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Survivable Smart Grid Communication: Smart-Meters Meshes to the Rescue

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***Abstract*—Smart grids are critical cyber-physical infrastructures in the world now. Since these infrastructures are prone to large scale outages due to disasters or faults, a resilient and survivable communication architecture is desired. In this work, we propose a resilient and survivable hierarchical communication architecture for the smart grid that mirrors the hierarchy of the existing power grid. Post-disaster resilience in grid communication is achieved through the *grid flattening* process. This process involves smart-meters and other disaster surviving elements of higher system levels of the grid forming a wireless mesh network. The flattened network of grid elements with one-hop communication links help in reliable and timely relaying of grid's health information to working regions of the grid. This allows for swift action by control engineers of the utility provider and emergency services with real-time data. We propose analytical models to study the performance of the flattened architecture as a function of outage area, smart-meter density and smart-meter's neighborhood size. The results from the analytical model will be compared with simulation results from OPNET.**

I. Introduction

Integration of digital computing and communication technologies with the power-delivery infrastructure defines a smart grid, a critical cyber-physical infrastructure in today's modern world. The NIST conforming architecture [1] is designed to support control information sharing in the downstream links and measurement information from smart-meters in the upstream links. Recent research in smart grid communication and architecture have focused on evaluation of wireless technologies and use of cognitive radio and white space communication for the smart grids [2][3][4]. Focus has also been on control architecture for high assurance in smart grids [5] and RF mesh systems for smart metering and architectures have been studied for the smart grid [6]. However, the current smart grid architectures are not resilient to large scale blackouts and hence lose the ability to communicate [7].

In this paper, we propose a disaster resilient communication architecture using wireless mesh networks. On experiencing an outage due to a disaster, our proposed communication architecture reorganizes itself by the *grid flattening* process. Grid flattening process involves disaster surviving smart-meters and other working elements of the grid forming a wireless mesh network among themselves. Well established wireless mesh communication research [8] proves that efficient communication can be achieved even with battery operated transceivers.

We envision this communication architecture to mirror the existing power grid architecture and have multiple wireless mesh networks, each at a different system level. Bottom-most layer of the architecture comprises of the customer locations equipped with smart-meters which communicate with a local distribution center. The local distribution centers then communicate with regional control centers which then communicate with Supervisory Control and Data Acquisition (SCADA) centers. At each of these system levels, wireless mesh networks are formed by grid elements communicating with their peers. When the system levels above the customer domain fail, smart-meters can form a wireless mesh network by communicating with their one-hop neighbors via the grid flattening process.

Advantages of this proposed architecture are, 1) Local and minor outage warning in a neighborhood can be quickly disseminated to other elements in the neighborhood through downstream communication in the hierarchy plus the neighboring areas through the wireless mesh, 2) Allows for control engineers to analyze data specific to areas seeing outages and could also collect health data shared with outage area's neighbors prior to the outage striking, 3) With intelligent advance warning systems in place, an area that could receive the spreading outage could be warned for evacuation or emergency services to be better prepared, or could also allow utilities providers for a graceful shutdown and 4) SCADA centers sharing data among themselves allows for health monitoring information to be shared across large areas. This allows for the grid to be gracefully shut down using the shared information.

Outage detection apart, the proposed architecture comes as a way to bootstrap a communication infrastructure that can help relay grid's critical health data. It is possible that grid's power line infrastructures are in place but with higher systems (local substations etc.) gone off-line. However, other externalities such as fire or flooding could make energy restoration hazardous even if higher system levels are functioning. With our proposed architecture, the data being sent across the network need not be only metering data, but could also be context specific data supplied by sensors on-board the smart-meter. These data could be local temperature, presence of flood water or even presence of toxic or flammable gases. All of these different kinds of data have an impact on the way the grid would function if there were automated self-healing procedures (if any in place) to restore energy in the grid. Safer and efficient decisions for acting on the grid could be made by control engineers or self-healing systems in remote locations with more features in grid's health data.

We present an analytical model to estimate the network performance of the flattened regions of the smart grid. We study the network performance as a function of smart-meter density, outage area size and smart-meter's neighborhood size. The results from the analytical model are compared with results from simulations for which OPNET [9] was used.

