Greedy Backpressure Routing for Smart Grid Sensor Networks

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Abstract—In this paper, a greedy backpressure routing protocol is proposed for multigate mesh networks. This protocol evaluates the greedy backpressure metric (GBM) value of mesh points and routes packets in the direction of the steepest gradient. The GBM value is calculated using a combination of traffic load and the mesh point's hop count to the closest gateway. The proposed routing algorithm can realize the effect of traffic load from all the nodes along the path to each gateway by iteratively updating information from neighbors through periodic beacon exchange. The consideration of incorporating traffic load helps to route packets around congested area. The results indicate that the greedy backpressure multigate mesh routing is capable of achieving significant improvement in the network reliability, latency, and throughput performance.

Keywords-Smart Grid, wireless mesh networks, routing protocols, greedy backpressure, WLAN, IEEE 802.11s

I. INTRODUCTION

The availability of new technologies such as distributed sensors that provide two-way, secure communications, can play a major role in future energy systems. They can provide cost-effective communications for deployment in various smart grid domains, such as home area networks (HAN), neighborhood area networks (NAN) [1-2], as well as in Substation/Plant-generation local area networks for real-time monitoring and control. They offer various unique features such as "self-configuration", where the network automatically incorporates a new node into the existing structure, and "self-healing", where the network is capable of finding the fastest and most reliable paths to send data. For the last mile coverage for instance, wireless NAN techniques such as the IEEE 802.11 family standards can be considered to provide communication from meters to the AMI (Advanced Metering Infrastructure) Head-end in order to access to the backhaul network.

To support a large coverage area and prevent the formation of a long hall commutation, multihop mesh networking can be considered as a viable approach for smart-grid last mile communication [3]. In a typical neighborhood area network communications between meters and an AMI Head-end can be achieved through multiple gateways (also, referred to as the Data Aggregator Points: DAPs) [3] located on neighborhood distribution poles. An important factor in managing meter traffic in such a network is that in the upstream link, nodes closer to their gateway point may have to forward not only their own packets, but also the aggregated traffic from further away meters. In other words, meters that are closer to their local DAP are more likely to create a bottleneck. In addition, date generated from far way meters may suffer longer delay as they have to hop over more meters before reaching their final destination (i.e., Head-end). Nonetheless, due to the variable nature of the traffic, some mesh access points may suffer from more congestions than other. In order to balance the traffic load amongst the DAPs, [3] proposes a simple backpressure-based packet scheduling algorithm, which is based on the multigate mesh network architecture that buses tree-based routing (TBR) protocols [4-6]. In the packet scheduling scheme in [3], the main objective is to select the next hop rather than the entire multihop path to the destination using the neighbor's queue length to calculate the backpressure metric. This simple approach is shown to be very effective in improving the throughput performance as well as reducing delay. Nonetheless, at the expense of more computational complexity, it may be possible to further enhance the network performance if the queue length of mesh nodes (meters) that are more than one hop away can be taken into consideration.

Therefore, in this paper we present a so-called greedy backpressure routing protocol which takes into consideration the traffic load of further away nodes in calculating the backpressure metric. In [7-8] potential-based routing is proposed, where the next hop neighbor is selected based on the higher potential value. However, the proposed potential-based routing is either only for single destination or not taking the traffic load into account. In our proposed multigate mesh routing approach, the GBM value of mesh nodes is evaluated in order to route the packets toward gateways in the direction of the steepest gradient. It uses a combination of traffic load and the mesh node's hop-count to the nearest gateway. In this algorithm by iteratively updating information from neighbors through periodic beacon exchanges, nodes can feel the effect of high traffic from further away nodes. Consequently, this helps avoiding packets to be routed through congested areas and hence balances traffic load amongst the multiple gateways.

The paper is organized as follows: In Section II, after a description of the multigate mesh network architecture, we present the routing protocol and the supporting analysis. The performance of the greedy backpressure routing protocol is provided in section III followed by the conclusion in section IV.

II. Greedy Backpressure-Based Multigate Mesh Routing

When considering wireless mesh networks, the primary challenge is to provide reliable metering services. Some user 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. In [3], by taking advantage of the multigate routing scheme, a simple backpressure-based packet-scheduling scheme, capable of blanching the traffic load amongst all the local access gateways, was developed. This scheme uses only the neighbors' queue size to calculate the backpressure metric. However, at the expense of some added computational complexities, in this paper we further extended this approach by using neighbors' GBM values to direct packets towards less congested gateways.

