Self-Organization of a Mesh Hierarchy for Smart Grid Monitoring in Outage Scenarios

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***Abstract*—Current hierarchical communication infrastructure in the smart grid is not robust for data collection from smart meters during outages. In this work, we propose a self-organizing multi-channel wireless communication framework to aid in data collection for smart grid health monitoring. Our proposed self-organization consists of two stages. First, smart meters form local mesh clusters by flattening the provisioned hierarchy. Second, the clusters interconnect to provide mesh connectivity from the outage region to functioning regions of the grid. We propose to construct this mesh-of-meshes hierarchy using a cross-layer strategy. The strategy jointly considers medium access limitations and the asymmetric traffic flow that becomes more heavy near the edges of the outage area. Our design framework allows an operator to plan network deployment, spectrum management, and medium access to perform as needed during an outage.**

I. INTRODUCTION

Smart grids are defined as the integration of communication and computation technologies with the power delivery infrastructure. Smart grids are envisioned to support critical and data-rich applications such as grid health monitoring [1]. In this application, the monitoring center periodically queries the operational status of the grid elements for diagnostic purposes.

A significant part of the smart grid comprises smart infrastructures with numerous sensors and actuators deployed throughout for monitoring purposes. Such smart infrastructures could generate energy using renewable sources. These sensors feed operational data of various energy consuming/generating elements in the smart environment to a gateway. We envision this gateway to be a smart meter that communicates wirelessly with a collector. The collector aggregates and relays monitoring data to the monitoring center via the communication infrastructure, establishing a hierarchy as shown in Figure 1. The collection of smart-meters and collectors form the smart grid Advanced Metering Infrastructure (AMI) [1].

Like any electric or mechanical system, smart grids are prone to outages, failure, and disasters. It has been shown that the smart grid loses its data communications capabilities during widespread disasters [2]. With failures of collectors during an outage, the AMI will no longer provide network connectivity to carry health data to the operations center. However, this data is of paramount importance for the operator to determine the root cause of the outage, monitor or predict the outage spread, or take preventative measures to stop the spread of the outage. In such situations, the grid operator can inform its customers of the expected duration of the outage and potential measures to minimize the impact of the outage by relying on locally generated energy using renewable resources. Hence, automated communication resilience is needed to relay data out of the outage area and into it using any surviving grid elements, including smart meters.

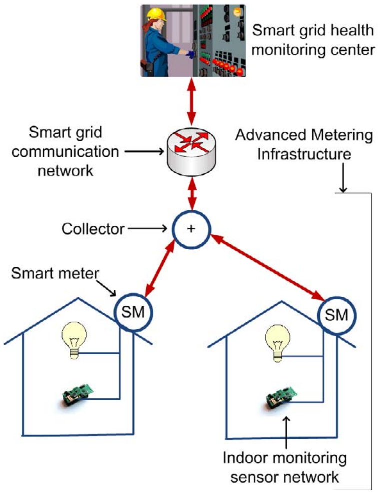

Fig. 1: This figure shows the smart grid's Advanced Metering Infrastructure in the grid's health monitoring eco-system.

In our previous work [3], we showed how to bootstrap a network to provide connectivity in the AMI during outages, but the approach did not scale due to the medium access scheme's limitations. A multi-hop self-organizing scheme for the AMI was proposed as an enhancement to Routing Protocol for Low power and lossy networks (RPL) [4]. However, the use of carrier sensing based medium access scheme restricts the scalability of their work for multi-hop networks trying to support uniform application demand rates [5]. Hence, in this work, we propose a self-organizing framework in the AMI using a *cross-layer strategy* that jointly considers medium access limitations and the asymmetric traffic flow that becomes more heavy near the edges of the outage region. Additionally, our strategy reduces the probability of collision for medium access, to support time-sensitive applications such as grid health monitoring.