The remainder of this paper is organized as follows. Section II describes the architectural elements, the proposed architecture itself and interactions between the architectural elements. Grid flattening process is explained in Section III and Section IV illustrates performance analysis of the flattening process and the flattened network. We summarize our contribution in Section V.

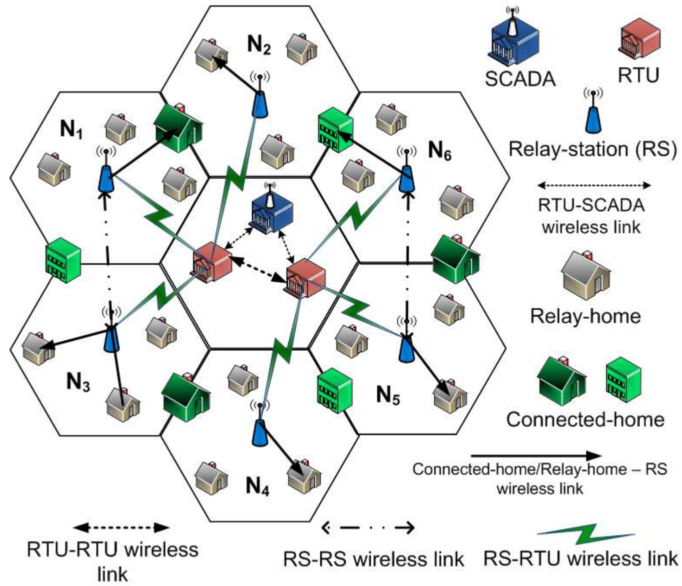


Fig. 1: This figure shows two macro-neighborhoods, each encompassing three micro-neighborhoods (N_1,N_2,N_3) and (N_4,N_5,N_6) respectively. The relay-stations form a wireless mesh network with their peers, and establish wireless links with RTU. RTUs form a wireless mesh network among their peers and establish wireless links with SCADA.

II. A COMMUNICATION ARCHITECTURE FRAMEWORK FOR THE SMART GRID

With the motivation for a hierarchical communication architecture in Section I, we start this section by discussing the network assumptions. We then define the architectural elements and discuss the interactions between them.

A. Network assumptions

The assumptions made in this subsection facilitates the wireless communication abilities of smart-meters and other power grid's monitoring entities to form a wireless network.

1) The customer domain of the smart grid is divided in to logical neighborhoods with a local distribution center equipped with a transceiver. This transceiver has the capability to communicate wirelessly with individual smart-meters.
2) Smart-meters in radio proximity of each other have the ability to communicate with their peers via one-hop wireless links.
3) Smart-meters periodically update their peers in neighborhoods and the local distribution center.
4) Smart-meters are capable of sensing failure of elements in higher system levels of the power grid.

B. Architecture elements and definitions

We define the elements in our architecture that show the bottom-up approach we take to achieve survivability in the grid's communication. The architecture elements are shown in Figure 1.

- **Micro-neighborhood**: A *micro-neighborhood* N_i is an area that consists of smart-meter equipped entities. The area of the micro-neighborhood depends on the density of homes or establishments in a geographical area equipped with smart-meters. The micro-neighborhood helps in defining the granularity level of the architecture to a specific smart-meter. This is the bottom-most layer in the proposed architecture. For ease in understanding and to avoid overlapping areas, each micro-neighborhood could be hexagonal in shape (closest approximation to a circle).
- **Relay-home**: A *relay-home* R_i is a smart-meter equipped entity and belongs to a micro-neighborhood. The relay-home periodically reports its energy consumption to local distribution center(s) of the micro-neighborhood as programmed by the energy provider or the vendor of the smart-meter.
- **Connected-home**: A *connected-home* C_i is a smart-meter equipped entity chosen in such a way that it is in radio proximity to at least two local distribution centers. For normal operations, a connected home is like any other relay-home reporting its energy consumption to the distribution center of the micro-neighborhood. However, a provision is made where a connected-home also reports to the distribution centers it can hear and establishes a communication link with the relay-homes in one-hop distance.
- **Relay-station**: A *relay-station* RS_i is a transceiver that relays messages to and from all R_is and C_is of the micro-neighborhood to an aggregation entity such as the Remote Terminal Units (RTU). A relay-station can establish peer connections with relay-stations of adjacent micro-neighborhoods. Each micro-neighborhood has a local sub-station that distributes power to a neighborhood. Such a sub-station can be envisioned as a relay-station in our architecture.
- **Macro-neighborhood**: A *macro-neighborhood* M_i is a collection of micro-neighborhoods. Each M_i has an RTU

