Multigate Communication Network For Smart Grid

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Abstract—It is envisioned that one of the most important issues in Smart Grid will be to design a network architecture that is capable of providing secure and reliable two-way communication from meters to other Smart Grid domains. While networking technologies and systems have been greatly enhanced, in wireless communication environments the smart grid faces new challenges in terms of reliability and efficiency. In this paper we present a multigate mesh network architecture to handle real-time traffic for the last mile communication. The paper consists of three parts; multigate routing, real-time traffic scheduling, and Multi-Channel (MC) aided wireless mesh routing. The multigate routing is based on a flexible mesh network architecture that expands on the hybrid tree routing of the IEEE 802.11s. The network is specifically designed to operate in a multi gateway structure in order to meet the smart grid requirements in terms of reliability, self-healing, and throughput performance. This includes developing a timer-based multiple-path diversity scheme that takes advantage of the multi gateway network structure.

With respect to packet scheduling, we introduce a novel and efficient scheme that is capable of balancing the traffic load amongst multiple gateways. The proposed scheme, which is based on the backpressure concept due to its simplicity, is suitable for practical implementation. We also present a Multi-Channel (MC) aided wireless mesh routing protocol which is specifically designed for multigate smart grid networks. The results indicate that a combination of multipath routing and the backpressure-based packet-scheduling scheme can show a significant improvement in the network reliability, latency, and throughput performance. We also show an improvement in the order of magnitude can be achieved via the proposed multi-channel aided routing protocol.

Keywords-Smart Grid, wireless mesh networks, routing protocols, backpresure, packet scheduling, multpath route, multigate mesh, multichannel routing, WLAN, IEEE 802.11s

I. INTRODUCTION

The Smart Grid is comprised of many networks (domains) with various boundaries that have to be interconnected to provide end-to-end services. The challenge is to design network architectures that can meet the interoperability requirements for inter- and intra- domain communications, as specified in the NIST conceptual reference model [1]. Such networks, according to the Energy Independence and Security Act of 2007, should provide secure and reliable end-to-end two-way communications. In this respect, one of the most important challenges is to provide a reliable last mile communication that covers the connectivity from the meters to the Advanced Metering Infrastructure (AMI) head-end. The design of such a network, which may consist of the Neighborhood Area Network (NAN) and Home Area Network (HAN), depends not only on the application layer requirement, but also on the nature of its Medium Access Control (MAC) and physical (PHY) layer. There are a number of diverse communications technologies and standards that can be deployed for NAN. In terms of the physical links, these technologies can be broadly classified into two major categories: wireless and wired.

One example of the latter is Power Line Communication (PLC), which includes the Broadband PLC (BPLC) [2], [3] and Narrowband PLC (NBPLC) standards [4]. At the same time Wireless LAN (WLAN) techniques, such as the IEEE 802.11 family standards [5] with their maturity and cost effectiveness, have been extensively deployed for wireless access and home entertainment networking. For smart grid applications, the main issue is how to effectively apply this technology to handle the last mile communication. For instance, an IEEE 802.11 WLAN Access Point (AP) [5], which operates in a single hop (infrastructure mode), can be used as a gateway (e.g., representing Data Aggregation Point: DAP) between meters and the AMI head-end. However, to provide a large coverage area, multihop communication is vastly favored over long-range single-hop links. Indeed, the use of multihop is to combat the rapid decay of the electromagnetic received signal strength as the communication distance increases. In addition, multihop communication between distributed nodes offers pathways around electromagnetic transmission obstacles that would otherwise prevent the formation of a long-range network [6]. This would require deploying a mesh network that can meet the requirements of Smart Grid, which includes a high degree of reliability, self-configuring, and self-healing. In addition, the time-varying nature of traffic generated in an emergency poses a significant challenge in ensuring the reliability of the network. In particular, outage management is a specific example where a system expects to receive power outage notifications and exchanges, which tend to increase traffic load and could consequently cause severe network congestion.

Therefore, the main objective in this paper is to develop a flexible mesh-networking scheme to handle smart grid last mile communication. We propose a flexible multigate network structure. An important feature of this network is that all the meter nodes have a separate path to each gateway. To exploit this feature it would be necessary to design a packet scheduling technique that can allow traffic flow to/from meters to the head-end though a dynamically selected gateway. The selection depends on how the traffic load is distributed amongst neighboring gateways. Therefore, the most significant contribution of this paper is the development of a novel backpressure-based packet-scheduling scheme capable of balancing the traffic load amongst the gateways.

The organization of the paper is as follows: In section II, we discuss issues related to deploying mesh network architecture using IEEE 802.11s as its core technology. The mesh routing, which is on a hybrid tree-based routing protocol in a multiple gateway environment is presented in Section III. To enhance communication reliability Section III-A presents a timer-based multiple-path diversity routing scheme. To balance the traffic load amongst the multi-gateway Section IV presents our backpressure-based packet-scheduling scheme. In Section V, a Multi-Channel (MC) aided wireless mesh routing protocol is specifically designed for multigate smart grid network*s*. The performance of the mesh network under various test environments is presented in section VI.

II. MESH NETWORK ARCHITECTURE

The architecture and design of mesh networking plays a crucial role in reliable access to/from meters. For instance, to avoid service disruption, routing protocols must be robust to link failures. In most cases however, covering a residential area may not terminate in a single access point, but requires multiple Data Aggregation Points (DAPs). Fig. 1 shows a network architecture that includes communication between home appliances and their home gateway (meter) as well as communication between meters and an AMI head-end through one of the DAPs. Based on this network architecture, we consider the IEEE 802.11 technology in our network implementation. In this architecture a meter represents a home gateway node that provides access to home appliances as well as functioning as mesh node that can communicate with its DAP located on neighborhood distribution poles. However, in order to deploy IEEE 802.11 WLAN devices to represent a meter as a mesh node, it would be necessary for these nodes to operate in distributed mode (i.e., as a router) [6]. Bear in mind that IEEE 802.11 WLAN standards can either function in an infrastructure mode as single hop access point (AP) or a distrusted multihop mode. To design a peer-to-peer multihop mesh topology in the form shown in Fig. 1, it would be most convenient if these nodes can operate in both modes.

For the IEEE 802.11b for instance, an arrangement that can expand the functionality of the extended service set (ESS) was developed in [6]. As a result, a slave node (i.e., representing a home appliance), which does not have mesh capability, can send data over the mesh network via its access point. Under these conditions the routing has to be provided at layer 3. Recently, the PIEEE 802.11s group extended multihop mesh techniques to specify the same functionality of a wireless distribution system that interconnects 802.11 devices [7]. An important feature of the PIEEE 802.11s is that it supports frame forwarding and path selection at layer-2 instead of layer3 (network layer). More specifically, the routing protocol uses MAC addresses and an optional radio-aware routing metric that can support unicast, multicast, and broadcast data delivery. Although PIEEE 802.11s modifies the MAC, it does not require any changes to the PHY layer and hence, its implementation is based on any existing PHY layer of IEEE 802.11. In addition, it is fully compatible with higher layer protocols. PIEEE 802.11s also defines a default routing protocol, which is known as the Hybrid Wireless Mesh Protocol (HWMP) [7].

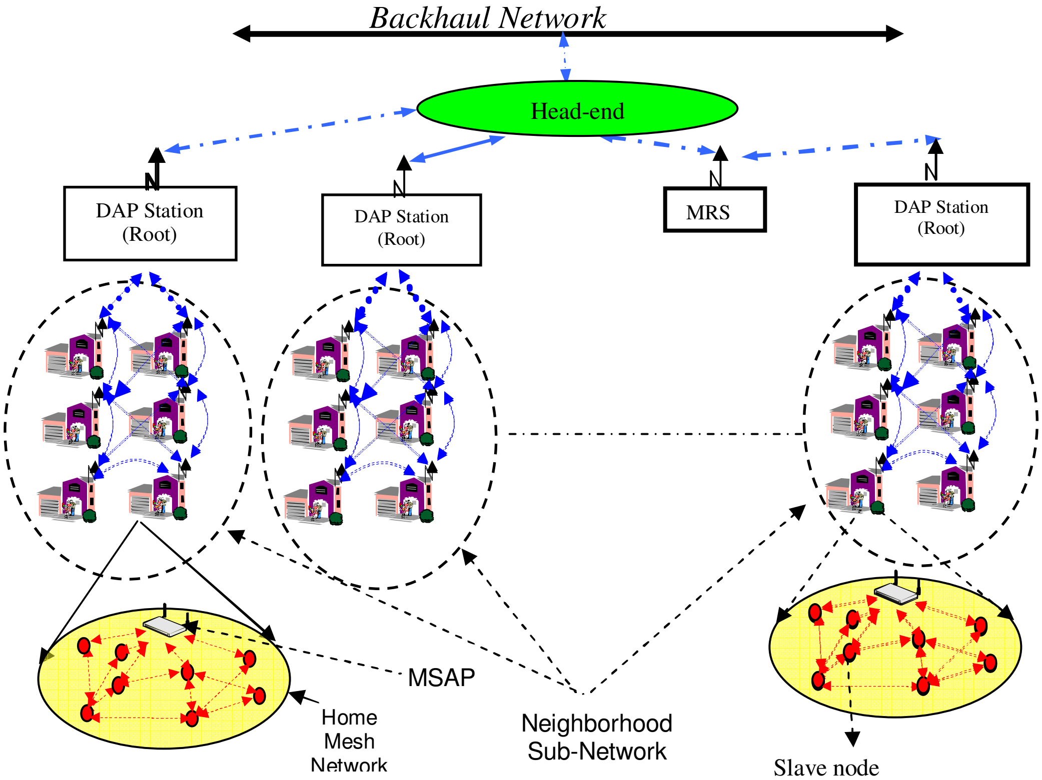


Fig. 1: Mesh network architecture for the last mile smart grid.