In this paper, we propose a mechanism to bootstrap a wireless mesh hierarchy using outage-surviving battery-powered smart meters to connect them to the operations center without relying on external infrastructure. Our design focuses on three primary goals, 1) connectivity and allocation of resources needed to relay sensor data from all surviving smart meters in the outage region to the functioning grid, 2) consistent network

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performance in the outage area for the duration of the outage and 3) the bootstrapped wireless mesh network's ability to self-adapt to a data rate compensating for local failures or disaster spread in the outage region. Towards these goals, we propose a network design framework that a grid's operator can use to estimate network performance during outages.

Our proposed approach comprises two stages. First, clusters of wireless mesh networks are self-organized via *localized grid-flattening*, maintaining the rough neighborhood structure of the working grid, but without relying on higher-level devices. Second, a subset of the surviving smart meters bootstrap a hierarchy of *access networks* to interconnect the numerous clusters to surviving parts of the grid, thereby restoring connectivity to the outage region. We refer to our framework as *Triple Jump*, named after the athletic sport also known as "hop-skip-and-jump", as the critical data from smart meters *hops* onto a nearby access network, *skips* across a sequence of access networks, and finally *jumps* to a functioning part of the smart grid. We present two instances of our Triple Jump design framework and provide simulation results using OPNET [6].

The remainder of the paper is organized as follows. Section II outlines our assumptions and network model in this work. In Section III, we describe the two stages of self-organization. In Section IV, we formalize the resource management and network design for our proposed self-organization process. We evaluate two instances of Triple Jump via simulation in Section V. Finally, we conclude the paper in Section VI.

II. ASSUMPTIONS AND NETWORK MODEL

Our assumptions in this work are 1) smart-meters with multi-radio interfaces communicate wirelessly with their peers, 2) sufficient wireless spectrum is available to support smart grid communications, 3) no other telecommunication infrastructure is available to support post-disaster communications in the AMI, 4) each smart meter and grid element has a backup battery to enable communication during an outage and 5) to be able to connect all smart meters in the outage region the surviving smart meters should be in radio proximity to at-least one other smart meter.

We now discuss the network model of the AMI and its elements. In our architecture, smart meters serve as both end nodes and mesh routers. A subset of smart meters in radio proximity to two collectors, serve to interconnect clusters of smart meters when their respective collectors fail. The smart meters in such a subset are called *gateway smart meters*. We define a micro-neighborhood as a cluster of smart meters within a physical area of the customer domain. Data from smart meters of a micro-neighborhood are aggregated by a collector, which is then relayed to the monitoring center as shown in Figure 1. Collectors form a mesh by connecting to their peers allowing for sharing critical data during outages or operational status of neighborhoods during normal operations.

III. SELF-ORGANIZING MESH NETWORK

We now propose a self-organizing communication framework to reconnect the region experiencing an outage to an unaffected region. In our framework, connectivity and communications are restored in the outage region by forming a hierarchy of mesh networks in two stages: *localized grid-flattening* and *access network formation*.

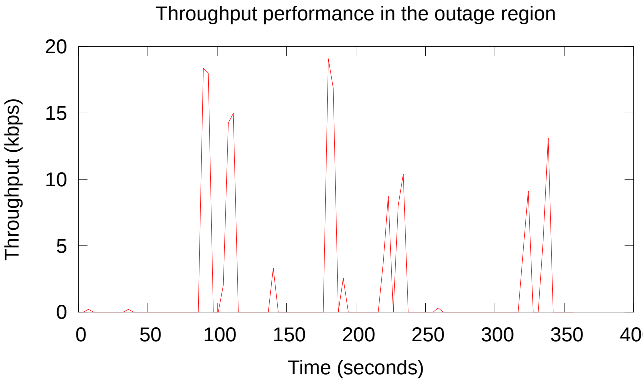

Fig. 2: We demonstrate the inconsistent network performance for a link between two smart meters in the single-channel, multi-hop mesh network when contention size is larger than what is supported the medium access scheme. For clarity, we illustrate only a single link, but we note that other links in the outage area behave similarly.