that collects information and reports it to the SCADA for processing. Thus a collection of macro-neighborhoods can be a larger hexagonal area encompassing many N_is, similar to the model used for cellular topology.

C. Hierarchical communication architecture for the smart grid with multiple overlaid wireless mesh networks

We envision this communication architecture to have multiple wireless mesh networks, and each at a different system level as shown in Figure 1. The bottom-most layer of grid is formed by the consumer domain consisting of C_is and R_is that communicate with a RS_i. The RS_is form the first and bottom most layer of the mesh network. The RS_is communicate with an RTU, and the RTU's form the second layer of mesh-network in the architecture. Finally, RTU's communicate with SCADA and a collection of SCADA centers could form a wireless mesh spanning a larger area. This a very simplified model, there could be more division in system levels based on implementations. Each of these levels could follow the same communication hierarchy.

D. Status codes

We define status codes as numerical strings that convey to the elements the severity levels of the message. The status codes are listed in Table I in the increasing order of priority. Priority is given to the larger outage information to be propagated first and then smaller outages are acted upon. These numerical strings will help in aiding the process of grid flattening as we shall see in Section III-B.

TABLE I: Status code and their descriptions listed in **increasing** order of priority/severity level

Status Code	Description
101	ALL OK
191	LOCAL TROUBLE with ID of architecture entity facing outage
201	relay-home Failure
301	connected-home Failure
401	Micro-neighborhood failure
411	Informing neighboring micro-neighborhood failure to RS
421	Warning neighboring areas of micro-neighborhood failure
501	Macro-neighborhood failure
511	Informing neighboring macro-neighborhood's failure to RTU
521	Warning neighboring areas of macro-neighborhood failure
911	Emergency, Immediate shut down and evacuation

We define a simple message format with key attributes that will not only convey status description, but also allow for actions with more detailed inputs. The notation $C \rightarrow R : \langle M_1, M_2 \rangle$ denotes an entity C communicating with entity R and conveying messages M_1 and M_2. An entity C broadcasting a message M is denoted by $C \rightarrow *$: $\langle M \rangle$. The identification tag linked to an entity such as connected-home, relay-home etc is denoted as ID_{entity}. Use of time-stamp in messages will help control engineers understand and better study the behavior of certain entities if auditing is performed. The messages convey entities ($ID_{affected\,entity}$, $RS_{affected}$) or neighborhoods ($M_{affected}$,$N_{affected}$) facing minor outages or reporting minor anomalies. Fine grained location information is shared along with status codes which proves very effective for control and emergency operations. The format of the messages being shared can as follows, ⟨Status Code, ID of neighborhood, ID of reporting entity, time-stamp, outage information⟩.

III. Post-disaster survivable communications via grid flattening

Having defined the basic architecture and its elements, we now show how grid communication can survive an outage due to a disaster and thereby achieve resilience. We start this section by analyzing the after-effects of a series of failure in the power grid. We then discuss achieving resilience in communication after the disaster has struck.

Let us assume that a few RS_is see an outage due to some event such as fire or flooding, this means health monitoring information from smart-meters have no parent in the hierarchy to report the data. This sort of a failure leaves communication capable smart-meters in R_is and C_is to send out any critical measurement only via one-hop communication with their peers to an unaffected RS_i which could then report to RTU and finally have emergency services to act swiftly. This clearly explains the need to have strategic placements of C_is that could help relay out critical data from affected regions of the grid to RS_i of unaffected regions. This is possible because they are aware of one of the RS_i failing and the other still normally operating, since a C_i in the radio range to two RS_is can quickly inform its peers of a way to reach the unaffected region of the grid.