Hybrid tree-based routing protocols are generally formed as a combination of the on-demand (reactive) and proactive routing protocols. The function of the Proactive is to maintain routing state, while the reactive aims at reducing the impact of frequent topology changes by acquiring routes on demand. An example of hybrid tree routing is the Hybrid Wireless Mesh Protocol (*HWMP*) [7]. As shown in Fig.1, for our multigate network, four types of nodes are defined;

- Mesh-Relay-Station (*MRS*), representing the relay node (see Fig. 1).
- Mesh-Station with Access Point (*MSAP*), which represents a residential meter in our model and operates as the gateway of the home network to the meter and from meter toward its local DAP, as shown in Fig. 1. Note that a slave node in this figure represents in-home devices (e.g., smart home appliances) and operates in an infrastucure mode similar to the network configuration in [6].
- DAP-Station (*DS*), which represents the neighborhood gateway point. This station respresnts the root of the tree in each sub-network.
- Master-Gateway-Station (*MGS*), representing the AMI head-end, which is connected to the backbone network.

As the proactive part of the routing, a DAP representing a *DS* periodically broadcasts root announcements by increasing the sequence number each time such a message is generated. The root announcement allows proactive routing towards each meter (MSAP) in the residential area. When a meter receives such a message, it catches the MAC address of the transmitting node, then adds it to its list of parent nodes. It should be noted that a meter node, before re-broadcasting the *DS* announcement message, should wait for a pre-defined time to check whether there are more of the same root announcements from other neighbor nodes. After expiration of the period the meter node, which now knows the path to the DAP as well as its MAC address, may unicast a Path Request (PREQ) through its best parent to the DAP acquiring a path to it. We should point out that PREQ is used by the child node (meter) to confirm the paths to its selected parent and hence to validate its parent and its destination DAP. The DAP (RS) will then unicast a Path Reply (PREP) back to the meter. The tree formation process is continued by every new child (meter) by re-broadcasting the root announcement to neighboring nodes. It is important to point out that due to the static nature of the network, the route announcement plays an important role in meeting the self-organization and self-healing requirements of the smart grid. For instance, in the case of a meter malfunction, the root announcement can update the routing tree by trying to bypass the faulty nodes.

For smart grid applications where meters, DAPs, and relay nodes are predominantly stationary, the on-demand part of routing mainly deals with the effect of interference that can cause path-breakage. Note that amongst many on-demand protocols, Ad-hoc On Demand Distance Vector (AODV) [11] and Dynamic Source Routing (DSR) [12] have been perceived as the most popular and well-tested. There are a number of distinctions between the two protocols. For instance, in DSR every packet must carry the Internet protocol (IP) addresses of all the nodes along the source to the destination route, whereas in AODV only the destination address is carried in each packet. Obviously, for a large network where there is the possibility of a link with a high number of hops, DSR can lead to a significant increase in the packet overhead.

III. MULTI GATEWAY (DAP) ROUTING

According to the general architecture depicted in Fig. 1, a residential network may consist of multiple mesh sub-networks, where each is managed independently by its local gateway (DAP). However, due to the variable nature of the traffic, some gateways may suffer from more congestion than others. Under such conditions, nodes belonging to neighboring sub-networks cannot participate in reducing the traffic load. In order to allow collective participation in the routing, it would be advantageous to combine all the sub-networks into a larger network with multiple Gateways (DAPs) where all the meters can access any of the gateways. In addition, such an arrangement can enhance the self-healing and self-organization abilities of the network if some of the gateways and nodes become non-operational or new nodes are added to expand the network.

The first step towards achieving this is to develop flexible multigate routing in such a way that meters can have an option to select the best path to one of the gateways. With such routing flexibility together with the help of an efficient packet scheduling technique, it would then be possible to enhance network performance. Fig. 2 shows an expansion of a single DAP sub-network to a multi-DAP network. To construct multiple DAP routing based on the network structure shown in this figure, DAP-1, DAP-2, …and DAP-N broadcast root announcements periodically to set up their trees. We use a randomization technique to avoid collisions. The MAC addresses of DAP-1, DAP-2, … and DAP-N are employed as the unique identification of the corresponding routing trees. In contrast to single DAP, a node in a Multiple DAP (MDAP) topology has multiple entries in its Tree-Table representing a separate path to each DAP. For example, one entry represents a tree with DAP-1 as its root, which also includes its parent information, as well as the status of the tree (i.e., whether it is active or not). A mesh node (meter) when receives a (DAP) announcement, will check its tree-table to see if there is a tree with the same root announcement:

> If not, the meter will generate a new tree in its table by using the information from the received root announcement message, where DAP and parent information, as well the tree-status are created and maintained.

If yes, the meter will upgrade the existing tree with the same DAP if newer or better path information is contained in the received announcement message. Otherwise, it will discard this announcement message.

Meanwhile, a meter will set up a path to the new DAP in its route table if there is no route available to this DAP. It should be noted that the main objective is for every mesh node (meter) to systematically select the most suitable DAP as its gateway to the head-end. To improve network reliability we further exploit this multi DAP network topology by introducing a timer-based multipath diversity routing. For instance, if the connection from one DAP to a meter is damaged, the same service can be provided from a different route, including any of the neighboring DAPs.

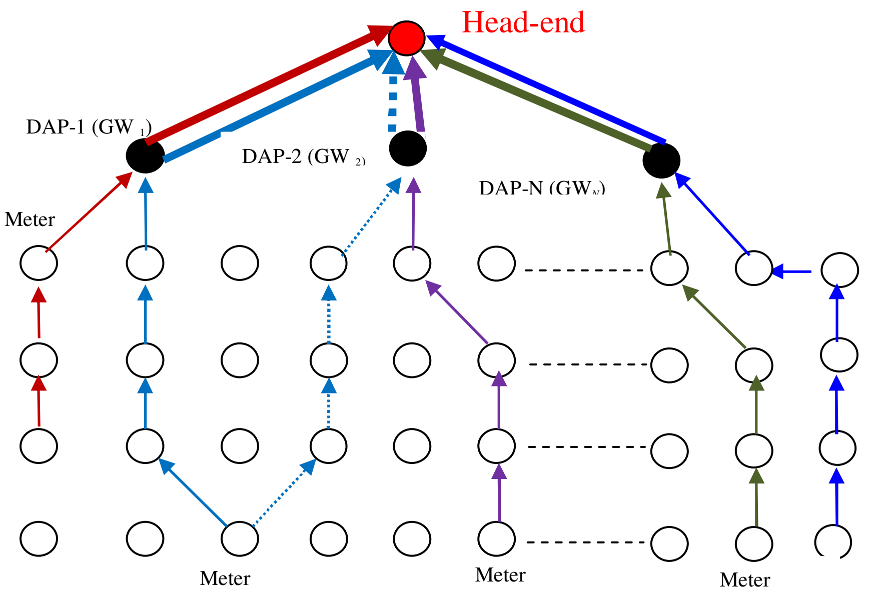


Fig. 2: An example of the Grid static wireless mesh network with an N gateway (DAP) scenario.

A. Reserve-Path Multigate Diversity Routing

Multiple path routing protocols for Ad Hoc networks have been extensively studied in recent years [13-17]. Generally, there are two types of multipath routing protocols: simultaneous routing and reserved-path routing. In the former approach, packets are transmitted simultaneously to the same destination, but via different paths [16], [17]. This approach could substantially increase the network load, unless methods such as multiple description coding are applied [18]. Alternatively, a reserve path approach would be the better solution in terms of bandwidth efficiency, but this would be at the expense of additional delay.

In this paper, we present a tree based multipath diversity routing scheme. The proposed route diversity takes advantage of the multi gateway tree-based routing scheme with the objective of managing the transmission of packets through a different path to possibly another gateway, which may suffer less from interference. For example, in the upstream link the same packet can be transmitted from a meter to the head-end through a separate DAP. In the downstream link, the same packets can be transmitted from multiple neighboring DAPs to a single destination (meter).

In the case of the reserved-path diversity approach, the first best path (e.g., based on a certain path selection metric) will be selected to send a data packet. As soon as a link breakage notification is received for this path, the source node will send the packet through to the second route. If both links break, the new routes have to be established via on-demand routing of HWMP. For implementation, we designed a timer-based reserved path routing scheme. To aid the description of multipath routing, Figures 3 and 4 show the standard and the timer-based HWMP-based routing procedures. In the timer-based reserve-path routing scheme, every meter has an additional backup HWMP buffer to store a copy of self-generated and already transmitted packets (see Figs. 4). Specifically, when a meter node receives data packets from its upper layer (a self generated packet) or neighboring meters (a relayed packet), it checks its route table to see if there are routes to DAP-1, DAP-2 and DAP-N. If there are multiple routes, it selects the best path by adding the next hop MAC address to the MAC header field of the packets. In the case when there is only one reachable DAP, it will choose the available route to forward its packet. These packets are then inserted in the data queue, waiting to be transmitted to the next hop. Meanwhile, a copy of the self-generated packet with time stamp is backed-up in the backup buffer as shown in Fig. 4. Note that only self-generated packets are stored in the backup HWMP buffer and those received from neighboring meters are not backed-up. This is mainly to avoid multiple retransmissions.

In the case of link failure, as soon as a link breakage notification (i.e., path error message: PERR) is received, the source node will first check whether there is a route to other DAPs. If so, it retrieves the affected packets from its backup buffer and sends them to the other DAP (s). The destination address and the transmitting meter address in the PERR are used to check whether the packets in the backup buffer are affected.

If there are no routes to any DAP caused by link failures, packets will be stored in the HWMP buffer, while nodes will check if RREQ has already been sent to the originally selected DAP. If so, nodes will wait for the RREP. Otherwise, a RREQ will be sent to this DAP. When receiving RREP from the original DAP, meters get packets from the HWMP buffer and input them to the data queue after updating the MAC header. Again, a copy of self-generated packets will be put in the backup HWMP buffer for possible retransmission.

Since source meters don't know which packets have already been successfully received by any of the DAPs, they will retransmit all the affected packets in their backup HWMP buffer. In order to remove backlog packets from the backup buffer, meters will start a timer to periodically delete such packets thus reducing the possibility of retransmitting those that may have been successfully transmitted. If the timer value is too high, many of the successfully transmitted packets will be retransmitted and this can result in high overhead in the network. On the other hand, when the timer value is too low, many unsuccessfully transmitted packets will be removed from the backup - buffer and therefore cannot be retransmitted through the reserved path. A trade-off of the timer value can be achieved which helps with a good performance. Due to space limitation, we only present the best achievable performance of the Timer-based reserve-path routing scheme in this paper.