A. *Localized grid-flattening*

In this work, we expand on the concept of grid-flattening from our previous work [3]. Grid-flattening connects smart meters in the outage region by self-organizing into a single channel multi-hop mesh network. While connectivity is established in the outage region, there is no mechanism to allow for a fair access to the medium. As a result, smart meters in dense neighborhoods experience a contention size that denies fair access to the shared medium, which leads to inconsistent network performance as shown in Figure 2. In this work, we use multi-channel communications with spatial reuse in the outage region. Each channel serves a finite-sized cluster of smart meters which is planned considering the constraints posed by the medium access scheme and the application's demand rate, thus applying grid-flattening locally, hence this process is called as *localized grid-flattening*. The clusters of locally flattened neighborhood are interconnected by the gateway smart meters via the *access networks*, which communicate with two neighborhoods simultaneously using multi-radio interfaces.

B. *Access networks*

We propose to construct multiple levels of *access networks* recursively, starting from functioning regions of the grid and building inward. We allow for the network size in each level of the access network to increase as the network grows into the outage region. Smaller sized access networks towards the collector reduce the contention size for the shared medium to support traffic aggregated in the access networks from interiors of the outage region. The network sizes are computed as a function of the expected aggregate demand in each level and the limitations posed by the medium access technologies. This multi-level access network formation is illustrated in Figure 3.

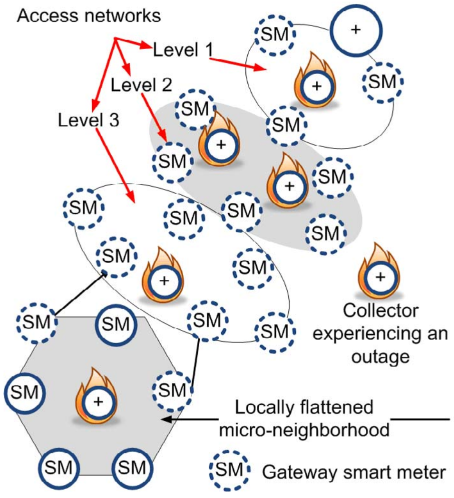

Fig. 3: In our proposed self-organizing model, localized grid-flattening connects regular smart meters to nearby gateway smart meters via a multi-channel wireless mesh network. The gateway smart meters bootstrap the access networks in levels, connecting the clusters of mesh networks to functioning collectors. The differently shaded regions indicate spatial reuse of channels.

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Access networks formation
Current level: $m \leftarrow 0$
Maximum level: $M$
Access Points (APs)of levels $AP\{1, ..., M\} \leftarrow 0$
Access network size of level $m$: $N_m$
Current network size of level $m$ :$\leftarrow S_m$
while All smart meters are not yet connected do
    if Level 1 not formed then
        $m \leftarrow 1$
        $AP[1] \leftarrow$ Collectors at edge of outage region
        Compute and broadcast, $M$ and $N_m \forall m \in \{1, ..., M\}$
    else if $m \geq$M then
        $N_m \leftarrow N_M$
    end if
    Start tree formation from $AP[m+1]$
    while $S_m < N_m$ do
        Add unconnected gateway smart meters to tree
    end while
    $AP[m+1]$ AP $\leftarrow$ Leaf smart meters of tree Level $m$
    $m \leftarrow m+1$
end while
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Fig. 4: This figure describes our proposed self-organizing communication framework in the smart grid's AMI during outages.

A functioning collector adjacent to the outage region first computes and broadcasts the number of levels that can be formed and their network sizes for the application's desired data rate in the outage region. The collector becomes an Access Point (AP - not to be confused with the access point of Wireless Local Area Network) for the first level and last-hop gateway smart meters in a level become APs for the next level. In each level, the AP advertises the formation of the access network and accepts responses to its advertisement until the size of the access network in that level has reached or no more smart meters need connectivity. If smart meters need connectivity even on reaching the maximum planned level, then additional levels of access networks are created with the same size as the maximum level planned by the collector. This recursive process continues till all smart meters are connected.