Relay-stations are not chosen as anchor nodes in establishing the communication links after a disaster for two reasons. First, if they are the local distribution substations they are more susceptible to go off-line first [7]. Second, they might not hear the neighboring relay-stations or RTUs if they also go off-line in large scale disasters. In this scenario, higher power and bandwidth are needed to support communications to reach the next available relay-station or RTU. However, with the use of connected-homes and relay-homes there could be delay in the control messages reaching the unaffected portion of the grid, but nonetheless it is more robust to link failures than depending on one centralized communication system.

A. Grid flattening

With RS_is failing first during an outage, it leaves the outage surviving smart-meters to communicate with their one-hop neighbors to relay out critical data to working regions of the grid by forming a wireless mesh network. This leads to a flat network formed by only the smart-meters. We call this process of establishing a survivable communication paradigm using only the metered entities as *grid flattening* as depicted in Figure 2. Even with the disaster spreading, this network formed by smart-meters can still survive and finally help data reach unaffected regions of the grid via multiple hops.

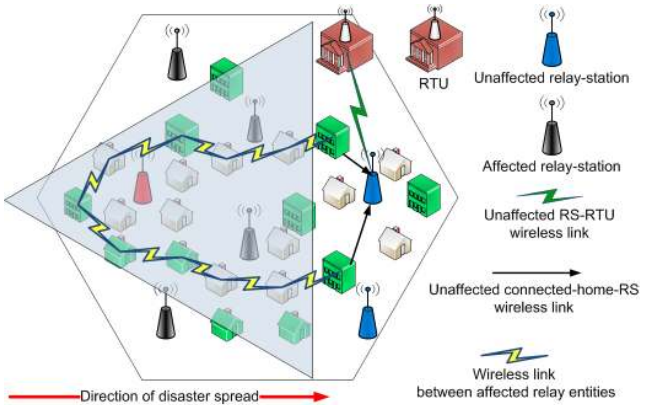


Fig. 2: This figure shows the outage facing area marked by the gray triangle of the smart grid is being flattened. The relay-homes and connected-homes form one-hop wireless links to create the flattened wireless mesh network.

B. *Communication among connected-homes and relay-homes*

When a connected-home senses the failure of the relay-station, it switches from the metering mode to the relay mode. The connected-home broadcasts the nature of the failure and a description with the status code 911. When a relay-home or connected-home hears this message, it broadcasts this information further and warns its neighborhood of the imminent disaster as shown in Figure 3. This information propagates until it has seen a neighborhood that is not affected yet. Thus this model serves not only to propagate critical information but also warn their neighborhood of an impending disaster.

Receive all broadcast messages
if status code of message == 911
  queue all non critical messages
  $\{R_i, C_i\} \rightarrow * :$ ⟨911, ID of neighborhood, ID of reporting entity, time-stamp, outage information⟩
else if status code of message != 911
  Follow normal outage reporting procedures
end if

Fig. 3: Emergency status message processing at a relay-home or connected-home.

IV. Performance analysis of the proposed communication architecture for the smart grid

In this section, we provide a modeling framework for the communication architecture and compare the results from the modeling framework with the simulated results.

A. *Simulation setup*

Typically energy measurements are timed by the utility provider for usage data collection. Knowing the number of smart-meters to collect data from (a constant after an area is developed), a good collection schedule would suffice a graceful operation of the communication architecture even if a measurement is missed. Under normal operating conditions, the parent in each level of the hierarchy can function as the scheduler and decentralized scheduling can used for data collection among peers when the grid is flattened. For these discussed reasons, Time Division Multiple Access (TDMA) becomes the automatic choice for medium access eliminating the need for contention based medium access schemes.