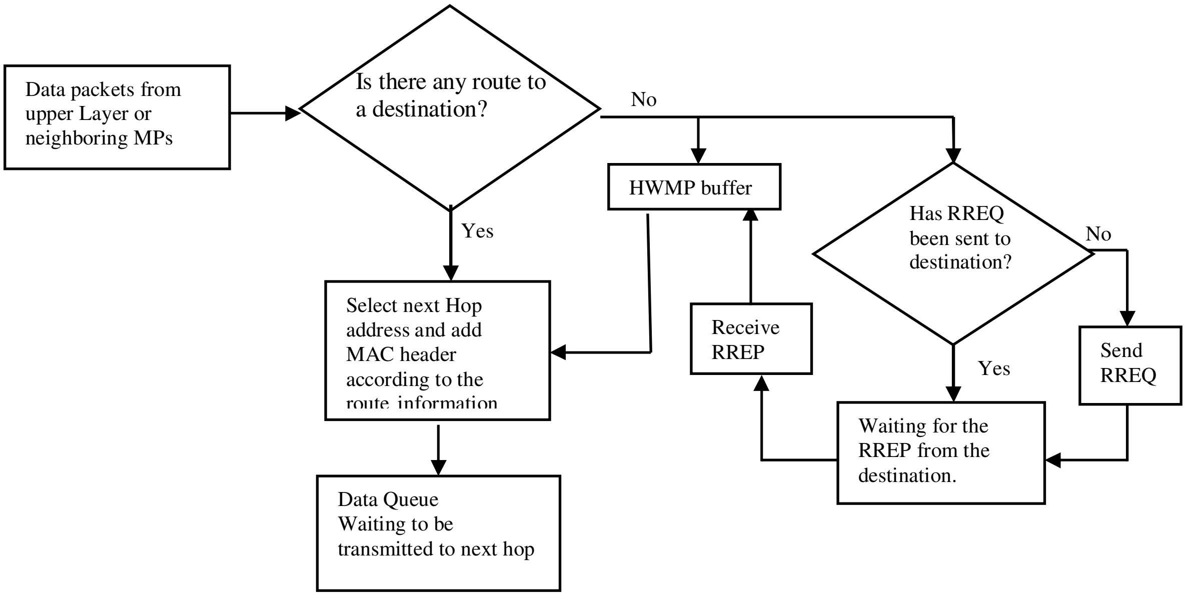


Fig. 3: Standard HWMP Routing Procedure

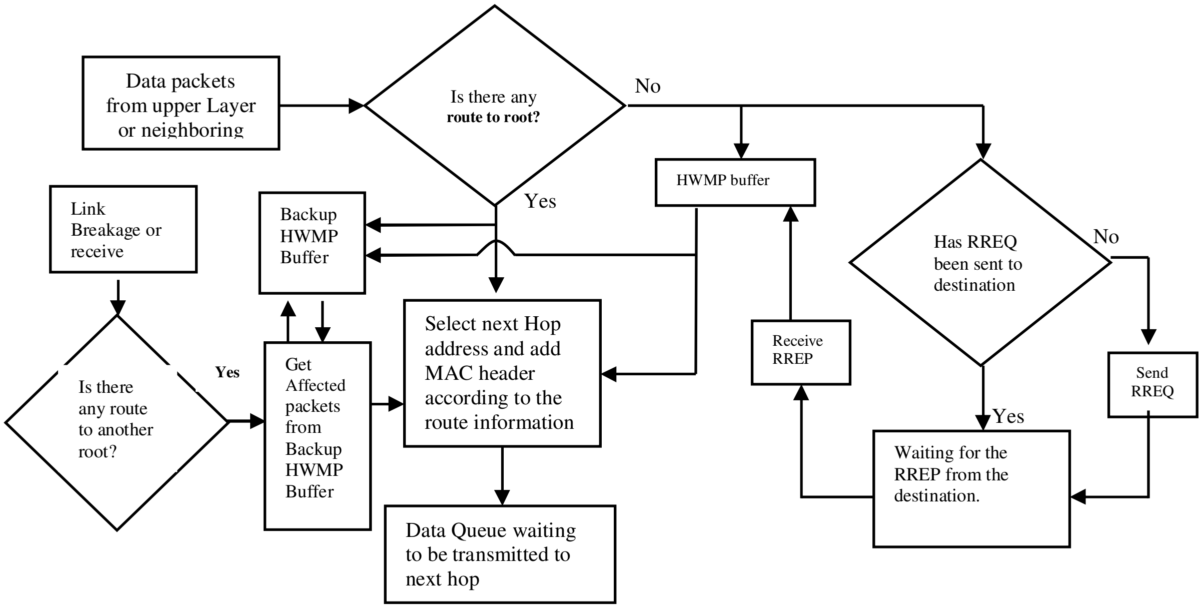


Fig. 4: Timer-based Source Reroute Multiple DAPs Routing Scheme

IV. PROPOSED BACKPRESURE-BASED PACKET SCHEDULING

When considering wireless mesh networks, the primary challenge is to provide reliable metering services. Some use case scenarios envision that under emergency situations, the load can rapidly increase due to more regular packet exchanges, and can indeed create a severe bottleneck. Thus, by taking advantage of the multigate routing scheme presented earlier, we can safely assume that all nodes possess an active path to each of the gateways. Based on this important routing property, the next step would be to develop a packet scheduling technique that is capable of directing traffic towards the gateways carrying lighter traffic in order to achieve a load balance amongst the gateways.

Therefore, in this section we introduce a novel and yet simple packet-scheduling scheme, which is based on the backpressure concept [18]. In backpressure algorithm, specific links at each slot are dynamically activated to transmit packets based on the queue lengths at all network nodes and average link reliabilities. The statistic analysis in [18] proves that the proposed backpressure algorithm is capable of stabilizing the network when achieving maximum throughput region. However, the backpressure algorithm, which was first introduced in [18] for multihop networks, is too complex due to its centralized computational property [19-22]. Indeed, despite many attempts, there is no simple solution for practical implementation in a distributed manner. Therefore, in the absence of any optimal distributed packet scheduling, we concentrate on developing a heuristic backpressure scheme. Our approach is specifically designed for the multigate network structure. It aims for balancing the traffic load amongst all gateways in order to maximize the overall throughput.

In this scheme, every transmitting node first evaluates the status of its neighboring nodes based on what is defined here as the Next Hop Selection (*NHS*) criterion. *NHS* is calculated using a combination of the queue size and the Best Path Metric (*BPM*) value of its neighbor nodes to ensure reliable first in first out (FIFO) delivery to the end destination. Bear in mind that in our multigate routing protocol, every node contains a separate path in its routing table to each gateway. The *BPM* value is then calculated using a certain path quality metric, such as the air-time link quality [7], or shortest path (e.g., hop-count).

For example; for an N-gateway system, GW_i, $(i = 1, 2....N)$, let us assume that a transmitting node has n neighbors where Q_j $(j = 1, 2, \ldots n)$ denotes the queue length of its j^{th} neighbor and P^k_j $(k = 1, 2, \ldots N)$ as its metric value (e.g., hop-count or air-time) to the k^{th} gateway (GW_k). Given that every node has a separate path to each gateway (DAP), the first step is to calculate the *BPM* for every neighbor; e.g., for the neighbor node *j* we can write,

$$BPM_j = min\ \{ \mathrm{P}^k_j \}\ , \quad k = 1,\ 2, \ldots .N. \qquad (1)$$

where *min {x}* represents the minimum value of *x*. Then the backpressure metric, *BM*, for this neighbor is defined as,

$$BM_j = \ Q_j * BPM_j\ . \qquad (2)$$

After obtaining the backpressure metric for all the neighbors, the next-hop selection metric (*NHS*) is then calculated as:

$$NHS = min\ \{ BM_j \}\ ,\ j\ = 1,\ 2, \ldots .n,. \qquad (3)$$

Based on the above equation, a neighbor node with the smallest *NHS* (best neighbor) will be selected as the next hop node. It should be noted that this selection process includes a path to the best gateway from the selected neighbor's point of view and may change when this neighbor begins its own next hop selection process. This will continue until one of the gateways is identified as the best neighbor in the next hop selection process. As soon as the best next hop neighbor is selected, the transmitting node will begin forwarding its packets towards it. In the event of link failure, the neighbor with the second lowest *BM* value in (3) is used to construct a virtual reserve-path. Note that a transmitting node will consider a link as broken after a predefined number of unsuccessful retransmission attempts.

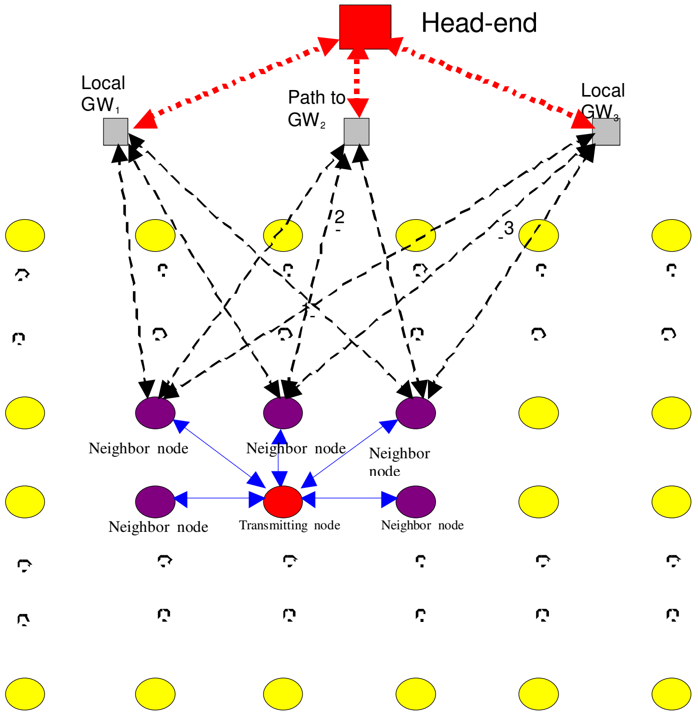


Fig. 5: An example of a 3-gateway (GW_1, GW_2, GW_3) routing configuration for the proposed backpressure packet-scheduling.