In the proposed scheme GBM values of mesh points are evaluated first before routing packets in the direction of the steepest gradient. Note that similar to field diffusion in physics where an element (e.g., a test charge in an electrical field) will diffuse in the direction of the steepest gradient of the potential field [7], the greedy backpressure routing mechanism forwards packets to the neighbor with the highest GBM value, which takes into consideration the traffic load of further away nodes. In this routing protocol, the GBM value is calculated using a combination of traffic load and the mesh point's hop count to the closest gateway. Specifically designed for the multigate mesh network, our approach aims at balancing the traffic load amongst all gateways in order to maximize the overall throughput.

Here, a GBM field is defined on the multigate mesh network over which packets are routed towards the steepest gradient of the field. Mesh points decide the steepest gradient by comparing the GBM value P of its neighbors. Mesh points' GBM value P is composed of two components, namely the distance-based GBM and the traffic-based GBM. The distance GBM of node i is defined as:

$$\Psi_i = -\frac{1}{H_{min}^i}, \qquad (1)$$

where H_{min}^i is node i's hop count to its closest mesh gateway. With this definition, the distance GBM field's shape formatted resembles a landscape as shown in Fig. 1, where the poles in the field denote the location of the gateways (Gateways' hop count to their closest gateway is zero hops). In this paper, hop count is used to calculate the distance between nodes. However, air-time link quality can also be employed to calculate the distance, since the distance GBM function using any of them keeps strictly decreasing.

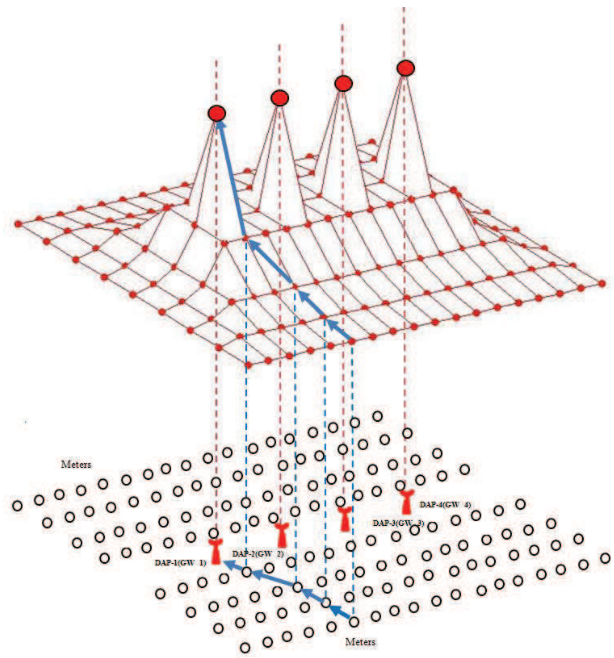

Fig. 1: The distance GBM field of a multigate mesh network, where the poles correspond to the gateways (DAPs).

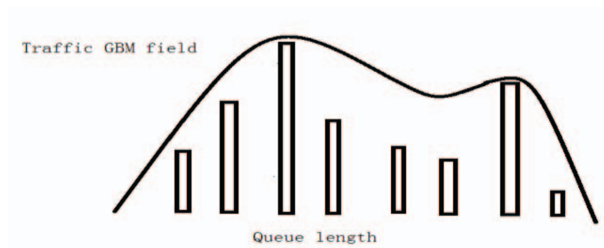

Fig. 2: The traffic GBM field, where the poles correspond to mesh nodes' queue length.

THEOREM 1. *When only considering the distance GBM, the routing algorithm for the static multigate mesh network is loop free.*

Proof*:* By using the distance GBM Ψ defined in equation (1), nodes can always find a neighbor with lower distance GBM value (The neighbor j, which is the next hop in the node i's path to the closest gateway, obviously has a lower distance GBM value $\Psi_j = -\frac{1}{H^i_{min}-1}$). Therefore, packets are always forwarded to the neighbor with lower distance GBM value and will not be looped back.