Once the access networks are formed, the collectors at the edge of the outage region will know how many smart meters each is servicing. They compute a new demand, *adjusted demand*, that allows each connector to approximately service equal number of smart meters. Hence, the access networks, by design, adapt to spreading outages or service restoration by initiating access network formation for the adjusted demand. Figure 4 explains our approach of access network formation, initiated when a functioning collector senses the failure of its peer(s) due to an outage.

After self-organizing, data and control messages from a regular smart meter *hop* to the nearest gateway smart meter of its respective micro-neighborhood, *skip* through a sequence of micro-neighborhoods via gateway smart meters in the access networks, and finally *jump* to a collector in the unaffected region of the grid, and then reach the grid's monitoring center.

IV. NETWORK DESIGN AND ANALYTICAL MODEL

In this work, we model the self-organization process with a bottom-up approach as part of our cross-layer strategy. In particular, we first show that contention size for medium access bounds the size of a smart meter cluster for a given application demand's data rate. For this, we derive the size for each cluster based on the limitations of the medium access scheme and the demand's data rate. We then use the limitations of the medium access scheme and the number of gateway smart meters needing connectivity to compute a new data rate for the application that can be supported in the outage region.

A. *Medium Access and Resource Management*

Health monitoring applications for the smart grid are typically time-sensitive. We claim that Time Division Multiple Access (TDMA) is a more suitable approach for the application of interest. This is because, Carrier Sense Multiple Access (CSMA) provides only a best effort service guarantee, and leads to a drop in performance for multi-hop communications [5]. Also, distributed TDMA locally avoids problems prevalent in CSMA, such as hidden and exposed terminals [7].

Using multi-channel communication for micro-neighborhoods with spatial reuse, for normal operations, we suggest the use of centralized TDMA for smart meters to cooperate with the neighborhood's collector. Once the collector fails, smart meters use distributed TDMA to access the same pre-defined spectrum that was previously managed by the collector. Multi-radio gateway smart meters can then serve to connect the adjacent micro-neighborhoods.

Unpredictable spatial behavior of outages makes spectrum planning hard, cognitive radios allow for opportunistic access in other available regions of the spectrum if the assigned fractions of the spectrum are unavailable [8]. Hence it provides greater assurance of network availability to support the communications during outages. However, multi-radio interfaces could still suffice to sense the available portions of the spectrum, to choose a channel not interfering with the underlying regular smart meters or with adjacent access networks.

B. Cross-Layer Network Design

Collision-free medium access in distributed-TDMA depends on the smart meter neighborhood size [7], and we have shown that uncontrolled increase in contention size leads to instability in network performance [3]. Hence, for consistent network performance in the outage region, in this work, we aim to design for the number of smart meters N in each micro-neighborhood, ensuring that a smart meter in a micro-neighborhood gets the required average k slots per frame to support the D bps application demand. However, the communication traffic toward the edges of the outage region increases, because each gateway smart meter is carrying its own local traffic and traffic from deeper levels. We generalize access network level's sizes to N_m smart meters for each level m, such that $N_m \leq N_{m+1}$, allowing for pre-provisioning (or over-provisioning) for traffic support in the access networks.

We now discuss the network design to support the performance requirements of the grid health monitoring application. We let the monitoring application specify a demand of D bits per second (bps) from smart meters in each flattened neighborhood. In the distributed TDMA scheme, we suppose frame lengths of t_f seconds, giving a total number of frames per second f_s as $1/t_f$. We let d denote the data payload in bits that can be transmitted in each data slot. However, due to synchronization bands at the start and end of each TDMA slot, only a fraction p_t of the slot is used to transmit, reducing the payload per slot to $p_t d$ bits. Moreover, let p_e denote the probability of bit error. Hence, the effective number of data bits per slot is $p_t p_e d$. The expected total number of slots n_D needed to transmit the demanded D bps is computed as Demand/(effective data bits per slot), $n_D = \frac{D}{p_t p_e d}$. Hence, the average number of slots per frame n_f to support application demand as n_D/f_s.