Implementation Model

The proposed scheme has been applied to the tree-based routing protocol described in the previous section. To obtain the *NHS* value, only the parent nodes may be used in the calculation. Note that since in our backpressure scheme the main objective is the selection of the next hop, there would be no need for on-demand routing. Furthermore, for a network with a large number of gateways (DAPs), it may be sufficient to consider the neighboring DAPs in order to limit the number of paths. According to (3) in the proposed backpressure scheme, the queue-length and *BPM* need to be calculated by a transmitting node before scheduling its packet to the next hop node. This would require the node to acquire this information from all its neighbors. As mentioned before, for *BPM* we can select the air-time metric according to (2) or the shortest path (smallest hop-count). In either case, the BM value needs to be exchanged and updated periodically among neighbors. To accomplish this, we consider using beacon frames, which are primarily used by a node to update its neighbors about its current route to the destination. For example; when a node receives a beacon frame (or an association request) from its neighboring mesh node, it creates (or updates) a neighbor list according to the information in the beacon frame. The period of sending a beacon frame would depend on the traffic model. At a high packet rate, a faster update for calculating (2) may be needed and this would be at the expense of higher overhead. It is important to emphasize that the proposed backpressure scheme relies on the multipath routing described earlier. More specifically, every node should possess an active path to all the gateways (or at least a few neighboring gateways for a large network). When a mesh node (meter) receives a packet from its upper layer (self generated packet) or a neighboring node (relayed packet), it checks its neighbor list and compares the corresponding metrics.

As the parent list is updated by a root announcement process, the neighbors' list is updated and maintained through the beacon frames. In our implementation, for the sake of simplicity, only nodes from the parent list are considered as neighbors for selecting the next hop node. In addition, the second smallest value in (3) will be selected from the same list to represent the next hop node when the next hop link breakage occurs. In order to reduce the overhead in the network we have blocked the route error message. For instance, when a link from node A to node B is broken due to consecutive packet losses, node A will re-schedule all the packets from its data queue by selecting the second best neighbor as its next hop destination. We should point out however, that since in this scheme the main objective is selection of the next hop, rather than the entire multihop path to the destination, there would be no need for on-demand routing. Whereas in the case of the timber-based reserve path diversity scheme presented in section III-A, the objective has been to find an alternative multihop path (s) to one of the gateways as the final destination.

Finally, the routing stability and loop problem, which normally exists in any distributed backpressure system, may occur when the traffic load increases considerably. Nonetheless, in order to guarantee a loop-free transmission we have imposed a hop-count limit by dropping those packets that traverse more than this hops limit.

V. MULTI-CHANNEL AIDED WIRELESS MESH ROUTING

Wireless multihop networks are error-prone; not only due to fading, but also the effect of co-channel interference. To mitigate the interference multichannel protocols have been extensively studied in the past [23]–[25]. Most of these protocols were concerned with the MAC layer aspects of multichannel transmission systems in order to achieve a higher throughput. In this section, however, we are mainly concerned with reducing the effect of co-channel interference in the context of the proposed multiage mesh network architecture. Therefore, we present a simple Multi-Channel (MC) aided tree-based wireless mesh routing protocol scheme. In this scheme we assign different non-overlapping frequency bands to each gateway. Hence, mesh nodes that are communicating with same gateway will operate in the same frequency band as shown in Fig. 6. In addition, a separate channel is assigned for control information, which includes root announcement messages and beacon transmission, as described in the previous section. Under such a condition, the multigate tree formation will be conducted in the same manner as before and according to the network configuration depicted in Fig. 6. Bear in mind that in our multigate routing protocol, every mesh node possesses a separate path to each gateway. Therefore, upon selection of the best path, a node will use the same frequency band as its destination gateway to transmit its data packets. For instance, for a network with N gateways there should be $N + 1$ non-overlapping frequency bands: $B_1, B_2, \ldots. B_{N+1},$ where B_{N+1} is reserved for control data and B_1, B_2, ..B_N are allocated to GW_1, GW_2,..GW_N, respectively (see Fig. 6).

We have further expanded the above multichannel scheme for a backpressure-based packet scheduling approach. Accordingly, the channel assignment will be done on a hop-by-hop basis, depending on the next hop selection. Bear in mind that in our backpressure scheme a neighboring node with the smallest *NHS* (best neighbor) will be selected as the next hop node. If the selected neighbor has the best path to gateway G_j, then its corresponding frequency band will be used for the data transmission to the next hop. With this arrangement, a packet may have to be transmitted under differing frequency bands before reaching its final destination. For example, in the case of the N-gateway network, as soon as a meter finds its best neighbor, it will then check the *BPM* in order to identify its corresponding gateway. If the gateway is GW_j, then its data packet will be transmitted on channel B_j. This hop-by-hop channel assignment will continue until one of the gateways is identified as the best neighbor in the next hop selection process. It should be noted that this is different from the multichannel-aided Best-Path multigate network where the channel assignment for data packets is decided only by the source meter and will remain the same until the destination gateway is reached.

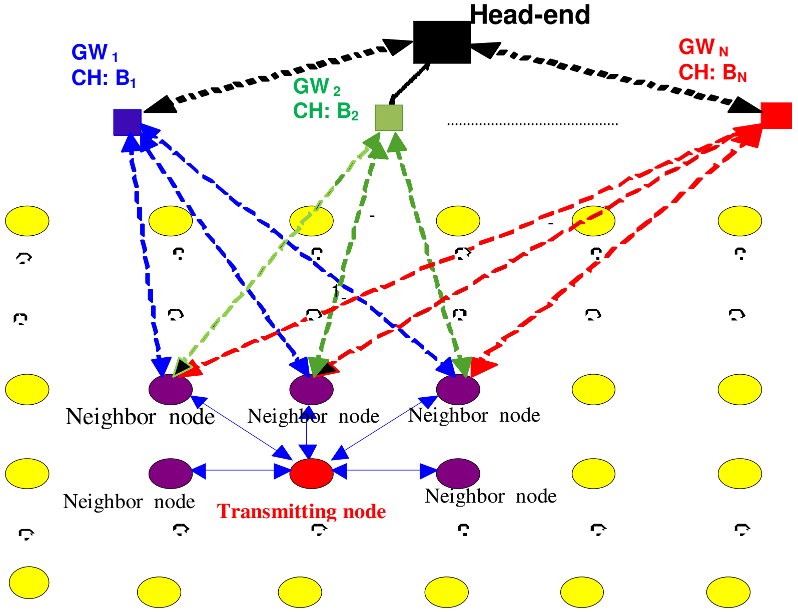


Fig. 6: Multi-Channel Aided Wireless Mesh Routing in a multigate network environment.

VI. Simulation Results

For simulation we first developed a residential network consisting of three wireless mesh sub-networks, according to the scenario shown in Fig. 1. In this scenario each sub-network is handled independently by its local gateway (DAP) before being connected to the master gateway (head-end). The Hybrid Wireless Mesh Protocol (HWMP), which is the default routing protocol for the PIEEE P802.11s [7], has been used as the core routing protocol in our simulation. This protocol is then extended to form our multigate network architecture presented in section III. In this model, the routing is designed in such a way that every node will possess a separate path to each of the gateways. For the on-demand part of the hybrid routing, we have used protocols.

We should emphasize again that, despite the static nature of the mesh network, the on-demand protocol is mainly used to cope with link failures caused by co-channel interference. The proactive part is primarily considered for the formation of the tree (e.g., self organization). In tree-based proactive routing each gateway, as the root of the tree, periodically floods the network by broadcasting a root announcement message. The period in which this message is generated depends on the nature of the application. For instance, in the case of the smart grid it should be sufficiently long to reduce excessive overheads, but short enough to handle changes in the network structure such as adding new meters or handling malfunctioning nodes (e.g., self healing). Subsequently, to enhance the reliability of the network our so-called timer-based reserve-path diversity is implemented to improve the network reliability in the presence of interference.

We have also implemented the packet scheduling aspects of the multigate/multipath network according to the methods described in Section IV. Bear in mind that in our multigate scheme the routing is designed in such a way that every node has a separate path to each of the gateways. We should emphasize that the proposed packet-scheduling scheme due to its distributed nature, does not require utilizing the on-demand routing protocol. Another important aspect of this scheme is its simple extension for providing reserve-path diversity routing in a distributed manner. This diversity routing, unlike our earlier timer-based scheme, does not need to utilize the on-demand routing.

In the simulations the input data generated at a Variable Bit Rate (VBR), is encapsulated into fixed 512 bytes User Datagram Protocol (UDP) packets. In the physical layer the IEEE 802.11b is used and the data-rate is 2 Mbps, while gateways are assumed to have an unlimited bandwidth. The noise factor is 10.0, as recommended for testing the IEEE 802.11b. The path loss factor used in this paper is 2. The retransmission limit is 7. A set of beacon interval values is also investigated to evaluate their impact on the system performance. Three scenarios are considered for 3-DAP networks in this paper. In scenario A, as shown in Fig. 7 the network consists of three sub-networks where nodes in each are handled by their local DAP (or *GW* as shown in Fig. 1). In this scenario there are 12 meters (nodes) in each sub-network and meters (nodes) are uniformly distributed within their coverage area.

In scenario B, a multi-gateway network is constructed that comprises three DAPs (*GW*s) and *36* meters (see Fig. 8). Each DAP, as the root of the tree, broadcasts its root announcements periodically by floating the entire network. The generation of the root announcement message by each DAP has been randomized to prevent collisions. In addition, a hop-count limit of 10 has been imposed on forming a tree. This number is selected to reduce the number of paths to the far away DAPs, but at the same time making sure that every node in the network has access to at least two neighboring DAPs (via a separate path). The MAC address of the DAP is employed as the unique identification of the corresponding routing trees.

In order to assess the traffic load balancing performance of our packet scheduling technique, we also modified the structure of the network in scenario B, where nodes are asymmetrically distributed. This network is shown in Fig. 9 and will be referred to as scenario C.