Before describing the greedy backpressure routing, we first introduce some notations as follows. Let q_{ij} denotes the length of the queue to node j in node i. $Z(i)$ represents the number of node i's neighbors while Z_{max} is the maximum value of $Z(i)$ in the whole network. Similar to the traffic potentials introduced in [9], the traffic GBM Φ_{ij} on link $(i \longrightarrow j)$ in this paper can be defined as:

$$\Phi_{ij} = max\left(\frac{1}{Z_{max}}\sum_{w\in nbr(j)}\Phi_{jw},\ q_{ij}\right), \qquad (2)$$

where $nbr(j)$ denotes the set of node j's neighbors. The traffic GBM field is depicted in Fig. 2, where the queues on the links can be thought of as poles that hold up the field. If the queue size q_{ij} on the link $(i \longrightarrow j)$ is large enough, it will prop up the field surface and the traffic GBM $\Phi_{ij} = q_{ij}$. Otherwise it does not touch the field surface and the traffic GBM $\Phi_{ij} = \frac{1}{Z_{max}}\sum_{w\in nbr(j)}\Phi_{jw}$, which is the field surface set up by other long queues. Node i collects the traffic GBM value of Φ_{jw} $(j \in nbr(i), w \in nbr(j))$ from its neighbors by exchanging the periodically broadcast beacon frame. In this way, the effect of long queues will be spread out to nodes that are further than one hop away. In other words, nodes can feel the effect of long queues hops away. Then we can define the traffic GBM Φ_i at a node i as:

$$\Phi_i = max\left(\frac{1}{Z(i)}\sum_{w\in nbr(i)}\Phi_{iw},\ \frac{\Phi_{max}+\Phi_{min}}{2}\right), \qquad (3)$$

where Φ_{max} is the maximum traffic GBM on an outgoing link of node i while Φ_{min} is the minimum. With this definition, the traffic GBM at node i is the maximum of two quantities—the average of the GBMs on node i's outgoing links, and an average of the maximum and minimum GBMs on its outgoing links.

Since the GBM field of the considered multigate mesh network is the superposition of the distance GBM field and the traffic GBM field, the GBM value at node i can be expressed as

$$P_i = (1-\alpha)\left(-\frac{1}{H^i_{min}}\right) + \alpha\Phi_i, \qquad (4)$$

and the GBM value on the link $(i \longrightarrow j)$ is given by

$$P_{ij} = (1-\alpha)\left(-\frac{1}{H^j_{min}}\right) + \alpha\Phi_{ij}, \qquad (5)$$

where α $(0 < \alpha < 1)$ is used to set the relative weights of the traffic GBM and the distance GBM. Then the "tendency" on packets at node i towards a neighbor $j \in nbr(i)$ can be expressed as

$$F_{i\to j} = (1-\alpha)\left(\frac{1}{H^j_{min}} - \frac{1}{H^i_{min}}\right) + \alpha\big(\Phi_i - \Phi_{ij}\big). \quad (6)$$

By comparing all the "tendencies" to its neighbors, node i will forward packets towards the neighbor with which the total tendency is maximum and positive. If the traffic patterns of the static multigate mesh network are stationary, then the GBM function P of equation (4) is time invariant. According to Theorem 1, the greedy backpressure routing algorithm is loop free when the traffic patterns are stationary.

THEOREM 2. *Except the gateways, there is no local minima in the network. In other words, any node in the network can always find a neighbor with which the tendency defined in equation (6) is positive.*

Proof: According to equation (6), when node i forwards packets to its neighbor j which is the next hop in the node i's path to the closest gateway, the tendency is

$$F_{i\to j} = \frac{(1-\alpha)}{H^i_{min}(H^i_{min}-1)} + \alpha\big(\Phi_i - \Phi_{ij}\big). \quad (7)$$

If this tendency is positive, node i is not a local minima. If not, we have

$$\frac{(1-\alpha)}{H^i_{min}(H^i_{min}-1)} < \alpha\big(\Phi_{ij} - \Phi_i\big). \quad (8)$$

Now consider the neighbor w such that $\Phi_{iw} = \Phi_{min}$, then the tendency $F_{i\to w}$ can be expressed as

$$F_{i\to w} = (1-\alpha)\left(\frac{1}{H^w_{min}} - \frac{1}{H^i_{min}}\right) + \alpha(\Phi_i - \Phi_{min}). \quad (9)$$