We used OPNET's TDMA wireless modeler to simulate the proposed architecture. The simulations were carried out with different sizes of N_i and with different transmission power of the smart-meters. Key parameters of the simulation setup are tabulated in Table II. The simulations were conducted over

TABLE II: Simulation fixed parameters

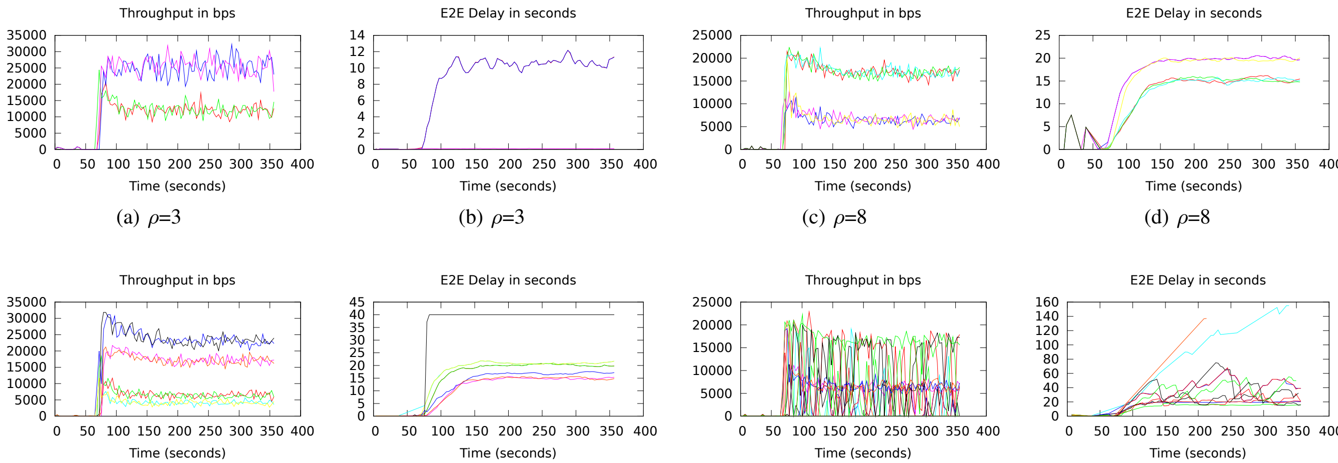
Simulation Parameter	Value
Base Frequency	850 MHz
Channel Bandwidth	10 MHz
TDMA Frame Length f_l	100 msec
TDMA Data slot length	2 msec
TDMA SLots per Frame	44
Maximum Data Payload per slot	200 bytes
Maximum data rate	25 kbps
Packets per second	50
Demand distribution	Uniform
Simulation time	0.1 hour
Radius of hexagonal area	0.25 km
Transmission range of smart-meters	0.20 km

the following scenarios, 1) All neighborhoods are functioning correctly, 2) N_1 is flattened and N_2 and N_3 collect the critical data from N_1, 3) N_1 and N_2 are flattened and N_4 and N_6 collect the critical data from N_1 and N_2 respectively and 4) One entire macro-neighborhood (N_1,N_2,N_3) is flattened and N_4 and N_5 collect data from the affected macro-neighborhood.

B. *Modeling neighborhood density*

In this modeling framework we show the optimum number of smart-meters per neighborhood that suffices for the flattened network to gracefully survive the disaster and exhibit disaster resilience.

- Smart-meter density: The smart-meter density ρ is the number of smart-meters per unit area. ρ follows the distribution of a spatial Poisson process. This means that ρ has a uniform density and the count of the smart-meters N_{sm} has a Poisson distribution with mean ρA_{N_i}. Since the current defined architecture has disjoint micro-neighborhoods, it follows that the count of smart-meters in micro-neighborhoods are also independent. Hence, this allows us to calculate the probability of k smart-meters in a smaller disaster area $A_{disaster}$ of a micro-neighborhood with n smart-meters, which follows a binomial distribution $\binom{n}{k}p^k(1-p)^{n-k}$ where p is given by $\frac{A_{disaster}}{A_{N_i}}$.
- Smart-meter coverage area: Assuming an isotropic antenna on the smart-meter, the coverage area A_{sm} is defined as the area spanned by the transmission signal of the smart-meter.



(a) ρ=3 (b) ρ=3 (c) ρ=8 (d) ρ=8

(e) ρ=3 (f) ρ=3 (g) ρ=8 (h) ρ=8

Fig. 4: This figure shows throughput and delay performance when a macro-neighborhood is partially flattened with one micro-neighborhood's failure and completely flattened for ρ = 3 in (a), (b), (e) and (f), and for ρ = 8 in (c), (d), (g) and (h) respectively. Each line in these plots are measurements as seen in each of the smart-meter in the flattened micro-neighborhood(s).