Based on the above scenarios, we then evaluated the network performance in terms of overall throughput versus the input bit-rate per second per node. In these experiments all the nodes in the network generate data packets at VBR. Fig. 10 shows the results of the 3-subnetworks according to scenario A (see Fig 7), multigate best-path scheme for Scenario B, which also includes the timer-based reserve-path scheme, and the backpressure scheme. Note that in the best-path scheme, the source node will select a DAP with the best route in order to send its data packets. The airtime link metric (see Appendix A) is used to select the best route. In the on-demand timer-based Reserved-Path scheme meters will select the first best path to send a data packet, while keeping keep a copy of the data packet in its backup HWMP buffer. As soon as a link breakage notification is received for this path, the source node will send the packet through the second route, while it updates its tree table to the first root (DAP). Bear in mind that in both methods on-demand routing is used when a node experiences a link failure. In the proactive-based backpressure scheme meters will forward data packets to one of its neighbors, based on the backpressure metric updated by beacon frames (see Section IV). From Fig. 10 we can observe a notable improvement in performance of the best-path approach compared with the 3-subnetworks in scenario A. This is mainly because in scenario B, the border nodes will have an option to select the better path to one of the neighboring DAPs. In addition, while the reserve-path scheme performs better than the best-Path scheme, neither is as good as the backpressure scheme, which shows a superior performance by a wide margin. This clearly indicates that a combination of multigate and backpressure schemes can work very well together in achieving a higher performance.

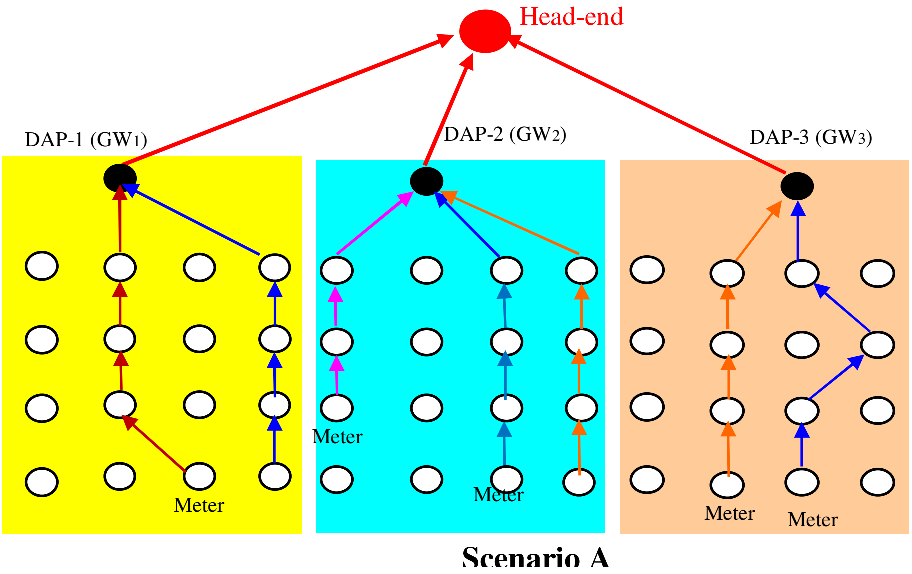


Fig. 7: A residential network consisting of three sub-networks each consisting of 12 nodes that are connected to the head-end via their local DAP.

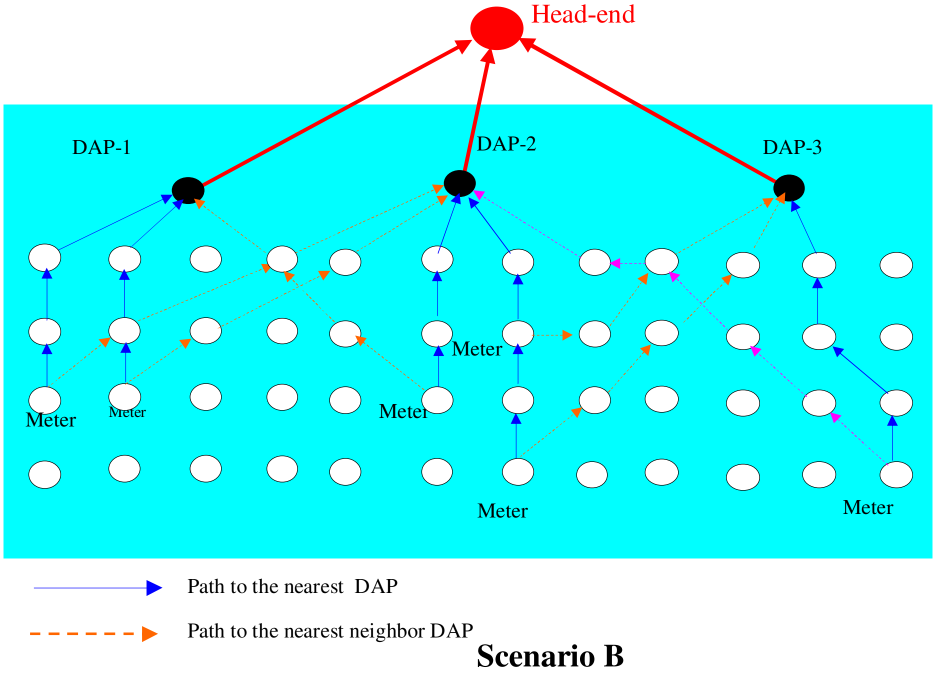
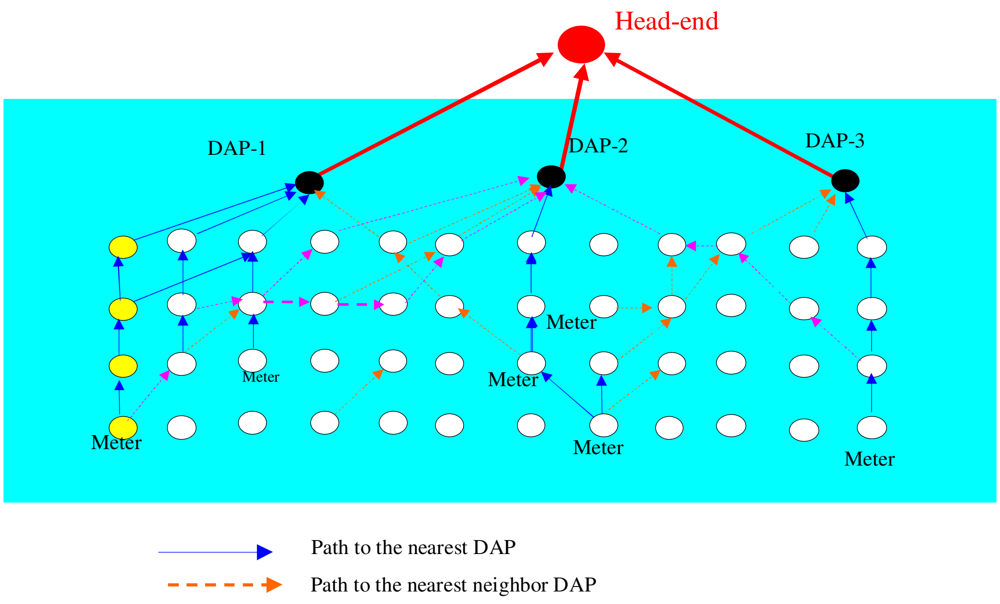


Fig. 8: A Multi gateway (GW) network scenario consisting of 3-DAP and 36 meters where every meter can have separate paths to at lease two of the neighboring DAPs.



Scenario C

Fig. 9: A Multi gateway (*GW*) with 36 asymmetrically districted nodes

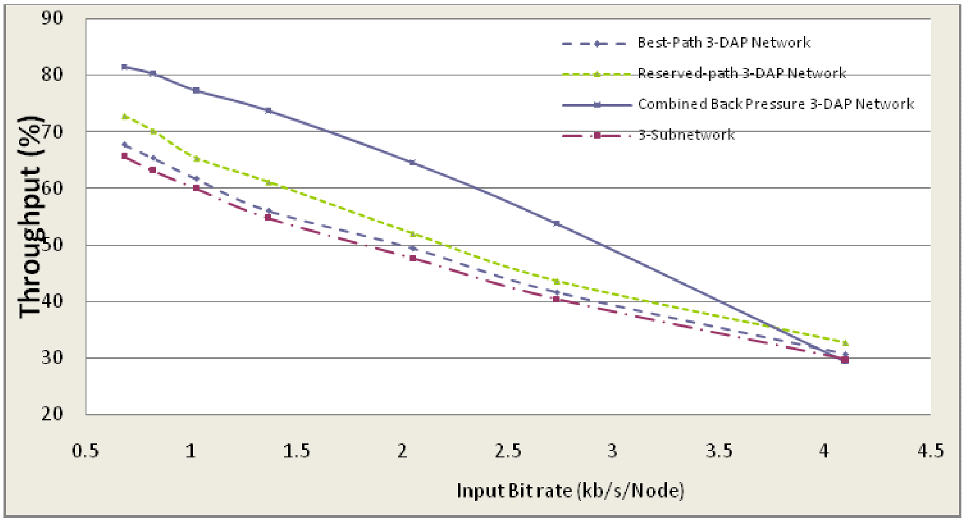


Fig. 10: Performance evaluations of the 3-Subnetwork of scnario A, best-Path, Reserved-Path scheme, and BackPressure schemes in scnario B.