We now define the parameters for a probabilistic framework to model the slot allocation per smart-meter in a TDMA frame. Let 1) $\boldsymbol{I}$ be a random variable that represents the number of slots a smart meter gets in a particular frame, taking values $i \in \{1, \ldots, n_f\}$, where n_f is the number of slots in each frame, 2) N represent the maximum number of smart meters in a flattened micro-neighborhood, and 3) p be the probability of a smart meter gaining uncontested access to a particular slot in the TDMA frame. When N smart meters contend for the same slot, the access probability p for a smart meter is $1/N$. The contention for each subsequent slot is independent of the outcome of contending for a slot previously in the same frame. The probability that a smart-meter that gets i slots in a frame is binomial, with i successes and $n_f - i$ access failures. Hence, the expected number of slots per node in each frame is $n_f p$, or equivalently n_f/N from the binomial distribution formulation. Thus if a health monitoring application needs an average k slots per frame to support the application's performance requirement, N is given by $N = \left\lfloor \frac{n_f}{k} \right\rfloor$.

Each gateway smart meter needs an average of $3k$ slots per frame per level. $2k$ slots to accommodate network traffic from the flattened neighborhoods as their gateway, and k slots to feed its own traffic. However, the level 1 gateways do not know exactly how many levels of access network are needed, so these gateways are forced to provision resources based on a worst-case estimate of M levels. In general, the m^{th} level AP needs an additional $3k$ slots on top of the $(m+1)^{th}$ level AP's slots, so the total number of slots needed per gateway in level m is $3(M-m+1)k$. Any access network that grow beyond level M respect the worst-case estimate and need the maximum allowable slot allocation $3k$. As a result, the size of each access network at level m is given by

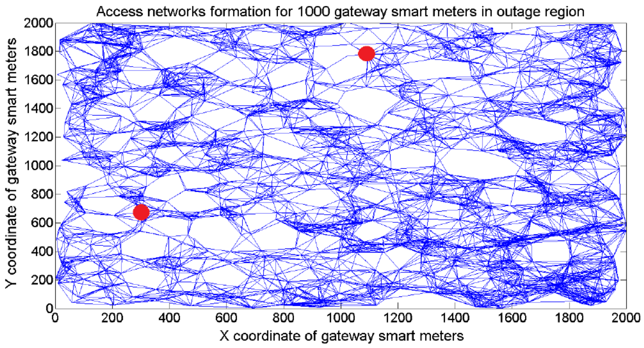


Fig. 5: This figure shows the graph of the self-organized network after adjusting the application's demand in the smart grid's AMI during an outage. The solid circles represent the functioning collectors and the lines indicate edges between smart meters. As the access networks get deeper (bottom-right corner), the graph is denser due to larger sizes of access networks in our cross-layer strategy for traffic provisioning.

$$N_m = \begin{cases} \frac{n_f}{3(M-m+1)k} & \text{for } m \leq M \\ \frac{n_f}{3k} & \text{for } m > M \end{cases}. \tag{1}$$

The net smart meters N_c serviced by collector c is given by

$$N_c = \begin{cases} \sum_{j=1}^{m^t} \frac{n_f}{3(M-j+1)k} & \text{for } m^t \leq M \\ \sum_{j=1}^{M} \frac{n_f}{3(M-j+1)k} + (m^t - M)\frac{n_f}{3k} & \text{for } m^t > M \end{cases}. \tag{2}$$

where m^t denotes the total number of levels of access networks formed by smart meters connecting to a collector c.