- Effective smart-meter count: Given ρ and A_{sm}, we define the effective smart-meter count $\eta_{effective}$ as $\rho\, A_{sm}$. This will indicate the number of smart-meters needed to cover the entire micro-neighborhood area. In reality, we would want this value to be greater than unity so that on an average, atleast 1 smart-meter is available to form a link to enable communication during the disaster.

Evaluation of smart-meter density: With simulation parameters as inputs, we calculate the minimum number of smart-meters needed to cover an entire micro-neighborhood. With the information from Table II, we see that $\eta_{effective}$ is 1.92, as A_{N_i} is $\pi\,(0.25)^2$ sq.km and A_{sm} is $\pi\,(0.20)^2$ sq. km. We see that, on an average 2 smart-meters are heard for by every meter in the neighborhood leading to which 3 smart-meters would suffice to cover an entire micro-neighborhood.

$\eta_{effective}$ will be greater than 1 even for ρ to be equal to 2. However, covering the same area with just 2 smart-meters means higher transmission power is needed. This shows that, atleast 3 smart-meters are required for the defined evaluation parameters. Hence we have arrived at an optimum number of smart-meters for $\pi\,(0.25)^2$ sq.km area needed to achieve network availability as far as the smart-meter as a device is concerned.

C. Evaluation of throughput and delay as a function of smart-meter density

In this subsection, we compare and analyze the performance of the flattened network in terms of throughput and delay with ρ taking values 3 and 8. Throughput in bps is defined as the amount of data that is successfully received at the network layer, and the end-to-end (E2E) delay is measured as time taken for demand to reach the destination from the source. From Figure 4, we clearly see a severe degradation in network performance when ρ is equal to 8. This shows that the throughput is not consistent and hence a particular node might not actually be available always for communication leading to the drastic increase in E2E delays. Analytical modeling explaining the drop in performance is discussed in Section IV-F.

The ideal behavior to characterize availability in this architecture is to have throughput degradation but with minimal variance around its mean. So, as long as there is consistent throughput in the flattened network, we are guaranteed of data being delivered at the cost of increased delay. This desired behavior is seen from the Figures 4a and 4e when ρ is 3.

D. Scalability property

We study scalability as a function of number of micro-neighborhoods failing. From Figure 5, we clearly see a graceful degradation in network performance, but not drastically dropping to an extremely low performance values that could render the flattened network unusable. Thus we show that even with an increase in micro-neighborhoods failing, we could still achieve a disaster survivable architecture. Figure 5 complements the results from Figures 4a and 4e which show network availability in both cases of one micro-neighborhood failing to all three micro-neighborhoods failing.

E. Impact of TDMA neighborhood size on flattened network performance

In the flattened network, smart-meters access the medium using a decentralized TDMA model. This means that for a given ρ and flattened network area increasing, the number of TDMA neighbors sensed by each smart-meter is bound to increase. Impact of this increase is, lesser number of data slots that would be available for each contending smart-meter leading to fall in throughput at each of the smart-meters.

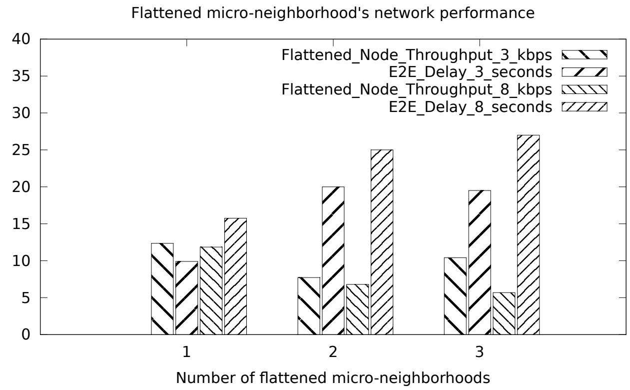


Fig. 5: This figure shows the network performance in terms of average throughput in kbps (Flattened_Node_Throughput_ρ_kbps) and average end to end delay (E2E_Delay_ρ_seconds) in the flattened micro-neighborhoods and also for ρ taking values 3 and 8. N_1 is flattened first, then N_1 and N_2 are flattened and finally N_1, N_2 and N_3 are flattened.

