

Smart Grid Communication using Next Generation Heterogeneous Wireless Networks

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Abstract — In this paper, we present a Smart Grid Home Area Network communication infrastructure solution that is based on future next generation heterogeneous wireless systems. The heterogeneous wireless system is composed of several Radio Access Technologies (RATs) available at consumer premises. The smart devices that use Smart Grid applications are assumed to have reconfigurable radios. A centralized Global Resource Controller (GRC) instructs the smart devices to use a particular RAT at any given time. The device-to-RAT association is made by the GRC using a two-step scheduling algorithm that accounts for the requirements of both best-effort and real-time Smart Grid traffic. To make the solution scalable, the approach utilizes Dynamic Spectrum Access methods to obtain additional open spectrum. We show up to 80% increase in real-time traffic support and 726% increase in best-effort traffic support in our proposed heterogeneous wireless system that uses reconfigurable radios, compared to the homogeneous wireless networks used today by smart devices with static radios.

Keywords — heterogeneous wireless networks; reconfigurable radios; smart grid

I. INTRODUCTION

The utility industry is evolving the current power grid to incorporate advanced two-way communications and distributed computing capabilities for improved control, efficiency, reliability and safety of power distribution and management. The resulting next-generation electric grid, known as Smart Grid, is expected to support a myriad of applications that have diverse traffic requirements. As described in [1], Smart Grid applications include Advanced Metering Infrastructure (AMI), Automated Demand Response (ADR), Feeder Automation (FA), Electric Vehicle Charging (EVC), and Mobile Workflow Management (MWM). The AMI application will enable utility companies to perform remote meter management. The ADR application will enable utility companies and the consumers to reduce the carbon footprints by utilizing real-time information to consume energy in an efficient manner. The FA service will enable utility companies to optimize their operating costs by controlling substations in emergency situations. The Electric Vehicle market is expected to grow considerably in the next few years and it is expected to have a penetration of 5% of the market by 2020 [2]. Millions of vehicles will need to be integrated into the power grid for EVC services. Although AMI enables utility companies to remotely manage readings, installation and repair of meters and other equipment still must be coordinated via MWM. One common requirement of all Smart Grid applications is their reliance on potentially large

number of sensors that communicate over local wireless networks using either Zigbee or 802.11 protocols. A critical factor in the required cyberinfrastructure is timely access to information via a reliable communication infrastructure.

Similar to the current telecommunication networks, the Smart Grid communication infrastructure is expected to be hierarchical in nature. The Smart Grid communication network will be spread over large geographical areas for generation, transmission, and distribution to the consumer premises [3]. Figure 1 shows a basic diagram that consists of an electric power grid and a hierarchical Smart Grid communication network. The home area network (HAN) provides access to in-home appliances. The HAN gateway acts as an ingress/egress point for the HAN. The neighborhood area network (NAN) connects several HANs to the power distribution center. The distribution center is connected to the core utility systems, such as a power generation center, transmission center, and command and control center, through a wide area network (WAN).

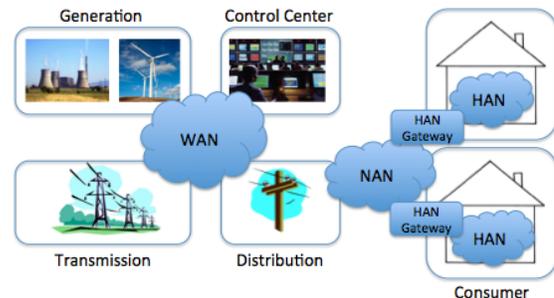


Figure 1. Smart Grid Communication Infrastructure

The traffic generated by applications running on these networks is heterogeneous in nature in terms of Quality of Service requirements (maximum delay, minimum throughput, reliability etc.) [4][5]. For example, AMI requires low throughput and can tolerate high latency, whereas ADR requires medium throughput and medium to low latency and FA requires high throughput and low latency. AMI is a member of Best Effort traffic class, whereas ADR and FA are examples of Real Time traffic class. These Quality of Service requirements for various classes of traffic often dictate the choice of network access technology. A HAN is likely to have multiple forms of wired broadband access such as DSL and cable, or Power Line Communications (PLC) as defined by emerging standards [6]. In addition, a HAN will have access to multiple wireless access networks such as Zigbee, Wi-Fi

and 3G/4G cellular networks. An assessment of communication technology options for smart grid applications is presented in [1]. Regardless of the choice of communication technology, deploying and maintaining a dedicated communication infrastructure is a costly proposition for utility providers. Therefore, we assume that Smart Grid traffic will use existing communication infrastructure. We limit our attention to HAN scenarios in which multiple wireless access networks are available.