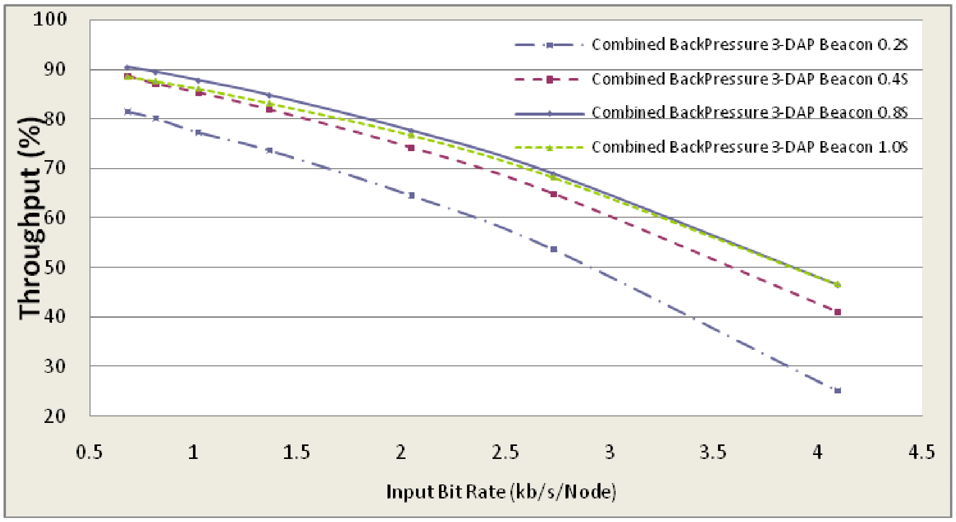


Fig. 11: BackPressure scheme using a set of beacon interval values is investigated in Scenario B.

In Fig. 11 a set of beacon interval values for updating the backpressure metric are investigated, in order to evaluate the impact of this parameter on the systems performance. The beacon interval of 0.8s was found to achieve the best results under scenario B test conditions for updating the backpressure. Bear in mind that the higher beacon interval value means less overhead over the network and hence results in less interference. Based on our experiments we noted that when the beacon interval value is too high, the neighbor list and the corresponding backpressure metric cannot be updated in a timely manner, resulting in the worse performance. With respect to the period in which a root announcement message is generated, due to the static nature of the network, it should be selected in such a way that it can take care of changes in the network in a timely manner. This includes adding new meters (nodes) or handling the malfunction node as will be discussed later.

In order to justify the throughput efficiency of the backpressure scheme, traffic load distribution amongst the three gateways for scenario B in the absence and presence of the backpressure scheme are shown in Figs. 12 and 13, receptively. These results indicate that by directing the traffic towards gateways with less traffic the backpressure scheme is capable of effectively balancing the traffic load between the gateways. Consequently, this enhances the throughput performance at the master gateway (head-end) as shown in Fig. 13. Furthermore, we compare the performance of the backpressure scheme in scenarios B and C, while in scenario C a higher number of meters (more traffic) are located in the vicinity of DAP-1 (see Fig 9). In this figure we also included the results of 3-sub-netwroks under asymmetrical node distribution. The results in Fig. 14 further confirm that the backpressure performance remains unaffected by asymmetrically distributed nodes, whereas in the case of 3 sub-network the throughput performance could suffer.

In Fig. 15, the average end-to-end delay performance of the single-path scheme and the backpressure scheme is investigated based on Scenario B and with the beacon interval of 0.2 seconds. Under these conditions, the backpressure scheme shows a significant improvement in delay performance compared with the single best-path scheme (i.e., without using a backpressure scheme). Bear in mind that the backpressure scheme reduces congestion and thus, result in lesser retransmissions. While in the absence of the backpressure packet-scheduling scheme, an excessive number of retransmissions, due to higher traffic congestions, (has) impacted the delay performance.

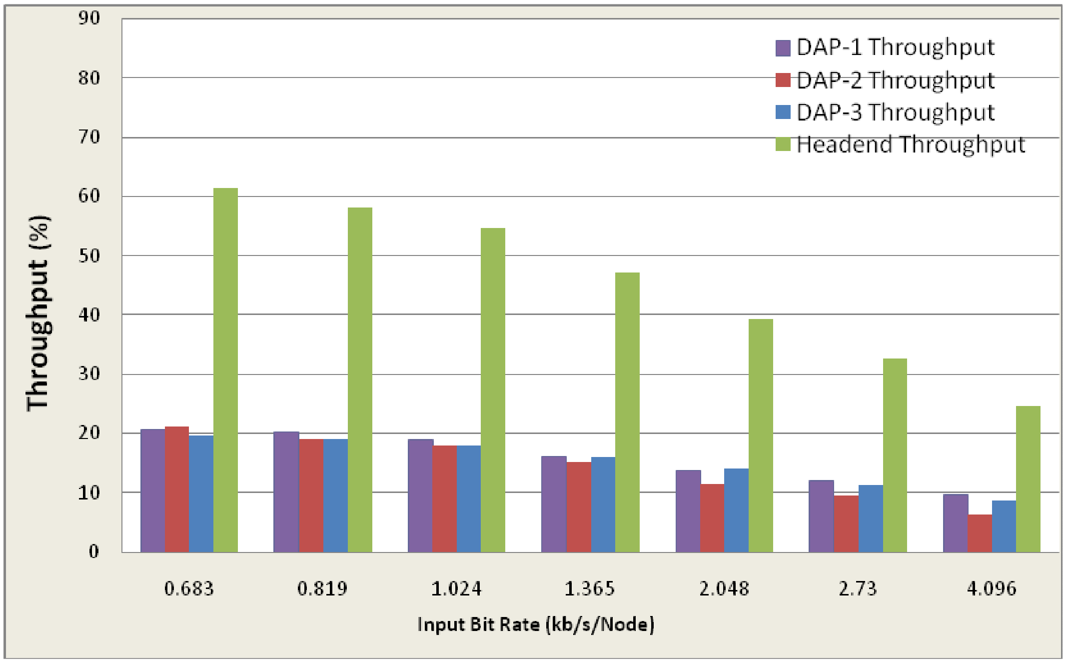


Fig. 12: The throughput performance of the Best-Path scheme in Scenario B with three DAPs , 36 flows and the beacon interval of 0.2 second.

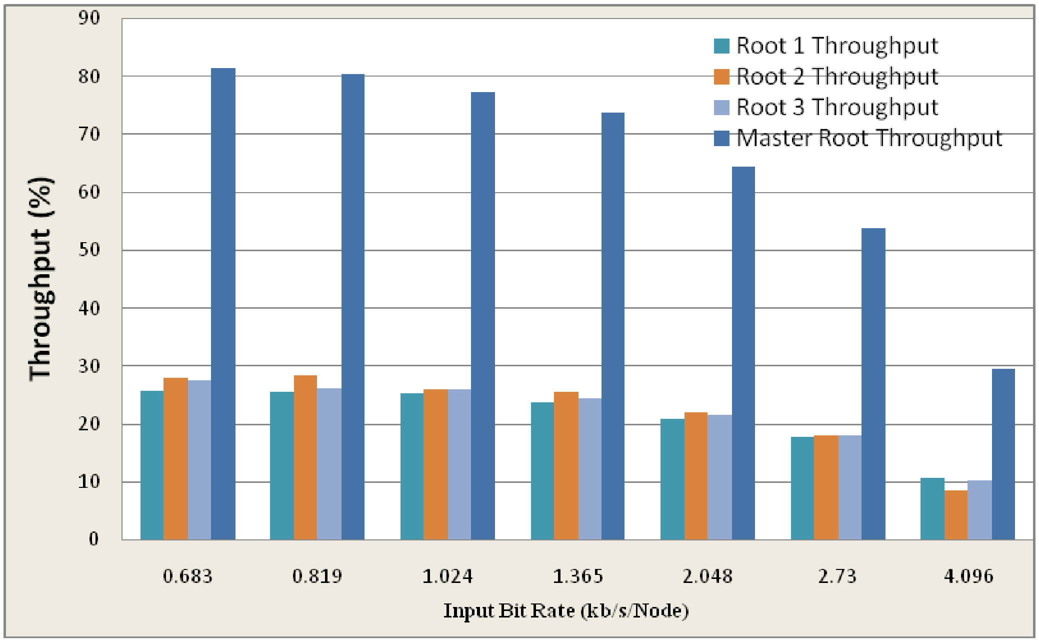


Fig. 13: The throughput performance of the BackPressure scheme in Scenario B with three DAPs, 36 flows, and the beacon interval is 0.2 second.

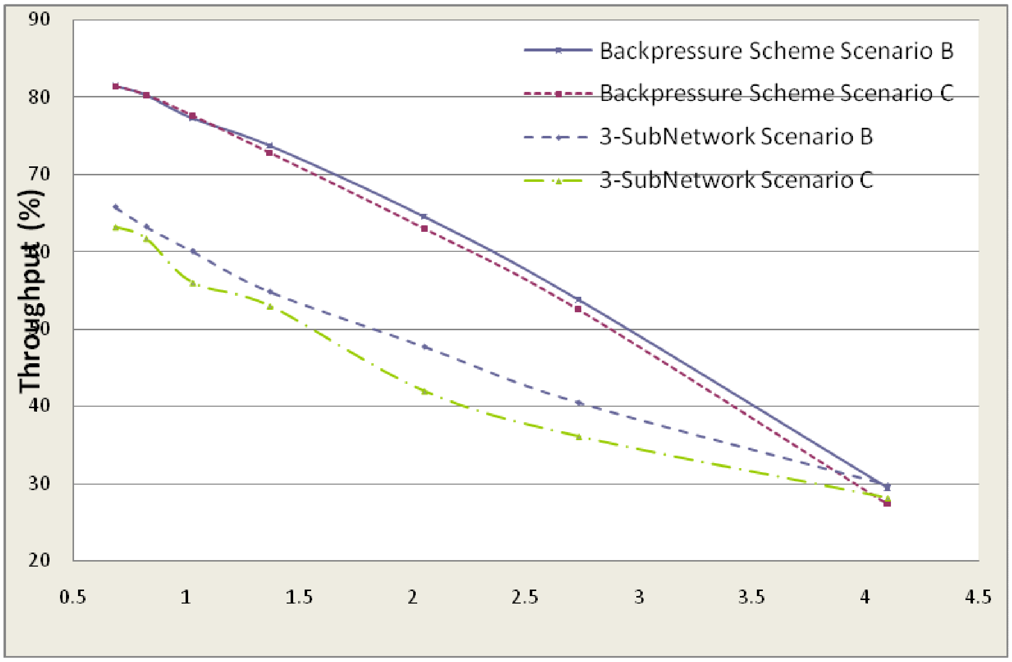


Fig. 14: The throughput of the BackPressure scheme in Scenario B and Scenario C with 36 asymmetrically distributed meters.