Network performance as a function of TDMA flattened neighborhood size from Table III is plotted in Figure 6. This figure clearly tells us that over provisioning the micro-neighborhood would lead to increasing in the number of TDMA neighbors seen by each smart-meter. This means that throughput will fall more rapidly and could bring down the network operation's efficiency when flattened. The throughput performance from Figure 6 also follow the scaling law as proposed in [10]. Hence, a definite trend in throughput performance degradation can be understood with increasing neighborhood size.

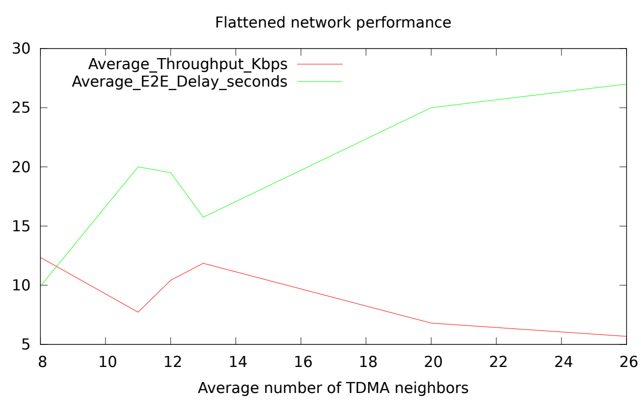


Fig. 6: This figure shows the network performance in terms of average throughput in kbps (Average_Throughput_kbps) and average end to end delay (Average_E2E_Delay_seconds) versus TDMA neighbor size

TABLE III: Evaluation of slot allocation expectation from the analytical model (E-n_f) to the results obtained from simulation (R-n_f)

Neighborhood(s) Flattened	ρ	N_{sm}	E-n_f	R-n_f
N_1	3	8	5.5	6.3
N_1, N_2	3	11	4	4
N_1	8	12	3.67	4
N_1, N_2, N_3	3	13	3.38	3.25
N_1, N_2	8	20	2.20	1.68
N_1, N_2, N_3	8	26	1.69	1.58

F. Modeling TDMA slot allocation and impact on delay performance

Given a TDMA frame, the data slots need to be shared by the contending smart-meters. In order to achieve reliability in the network performance, TDMA profile is designed to have 4 dedicated slots in each frame for each smart-meter. A probabilistic framework is developed in this subsection to estimate slots allocated to each smart-meter in each frame.

We start the problem formulation by defining some parameters that will help in arriving at the probabilistic framework. 1) n_f: Data slots per frame, 2) **i**: A random variable that represents the number of slots a station gets in a frame and takes values [1:n_f], 3) N_{sm}: Number of smart-meters seen on average as neighbors by each of the smart-meter in the flattened grid and 4) p: Probability of a smart-meter getting a slot in the frame. When the N_{sm} smart-meters contend for a slot in the frame, the probability p of a smart-meter getting that slot is $\frac{1}{N_{sm}}$. The contention for each subsequent slot is independent of the outcome of contending for a slot previously in the same frame. For a smart-meter to have gotten $\boldsymbol{i}$ slots in a frame, it has seen $\boldsymbol{i}$ successes and n_f-$\boldsymbol{i}$ failures.

Thus the probability of obtaining **i** slots in a frame is $p^i*(1-p)^{(n_f-\mathbf{i})}$. Since the **i** slots can be in any order, the probability mass function of **i** is binomial. Hence the expectation of **i** becomes $n_f p$.

This analytical framework developed gives us the average number of slots a smart-meter gets per TDMA frame n_{slots}. The results from simulations and from the analytical model are tabulated in Table III, and we see about analytical model's results are 4% within simulated results.