Each collector $c \in \mathcal{C}$ shares with each other the number of smart meters they are supporting, where $\mathcal{C}$ is a set of all collectors adjacent to the outage region. The collectors then obtain the net gateway smart meters in the outage area N_T given by $N_T = \sum_{j=1}^{|\mathcal{C}|} N_j$, where $|\mathcal{C}|$ is the cardinality of $\mathcal{C}$. The collectors will now cooperatively decide to each support equal number of smart meters N_B in the outage area, which is computed as $N_T/|\mathcal{C}|$. This aids in balancing the self-organized network's structure to some degree as seen in Figure 5. The smart meters were distributed over 1 $sq.km$ with a transmission radius of 0.2 km using a spatial Poisson process discussed in [3]. Two gateway smart meters served a micro-neighborhood (a circular area of 0.2 km radius) of 10 smart meters for an initial demand of 25 $kbps$. Thus the total network size we simulated was $5N_T + N_T$ smart meters.

The collectors now compute the smallest m' such that

$$\min m' s.t \sum_{j=1}^{m'} \left\lfloor \frac{n_f}{3(m'-j+1)k} \right\rfloor \leq N_B. \tag{3}$$

Thus, m' will allow the collectors to compute the new adjusted demand D'. The collectors now initiate the access network

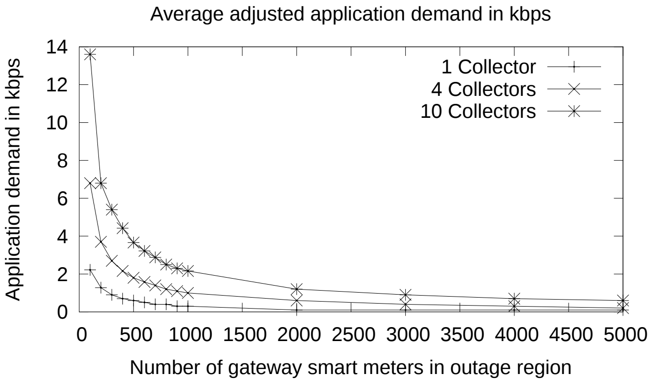


Fig. 6: This figure demonstrates the application's demand adjusted once the access levels are formed for an initial demand of $25,000\ bps$.

formation for the adjusted demand. Figure 6 demonstrates the pattern in which application demand is adjusted to provide reliable communication service to all surviving smart meters in the outage region. In the second pass of forming the access networks, to allow for load balancing the energy expenditures of the smart meters that act as a gateway in the access networks, their nearest neighbors become gateway smart meters.

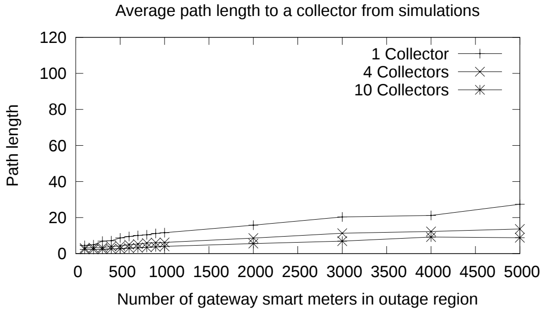
C. Analytical model

We now discuss our analytical model to capture the average path length to collectors in our proposed self-organizing process for restoring communications and connectivity in the AMI. $G(N_T, E)$ is a graph with N_T nodes (smart meters) and E edges between the nodes in the outage area. Henceforth in this work, we will use the terms nodes in a graph and smart meters, and edges in a graph and wireless links interchangeably. We define a variable j which takes values in $\{1, ..., m'\}$, where m' was computed by the collectors using Equation 3.