Since $\frac{1}{H^w_{min}} - \frac{1}{H^i_{min}} \geq \frac{-1}{H^i_{min}\left(H^i_{min}+1\right)} > \frac{-1}{H^i_{min}\left(H^i_{min}-1\right)}$ for adjacent nodes (i, w), we have

$$F_{i\to w} > \frac{-(1-\alpha)}{H^i_{min}\left(H^i_{min}-1\right)} + \alpha(\Phi_i - \Phi_{min}). \quad (10)$$

Using equation (8) and the definition of Φ_i, we can get

$$\begin{aligned} F_{i\to w} &> \alpha\Big((\Phi_i - \Phi_{min}) - \big(\Phi_{ij} - \Phi_i\big)\Big) \\ &\geq \alpha\Big((\Phi_{max} + \Phi_{min}) - \big(\Phi_{ij} + \Phi_{min}\big)\Big) \\ &\geq \alpha(\Phi_{max} - \Phi_{ij}) \geq 0. \quad (11) \end{aligned}$$

Therefore, node i is not a local minima, which proves the theorem. Since there are no local minima in the network, there will be no sink at intermediate nodes. All data will be forwarded to one of the gateways as expected.

As previously mentioned, the effect of a long queue on the traffic GBM is spread out over the neighbors as shown in Fig. 2. It can be concluded from equations (2) and (3) that a long queue will affect the traffic field surface, even at nodes hops away. This implies that nodes can feel the effect of high traffic hops away by iteratively updating information from neighbors through periodic beacon exchange. This helps to avoid congested area hops away and drains large queues in congested areas in a shorter period, resulting in balanced traffic load amongst the multiple gateways. Based on the observation that the size of long queues changes at a slow rate with respect to the large size of the queues, and the traffic field surface is almost decided by long queues, it is reasonable to conclude that the greedy backpressure routing algorithm is loop free and stable. This is demonstrated in our simulations.

III. SIMULATION RESULTS

For simulation we first developed a multigate mesh network consisting of three gateways (DAPs). The Hybrid

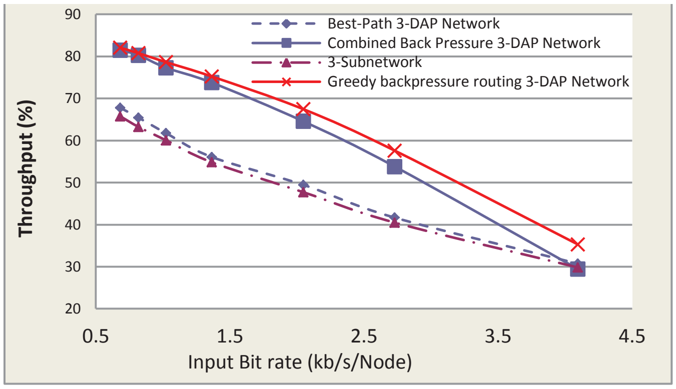

Fig. 3: Performance evaluations of the 3-Subnetwork of scenario A, greedy backpressure, backpressure and best-Path schemes in scenario B.

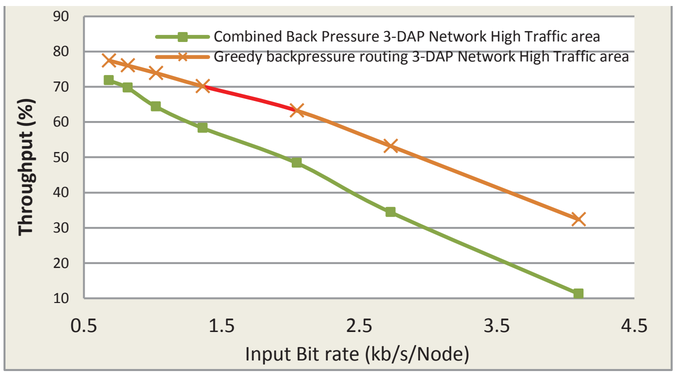

Fig. 4: Performance evaluations of the greedy backpressure and backpressure schemes in presence of the high traffic.