Given that we have modeled the slot allocation mechanism, we now go a step further to model estimated value of delay. We now restructure the problem as, what is the expected number of frames that are needed to transmit a given quantity of data. This expectation now should also factor the loss seen in the physical layer that affects the throughput seen at the network layer. We assume that no delay to exist in data transfers between layers. Hence, the only delay seen is due to the transmission and data being queued for transmission denoted by D_q.

We start this exercise with the data rate of the sender D bps. We now model what is the expected number of frames required for D bits of data to reach the receiver. Let the data rate on an average be scaled by a factor of $\frac{1}{\sqrt{n_{sm} log\, n_{sm}}}$, and lets call this scaled data rate as D' bps. Each smart-meter on an average gets n_f slots per frame who's length is 100 msec. Thus in one second, a smart-meter gets $10n_f$ slots on average. If D' bits are received in $10n_f$ slots, the total number of slots needed to receive D bits is $\lceil \frac{10n_f D}{D'} \rceil$. Our problem statement now is to understand how many frames k are needed to receive D bits factoring losses due to bit error in the channel given by p_e. Let the number of slots seen in k frames be denoted by N_f^D.

$$P\left[p_e\left(\sum_{j=1}^{k} n_f^j\right) \leq N_f^D\right] \leq \epsilon \tag{1}$$

Using D as 25000 bps, ϵ as 0.005 and values of n_{sm} from Table III, we tabulate N_f^D, k and D_q in Table IV. The probability of successful transmission p_e, we noticed that on an average 50% of the bits were in error as seen in simulation results and hence we use p_e as 0.5 in estimating k. The average delay calculated as $k\,f_l + D_q$, is compared with the delay from the simulations and is plotted in Figure 7.

TABLE IV: Delay performance from TMDA's analytical model

n_{sm}	Slots/second	N_f^k	k	D_q seconds
8	55	148	66	1.6
11	40	136	84	2.38
12	33.8	122	87	2.29
13	36.7	140	106	2.8
23	22	124	162	4.596
26	16.9	102	155	5.06

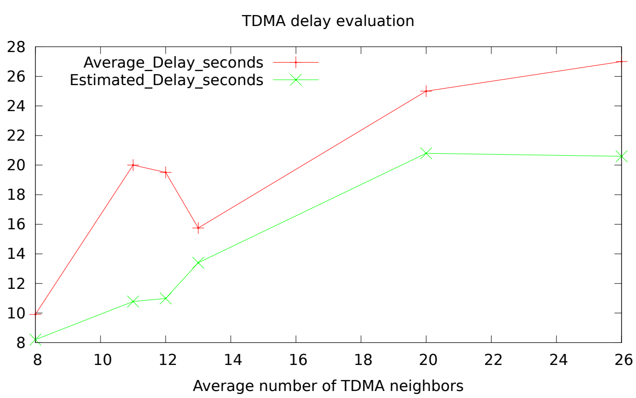


Fig. 7: This figure shows the comparison in delay as seen in the simulations with respect to the delay calculated from the TDMA's analytical model. The difference in analytical model's results to simulation results is due to the fact that we have not factored for all components that contribute to OPNET's modeling behavior.

We see that the analytical model performs equally well when compared to the simulated data. With this modeling framework, we have now provided a complete framework where a utility service provider can model the network performance and then accordingly plan the neighborhood and accordingly deploy the survivable communication architecture that supplements their current power grid.

V. Conclusion

We proposed a novel disaster survivable communication architecture for the smart grid was proposed. Our proposed architecture acts as an overlay on the existing power grid with post-disaster communication being facilitated by the grid flattening process. Timely and efficient dissemination of control data is possible through the hierarchical links and mesh networking at different system levels. We simulate this architecture using OPNET and use analytical models to study and compare the architecture's performance when the grid is flattened. Thus we have provided a complete framework to model a disaster survivable communication architecture for the smart grids. Simulated study results validate the results obtained from our analytical models. As future work, we will continue to develop the algorithms needed to flatten grid components using mesh networking fundamentals and make the architecture more scalable. We also intend to patch the difference in results from simulations and analytical models by further factoring in components that precisely model the OPNET modeler's behavior. As an interesting exercise, we also intend to setup a testbed of smart-meters that allow us to implement the grid flattening process we proposed.

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