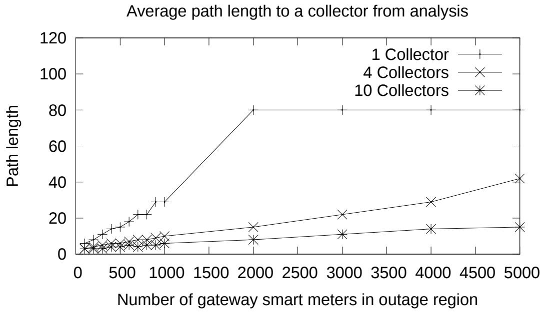
We define node neighborhood (degree of a node) as the number of smart meters in the transmission range of the particular node. The average degree of a node in a graph spanning an Euclidean area (in this work, area of the outage region) can be computed by treating G as a geometric random graph. The average degree $\mathcal{K}$ of a smart meter with a transmission range r_{tx}, in an outage area spanning $A\ sq.units$ with N_T smart meters is $N_T \pi r_{tx}^2 / A$. Each node connects with $\mathcal{K} - 1$ child nodes in its neighborhood, excluding the edge with its parent.

If $N_j \leq \mathcal{K} - 1$, N_j edges can be formed with N_j of $\mathcal{K} - 1$ possible edges. However, when $N_j > \mathcal{K} - 1$, multiple node neighborhoods are needed to find unique N_j in level j. On average, we need $N_j \ln(N_j)$ smart meters to obtain N_j unique smart meters using the *balls-and-bins* formulation. Hence, the number of node neighborhoods s_j needed to obtain N_j unique smart meters is computed as $s_j = \frac{N_j \ln(N_j)}{\mathcal{K}}$.

The average depth of a tree in level j, p_j is calculated as a function of $\mathcal{K}$ and s_j, and is defined as the distance from the AP of the current level to the farthest leaf of the tree. The formulation to compute p_j is given by,



(a) Path length to a collector from simulation



(b) Path length to a collector from analysis

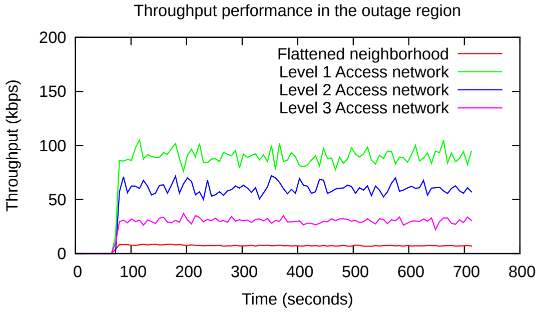
Fig. 7: Figure (a) shows the path length performance to a collector obtained by simulating our proposed self-organizing process in the grid's AMI. Figure (b) shows the path length performance to a collector obtained from our proposed analytical model. Since our model is not accurate enough in eliminating over-counted smart-meters, we see that simulation results perform better than the analytical results. Our analytical model captures the trend in path length variations that can be expected from the self-organization process.

$$\min\ p_j\ s.t \sum_{i=1}^{p_j} (\mathcal{K} - 1)^i \geq s_j, \tag{4}$$

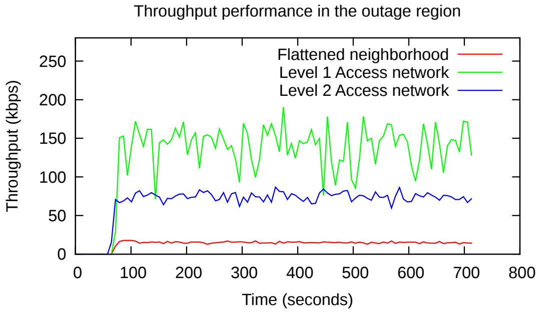
and $p_j = \frac{\ln(1 + s_j \frac{\mathcal{K}-1}{\mathcal{K}})}{\ln(\mathcal{K}-1)}$. The path length h from a collector to a node in level j is computed as a sum of path lengths to reach the AP of level j and the hops AP of level j. h as a function of p_j is computed as $h = \sum_{i=1}^{j} p_i + \epsilon$. where $\epsilon \leq p_j$ is the path length from a node to the AP of its respective level. The average h to all smart meters in the outage region over 10 instances of our proposed mechanism and random placement of collectors is plotted in Figure 7(b). The path length performance from simulations in MATLAB using parameters in Table I performs better than the analytical model's results in Figure 7(a), because our model does not fully eliminate over-counted smart meters while building the access networks. However, performance trends in Figure 7 for large scale outages (thousands of smart meters) shows that our solution is scalable as the path length grows at very slow rate compared to growth in network size.