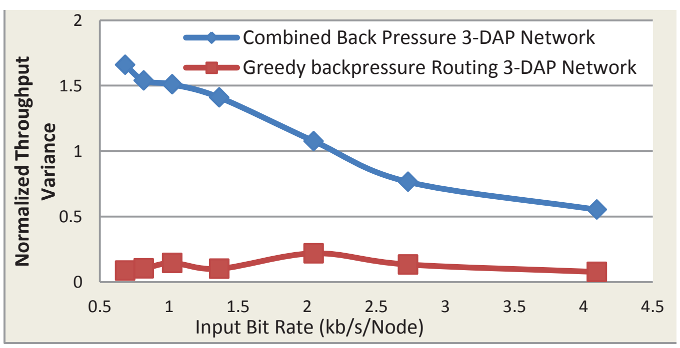

Fig. 5: The normalized throughput variance of three DAPs for the greedy backpressure and BackPressure schemes in Scenario C.

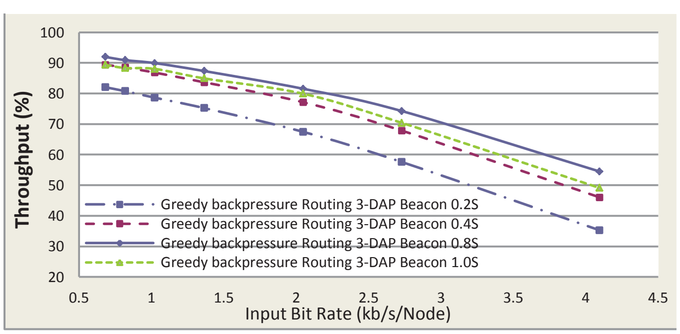

Fig. 6: Greedy backpressure routing scheme using a set of beacon interval values is investigated in Scenario B.

Wireless Mesh Protocol (HWMP), which is the default routing protocol for the PIEEE P802.11s [10], has been used as the core routing protocol and is extended to form our multigate network architecture presented in section II. In this model, the routing is designed in such a way that every node will possess a separate path to each of the gateways. 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 greedy backpressure routing protocol is then investigated in this 3-DAP mesh network. Similar to the backpressure-based packet-scheduling scheme in [3], the proposed greedy backpressure routing protocol does not require utilizing the on-demand routing protocol, due to its distributed nature.

In the simulations the input data generated at a Variable Bit Rate (VBR), is encapsulated into fixed 512 bytes 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 retransmission limit is 7. Three scenarios are considered in this paper. In scenario A, the network consists of three sub-networks where nodes in each are handled by their local DAP. 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 (GWs) and 36 symmetrically distributed meters. 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 routing schemes, we also modified the structure of the network in scenario B to scenario C, where 36 nodes are asymmetrically distributed.

Based on the above scenarios, we then evaluated the network performance in terms of overall throughput versus the input bit-rate per node. In these experiments all the nodes in the network generate data packets at VBR. Fig. 3 shows the results of the 3-subnetworks according to scenario A, greedy backpressure routing protocol for Scenario B, which also includes the backpressure scheme [3] and multigate best-path scheme [3]. In Fig. 3, the beacon interval is set to 0.2 seconds while the path loss factor is 2. From Fig. 3 we can observe a significant improvement in performance of the greedy backpressure routing scheme and the backpressure scheme, which shows a superior performance by a wide margin to the best-path approach and the 3-subnetworks in

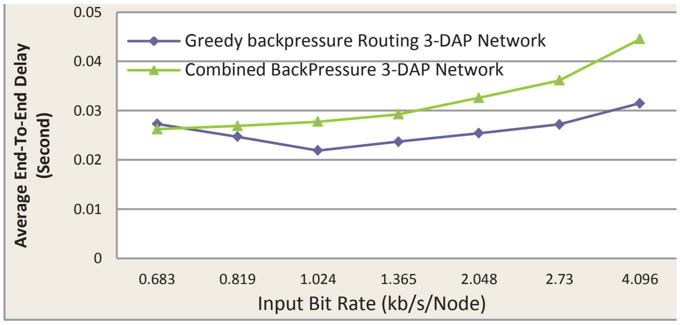

Fig. 7: The delay performance of greedy backpressure scheme and backpressure scheme are investigated in Scenario B.

