the grid from 6x6 (36) to 11x11 (121). For each network topology, we run the simulation for 250s.

The location of the data collector may cause the proactive routing of HWMP to build deep tree topologies as the number of nodes in the network increases. Therefore, we set the value of *dot11MeshHWMPnetDiameterTraversalTime* parameter of NS-3 to 2s to accommodate various depths of the network topologies. This value is chosen to ensure enough time for PREQ message propagate across the mesh network. This parameter is used to: (1)control when the PREQ retry attempts should be made; and (2) for path stability by preventing a node from frequently changing the path to the originator of PREQ [3]. During the path discovery, while the number of attempts is controlled by *dot11MeshHWMPmaxPREQretries* parameter, the minimum waiting time before a node sends another retry attempt for path discovery to the same destination is defined as 2 × *dot11MeshHWMPnetDiameterTraversalTime*. For path stability, this value is used to control the increment of the originator HWMP sequence number. The sequence number is incremented only after at least *dot11MeshHWMPnetDiameterTraversalTime* has elapsed since the previous increment.

B. Performance Metrics and Baseline

We used three performance metrics to assess the performance: (1) Average Packet Delivery Ratio (PDR): number of packets received at the root divided by the number of packets transmitted. This metric is crucial in understanding the positive impact of the proposed method for packet delivery; (2) Average end-to-end delay: the sum of the delay of all received packets divided by the number of received packets; and (3) Average throughput: the number of bits received divided by the difference between the arrival time of the first packet and the last one.

We build the baseline based on the basic operation of HWMP where there is no piggybacking of ARP. This is shown as the *baseline* in the graphs.

C. Performance Results

Fig. 3 shows the average number of broadcast messages per node triggered by ARP during the simulation time for the *baseline*. Typically, these broadcast messages are sent during the creation and maintenance of ARP cache. By default, the ARP alive time out is 120s and each node will send an ARP broadcast message when the ARP alive time out expires. Even though each node only sends a small number and small size of broadcast messages (28 bytes), each node receives and forwards a much bigger number of broadcast messages. These results show that larger networks experience greater broadcast storm than smaller network.

As shown in Fig. 4a and Fig 4b, this broadcast storm affects the packet delivery ratio and throughput of the baseline as the network scales. Even worst is that the throughput for

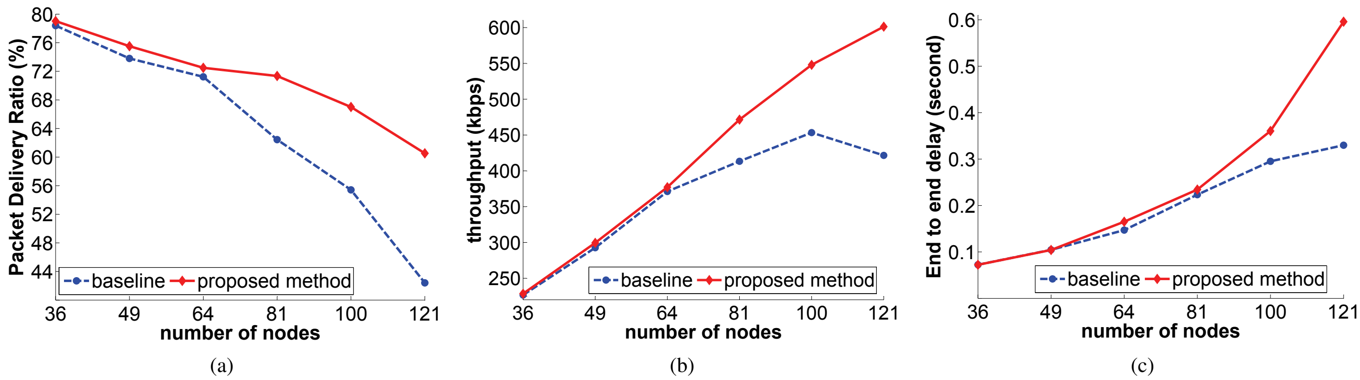

Fig. 4: PDR, Throughput, and End to end delay for varying node count.

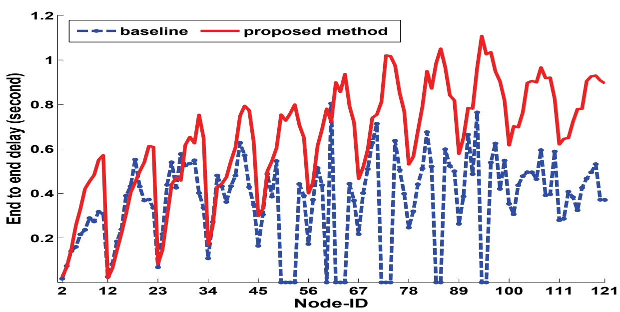

Fig. 5: distributions of message delays for 121 nodes. Node-id 2 and 12 are one hop from root in horizontal and vertical direction respectively

121 nodes becomes lower than that of 100 nodes which is conflicting. This is because the root node is unable to receive any data packets from some of the smart meters. In other words, some of the nodes have 0% packet delivery ratio and hence, they have zero end to end delay as shown in Fig. 5.

Our proposed approach on the other hand, eliminates the broadcast storm caused by the broadcast ARP request and hence improves the packet delivery ratio and throughput of large networks significantly. The gain in PDR is increasing with the increased network size and becomes 42% increased when the network size is 121. Given that SG AMI network will have even bigger sizes, this gain is significant. Similar observation is true for the throughput. We would like to note that both PDR and throughput decreases for both approaches with the increased node count. This is expected due to increased multi-hopping and interference in the network as was also confirmed in previous studies [6].

Looking at the delay results, as shown in Fig. 4c, the end-to-end delay of our proposed approach is slightly higher than the baseline for large networks. The higher end-to-end delay is due to the fact that more data packets are able to reach the data collector and this causes much higher contention for medium access. Furthermore, with the increase of the packet delivery ratio of the farther nodes, the end to end delay of data packets from these nodes to the data collector will contribute to the overall end-to-end delay as shown in Fig. 5 for 121 nodes.

V. Conclusion and Future Work

Large-scale WMNs used for SG AMI applications suffer from broadcast messages such as ARP request. In this paper, we proposed a mechanism to reduce the broadcast messages by piggybacking the distribution of the MAC address resolution in the proactive PREQ message of HWMP. The simulation results indicated that such piggybacking significantly increases the PDR and throughput which is crucial in reliable data collection for large-scale AMI applications.

Piggybacking the MAC address resolution in proactive PREQ may pose security threats such as ARP cache poisioning attack. An external attacker who knows this extended proactive PREQ message could change the address mapping since there is no security protection mechanism. Therefore, providing security for our approach will be considered as the next step for our future work.

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