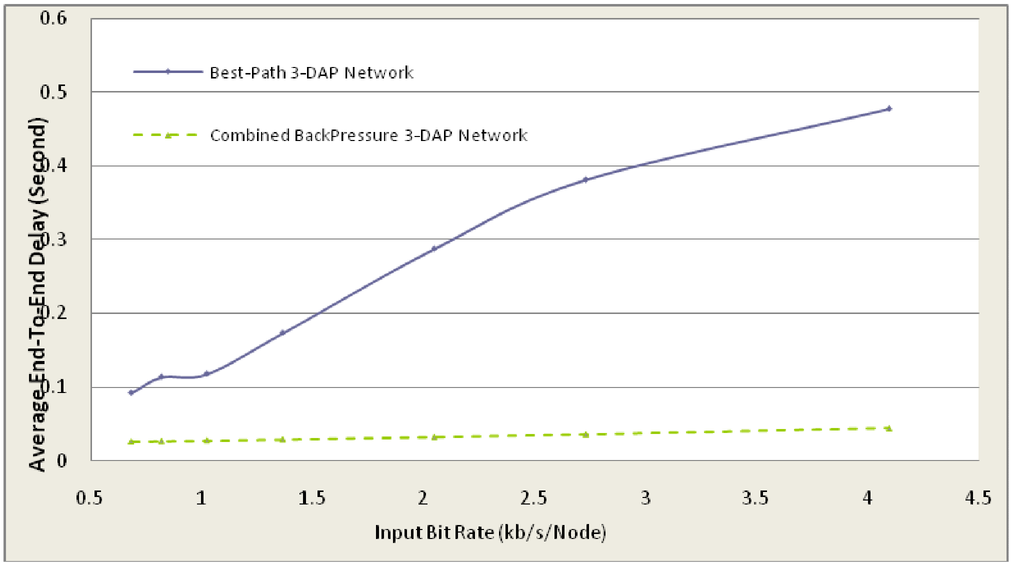


Fig. 15: The delay performance of Best-Path scheme and Backpressure scheme are investigated in Scenario B.

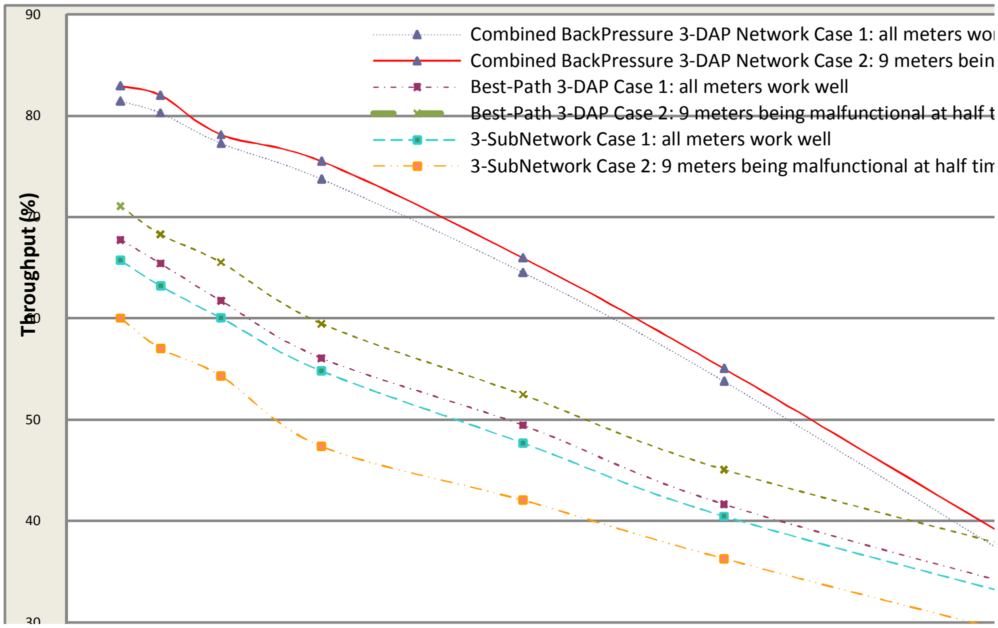


Fig. 16: Self-healing performances of in scenario B and scenario A where 9 meter nodes begins stop functioning.

In Fig. 16, we evaluate the self-healing aspect of the network in situations where some nodes (meters) or gateways malfunction. Fig. 16 shows the throughput performance of scenario A, as well as scenario B with best-path (airtime-link-based) and the backpressure scheme under the following cases: Case 1 when all the meters work properly, Case 2 when 9 meters (3 meters in each region with more than two hops away from each DAP) stop functioning as soon as the simulation time reaches the half way point.

From this figure it can be clearly observed that the flexibility of the backpressure scheme combined with the multipath feature of the multigate network structure can effectively allow packets to be re-routed by bypassing the malfunction nodes.

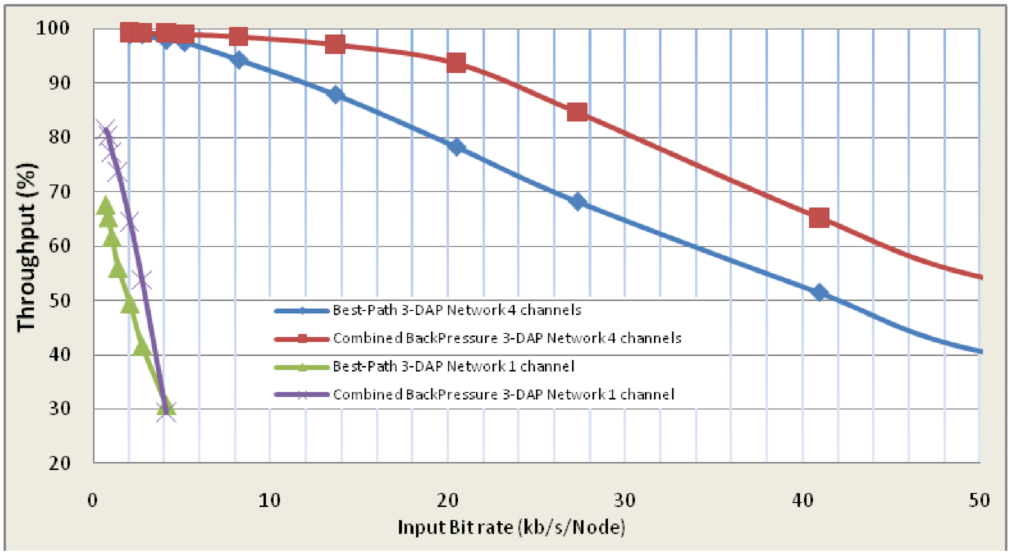


Fig. 17: Throughput performances of the Multichannel-aided Best-Path and Back-Pressure 3-DAP Network schemes, compared with the single channel Best-Path and Back-Pressure 3-DAP Network schemes.

In Fig. 17, the Multichannel-aided Best-Path and Back-Pressure schemes are investigated and compared with single channel Best-Path and Back-Pressure schemes. As described earlier, in the Multichannel-aided 3-DAP networks, four channels are employed. One channel is for control signals and the remaining three channels for data packets. In the Multichannel-aided Best-Path 3-DAP network, when a source meter finds the best path to transmit a data packet to one of the gateways (DAP), it will then use the same frequency band to transmit its data packets. For example, if a source meter has the best path to DAP-1, it will assign channel-1 to the data packet and this data packet will then be transmitted and received on channel-1 by the source meter and all the intermediate meters.

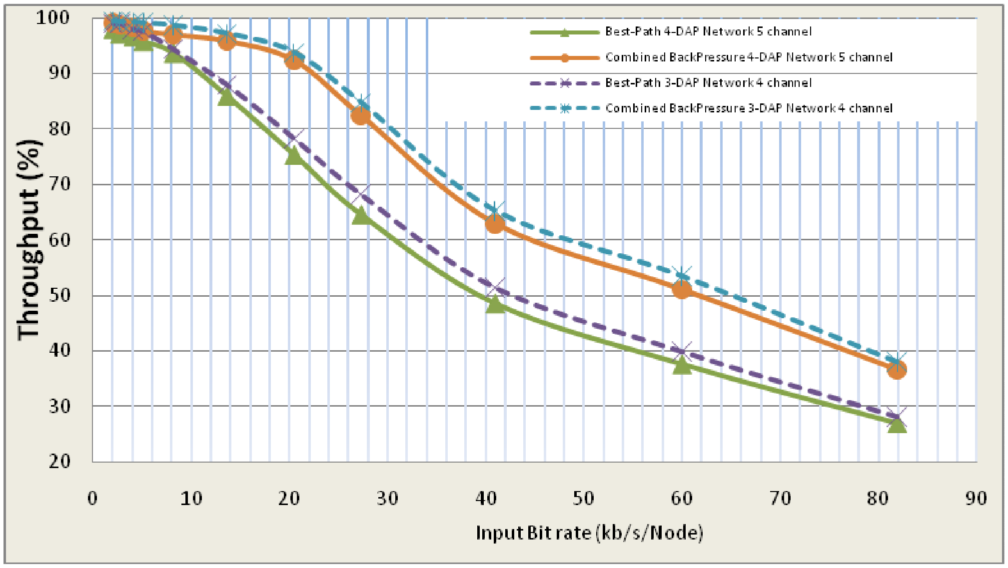


Fig. 18(a): Throughput of the Multichannel-aided Best-Path and Back-Pressure 4-DAP Network schemes, compared with the 3-DAP Network schemes.