V. TRIPLE JUMP PERFORMANCE

We used the TDMA wireless modeler in OPNET [6] to simulate different instances of the Triple Jump framework



(a) Average throughput in Setting 1



(b) Average throughput in Setting 2

Fig. 8: In this figure we show network performance using Triple Jump. In Setting 1 shown in Figure (a), the flattened neighborhoods supported a throughput of 10 $kbps$ and allowed for $M = 3$. In Setting 2 shown in Figure (b), the flattened network supported 25 $kbps$ and allowed for $M = 2$. For each setting, the average throughput across all links in the outage area is consistent in each level, with higher throughput achieved at levels closer to the edge of the outage.

during small scale outages (a few hundred smart meters). The two instances, referred to as Setting 1 and Setting 2, place demands of $D_1 = 10\ kbps$ and $D_2 = 25\ kbps$ on each locally flattened micro-neighborhood. We use our network design framework discussed in Section IV-B to design access networks. We chose p_e as 0.5 in our simulations, a parameter chosen based on observations from the OPNET modeler. Also from the OPNET modeler, we observe synchronization guard slots of 15% at the start and end of each slot, yielding $p_t = 0.7$. Although unavailable today, we envision that in the future licensed spectrum will be made available to communications in the smart grid. These and other parameters used in our study are given in Table I.

TABLE I: Fixed simulation parameters are given.

Base frequency = 850 MHz	Channel bandwidth = 10 MHz
$t_f = 100\ msec$	$n_f = 44$
$d = 200\ bytes$	$p_t = 0.7$
$p_e = 0.5$	Demand distribution = Uniform
$D_1 = 10\ kbps$	$D_2 = 25\ kbps$

In Setting 1 with $D = D_1 = 10\ kbps$ and parameters from Table I, $M = 3$ levels of access networks are supported. Levels 1, 2, and 3 respectively hold 3, 4, and 8 gateway smart meters based on (1). Similarly, in Setting 2 with $D = D_2 = 25\ kbps$, we have $M = 2$ levels of access networks with level 1 and 2 respectively holding 3 and 4 gateway smart meters. We chose two different settings with different throughput being supported in the flattened neighborhoods to study the impact of different sized access networks and number of levels in access networks needed to connect the same number of smart meters. In both Figure 8(a) and Figure 8(b), we see that starting from the flattened neighborhood at the bottom of the hierarchy, each higher level of access network supports throughput consistently through the duration of the outage plotted on the x-axis. In each level, in addition to the traffic being forwarded from the previous level, three times the flatted neighborhood's throughput is supported by the gateway smart meters. This demonstrates that our cross-layer strategy pre-provisioned the resources for access networks to support consistent network performance throughout the outage region.

VI. CONCLUSION

In this work, we proposed a self-organizing communication framework to restore communications to regions of the smart grid experiencing outages, allowing for transport of critical sensor data from the outage region to reach a system operator. Our self-organizing framework is made up of two stages. First, localized grid-flattening clusters the surviving smart meters and, second, a subset of the smart meters act as gateways to the formed clusters and interconnect with other cluster's gateway smart meters, providing multi-hop connectivity to function regions of the grid. We presented a cross-layer strategy that combines aspects of spectrum management, medium access, and traffic flow to provide consistent network performance throughout the outage area. As part of our future work, we will formalize the scalability and convergence characteristics of our approach in widespread disaster scenarios.

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