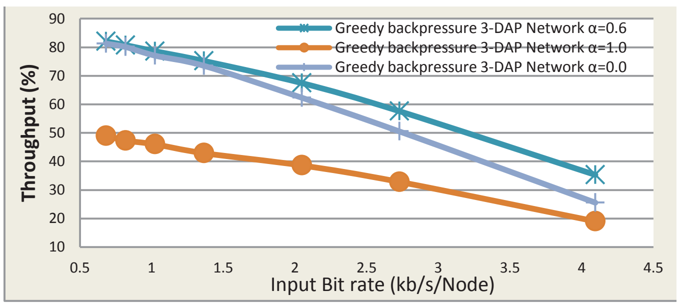

Fig. 8: Greedy backpressure routing scheme using a set of weight factor values is investigated in Scenario B.

scenario A. The greedy backpressure routing protocol outperforms the backpressure scheme, especially in high input-bit-rate area. The reason is that the greedy backpressure routing protocol can feel the effect of high traffic hops away. This helps to avoid the congested area far enough and drain the large queues on congested area in a shorter period, resulting in a better performance than the backpressure scheme. In contrast, in backpressure scheme, only neighbors' queue length is used to calculate the backpressure metric. The queue length of mesh points hops away is not taken into account. Therefore, the congested area cannot be avoided from far enough away. This may result in a longer time to drain large queues on congested links and cause bottlenecks to last longer.

In order to incorporate the effect of aggregated traffic by those nodes that are closer to the gateways, we set up a high traffic area in the vicinity of DAP-2, where nodes' queue sizes are expected to reach their maximum capacity. As shown in Fig. 4, the greedy backpressure routing scheme achieves a considerable gain over the back pressure scheme in the presence of high traffic areas.

In Fig. 5, we compare the normalized throughput variance of the greedy backpressure and backpressure schemes in scenario C, where a higher number of meters (more traffic) are located in the vicinity of DAP-1. The normalized variance is defined as the variance of the three gateways' throughput divided by the master gateway's throughput. The results indicate that the greedy backpressure scheme defeats the backpressure scheme in balance performance, since the former is capable of avoiding the congested area and of forwarding packets to the gateway with less throughput. This mechanism helps to balance traffic amongst the multiple gateways and hence maximize the total throughput at the master gateway.

In Fig. 6 a set of beacon interval values for updating the GBM value are investigated in order to evaluate the impact of this parameter on the systems performance. A beacon interval of 0.8s was found to achieve the best results under scenario B test conditions for updating the GBM. This is mainly because the higher beacon interval value means less overhead and hence results in lower interference. Based on our experiments we noted that when the beacon interval value is too high, the neighbor list and the corresponding GBM value cannot be updated in a timely manner, resulting in a worse performance.

We compare the end-to-end delay performance of the greedy backpressure scheme and the backpressure scheme in Scenario B, as shown in Fig. 7. Again, the greedy backpressure routing achieves a better delay performance than the backpressure scheme, since the greedy backpressure routing is better at avoiding the congested area far enough and draining the large queues on congested area in a shorter period.

In previous figures, the weight factor α employed by greedy backpressure routing is set to 0.6. In Fig. 8, a set of weight factor values are investigated. The scheme with weight factor being 0.0 is similar to the shortest-path anycast routing in [7], while the scheme with weight factor being 1.0 ignores the effect of distance to gateway. The weight factor of 0.6 was found to achieve the best results under scenario B test conditions, while the weight factor of 0.0 outperforms the weight factor of 1.0. This shows that without distance GBM, the scheme is no longer loop-free and stable, resulting in significantly degraded performance.

IV. Conclusion

One of the most important challenges in smart grid is providing reliable last mile network communication. In this paper we propose a greedy backpressure routing protocol for multigate mesh networks. We have proven that the greedy backpressure scheme is loop free and stable. Compared to our earlier backpressure scheme, the greedy backpressure routing can forward the packets around the congested area far enough away, resulting in better performance in the term of throughput, balance and end-to-end delay. The simulation results indicate that the greedy backpressure multigate mesh routing is capable of achieving a significant improvement in the network reliability, latency, and throughput performance.

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