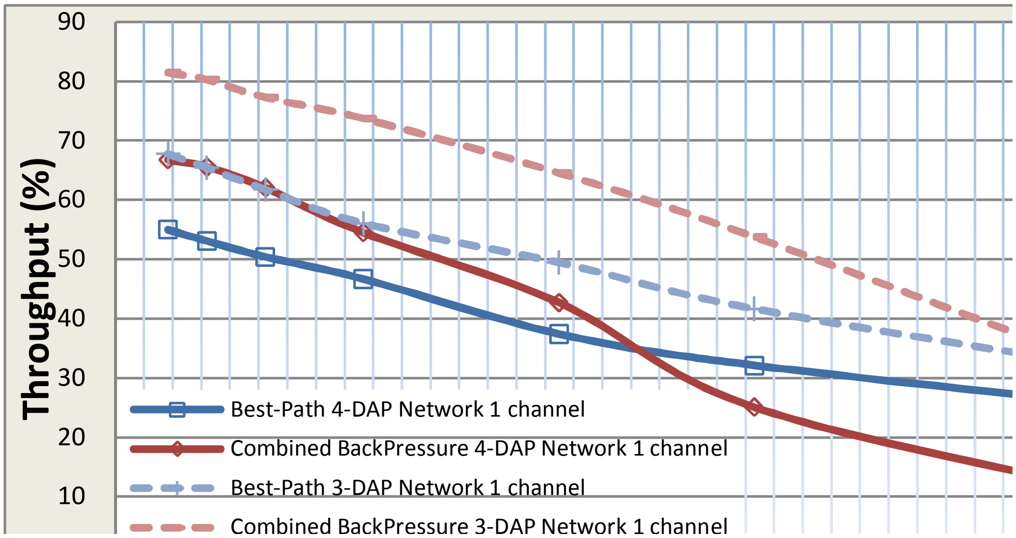


Fig. 18(b): Throughput of the single channel Best-Path and Back-Pressure 4-DAP Network schemes, compared with the 3-DAP Network schemes.

As opposed to the Multichannel-aided Best-Path 3-DAP network, the Multichannel-aided Back-Pressure scheme assigns channels to data packets according to the Best Path Metric (*BPM*) value of the best neighbor, which has the smallest next-hop selection metric (*NHS*). For example, when a meter finds the best neighbor, it checks the *BPM* of this best neighbor. If this *BPM* is related to DAP-1, then its data packet will be transmitted on channel-1. As mentioned in Section-IV, the best neighbor selection process includes a path to the best gateway from the selected neighbor's point of view and may change when this neighbor begins its own next hop selection process. This will continue until one of the gateways is identified as the best neighbor in the next hop selection process. Therefore, a data packet may be assigned to different channels on its way to one of the DAPs. This is different from the multichannel-aided Best-Path 3-DAP network, where the channel assigned to a data packet is decided only by the source meter and remains unchanged.

Fig. 17 demonstrates the significant improvement of Multichannel-aided schemes over Single-channel schemes. The advantage of the Back-Pressure scheme over the Best-Path scheme is also improved considerably with the help of the multichannel technique. Our observation shows that in the Multichannel aided Back-Pressure scheme, the possibility of transmitting signals simultaneously using different channels in a small area is much higher than in the Multichannel aided Best-Path approach.

In Figs. 18, 19 and 20, the proposed best-path and back-pressure schemes are investigated in a 4-DAP network. Their performances are compared with 3-DAP Network schemes. It can be seen from Fig. 18(a) that the 5-channel-aided 4-DAP network schemes achieve a very close performance to the 4-channel-aided 3-DAP network schemes, due to the significantly reduced interference by the employed multichannel technique. Again, the Back-Pressure schemes outperform the Best-Path schemes more than 15 percent when input bit rate is in the area of {20kb/s/Node ~ 60kb/s/Node}. In contrast, when a multichannel technique is not employed, there is a notable gap between the 4-DAP network schemes and the 3-DAP network schemes, as shown in Fig. 18(b). Obviously, there is more interference in 4-DAP networks. Meanwhile, the advantage of the Back-Pressure scheme over the Best-Path scheme is reduced when a single channel is used. In Figs. 19 and 20, traffic load distribution amongst the four gateways is investigated in the single channel Best-Path and Back-Pressure 4-DAPs networks. These results illustrate that the backpressure scheme is capable of effectively balancing the traffic load between the gateways and hence improves the throughput performance at the master gateway (head-end) as shown in Fig. 20.

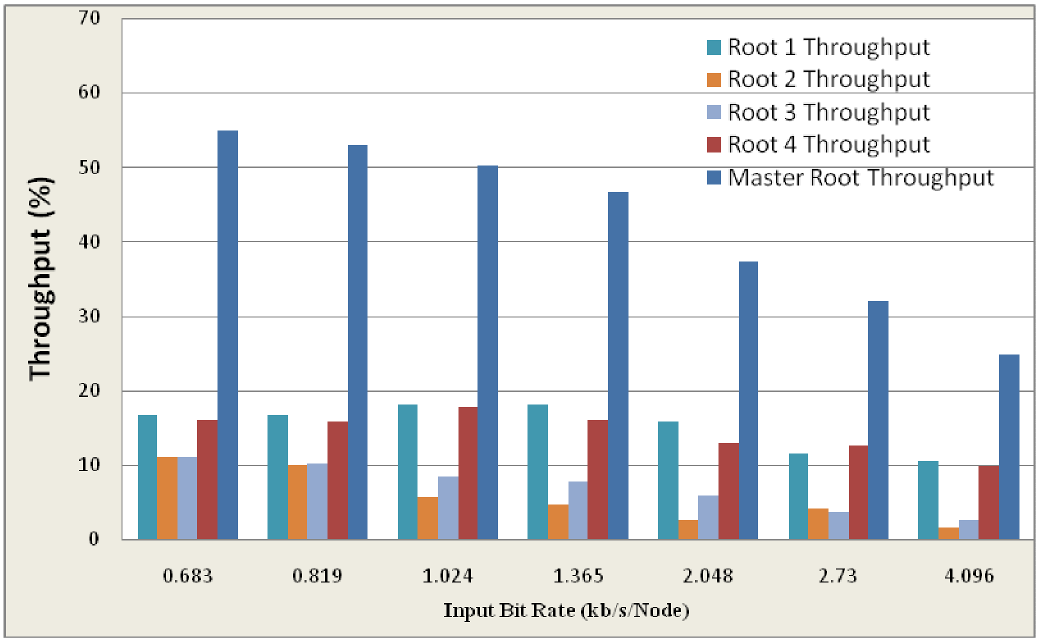


Fig. 19: The throughput performance of the Best-Path 4-DAPs Network scheme, where the beacon interval is 0.2 second, pathloss factor is 2.

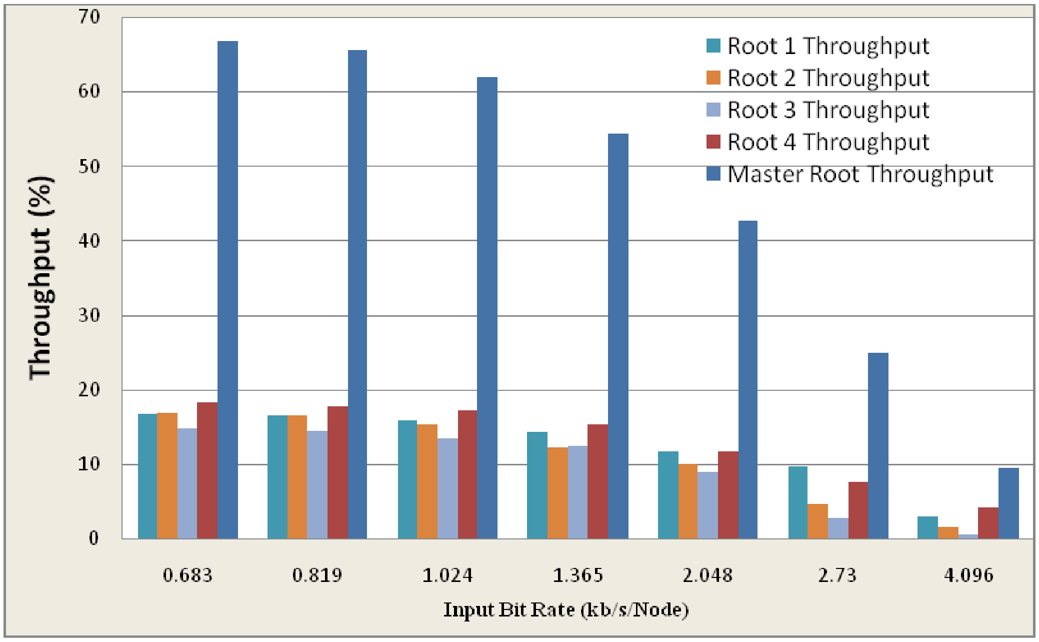


Fig. 20: The throughput performance of the Back-Pressure 4-DAPs Network scheme, where the beacon interval is 0.2 second, pathloss factor is 2.

VII. CONCLUSION

One of the most important challenges in smart grid is providing reliable last mile network communication. In this paper we propose a combination of the multigate network architecture and the simple packet scheduling scheme aimed at providing a reliable two-way communication from meters to the AMI head-end. In this multigate network structure we consider a tree-based routing scheme that is capable of providing every node with a separate path to each of the gateways. In addition, this multigate/multipath routing scheme is further exploited to provide a timber-based reserve-path diversity routing. The performance of this network is then compared with a regional mesh network system where nodes in each region can only access their local gateway. We have shown that multigate routing can indeed enhance the reliability of the network. Finally, in order to take full advantage of the multigate/multipath routing, we develop a simple packet scheduling technique to reduce network congestions. The packet scheduling technique is based on the backpressure concept and has been shown to be very effective in balancing the traffic load amongst the gateways (DAPs), hence enhancing the network throughput performance. This scheme has been further expanded to include multichannel aided routing in a distributed manner. We have shown that a combination of multiage routing, packet scheduling and multichannel routing can indeed provide a significant gain in network performance in terms of delay and throughput. In addition, we have shown the scheme can enhance the self-healing ability of the network, such as handling the effect of malfunction nodes.

Appendix A

The *airtime link metric* as defined in 802.11s is a measure of the channel resources consumed for transmitting a packet over multihop routes. It is based on the *airtime cost* C_a of a link,

$$c_a = \left[O + \frac{B_t}{r}\right]\frac{1}{1-e_f}, \quad (1)$$

where O is the channel access overhead, Bt is the number of bits in a test frame transmitted at the bitrate of r Mbit/s by a mesh node, and e_f is the frame error rate for transmitting a frame of the size B_t over erroneous channels. Note that the path metric is the sum of the metrics of all links on the multihop path.

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