In this paper, we propose the use of a heterogeneous wireless network composed of several Radio Access Technologies (RATs) to manage Smart Grid traffic in the HAN. It is likely that a combination of unlicensed and licensed spectrum will be used in a HAN. Further, it is likely that spectrum will be accessed in multiple ways, ranging from standards-based centralized methods (e.g., local Wi-Fi or operator supported 4G) to dynamic spectrum methods (i.e., based on emerging protocols such as 802.22 [7]). With these motivations, supported by recent work that explores cognitive radios in Smart Grids [8]-[11], we assume that the devices supporting Smart Grid applications, henceforth referred to as *smart devices*, are equipped with a reconfigurable radio (RR). Note that in a shared network, the ability of each RAT to support throughput and latency requirements of various smart devices varies depending on parameters such as network load, congestion and interference. To map the RR of each smart device to the most appropriate RAT, a Global Resource Controller (GRC) is used. In addition, to accommodate the future growth in the numbers and types of applications and connected devices, the Access Point (AP)/Base Station (BS) of each RAT is assumed to be capable of obtaining additional open spectrum through Dynamic Spectrum Access (DSA) techniques. The primary contribution of this paper is the development and validation of an approach for building a heterogeneous system that supports the diverse networking requirements of devices in a Smart Grid HAN. We further show that the robustness of the HAN is greatly increased when devices are agile and centrally coordinated. This result is important as this solution can potentially be achieved with the emerging 802.11ac standard.

The paper is organized as follows: Section II presents relevant background for heterogeneous wireless networks. We describe the system model and provide the research methodology in Section III. We discuss the results in Section IV. Section V provides conclusions and identifies possible future work.

II. BACKGROUND

The use of multiple wireless access technologies (heterogeneous wireless networks) in a Smart Grid context was first proposed in [12] to support the varying traffic requirements for overhead transmission line monitoring. At the network level, architectures and frameworks to support such hybrid or heterogeneous wireless networks have been suggested in [13]-[15]. A survey of these architectures is provided in [13]. Recent proposals are based on the Media Independent Handover function defined by the IEEE 802.21

standard, which provides a framework to support seamless transition through networks based on different RATs [14]. Another relevant standard, IEEE P1900.4, defines building blocks for enabling coordinated network-device distributed decision making that contributes to the optimization of radio resource usage, including spectrum access control, in heterogeneous wireless access networks [15]. Hierarchical resource managers have been proposed by the Common Radio Resource Management, Joint Radio Resource Management, and Multi-access Radio Resource Management schemes studied by the 3GPP group. Finally, perhaps most relevant for this paper are the emerging standards from the IETF and 3GPP communities to support *flow mobility* when a device switches its data flows over multiple wireless access systems [16]-[17]. A common attribute of all of these frameworks is that the local resource managers of various RATs interact with a centralized entity to jointly optimize the resource allocation process. The centralized GRC serves the same purpose in our system.

From a platform perspective, significant progress has been made in recent years in software defined radios, cognitive radios, and cognitive networking. For reconfigurable devices, a primary limitation is power consumption. In our prior work [18], we studied the tradeoffs in terms of spectral efficiency and power consumption as the reconfiguration capabilities of the devices increased. Although it is difficult to generalize results, one scenario that was analyzed suggests that it is possible to increase spectral efficiency by up to 75% but at the cost of twice the power requirement. Today, network equipment vendors package application specific circuitry that is sufficient to operate over relatively few RATs, but future devices are likely to incorporate more reconfigurable capabilities as the technology evolves.

The reconfigurable radio can operate over a range of communication modes and spectra. It has been well documented that in many geographic areas, licensed spectrum is underutilized [19]. The Dynamic Spectrum Access (DSA) community has paved the way for standards and implementations to enable unused spectrum to be used opportunistically. The LTE-Advanced standard defines carrier aggregation technique as a key feature, which enables the use of up to 100 MHz of contiguous or non-contiguous spectrum that may be obtained opportunistically via DSA [20]. Standards activities such as those related to LTE-Advanced [21] and IEEE 802.19.1 [22] are defining standards-based frameworks through which independent networks can interact with spectrum management services to negotiate controlled use of open spectrum. Our work assumes that a spectrum manager entity exists in the network. Furthermore, the IEEE 802.22 standard, which defines the air interface for a wireless regional area network (WRAN), is currently defining the use of available portions of television spectrum (TV white space) using cognitive radios [7]. Several authors have even proposed cognitive radio-based solutions using this standard for Smart Grid WAN [8][9]. To address the uncertainty about future growth of Smart Grid traffic, a scalable solution that obtains additional spectrum opportunistically, along with a unifying control scheme that creates a robust cyberinfrastructure based on multiple independent wireless networks, is crucial.

III. SYSTEM DESCRIPTION

A. System Model

Figure 2 illustrates the proposed system model. The system consists of smart devices equipped with a reconfigurable radio (RR) that can connect to one or more RATs. Two resource-controlling entities exist in our proposed system: 1) a Global Network Resource Controller (GRC) is present in the backend network; and 2) a Base Station (BS)/Access Point (AP) for each RAT. The GRC makes decisions on large time-scales (seconds), using average statistics to assign the most appropriate BS/AP to use for connectivity to each RR. The BS/APs operate over small time scales (milliseconds) to manage the resources of their corresponding RAT and account for fluctuations in connectivity parameters. The Spectrum Manager entity is located somewhere in the Internet; it maintains a database of available and leased open spectrum. The Neighborhood Area Network (NAN) aggregates traffic from multiple HANs and provides a portal to the utility's backend systems.

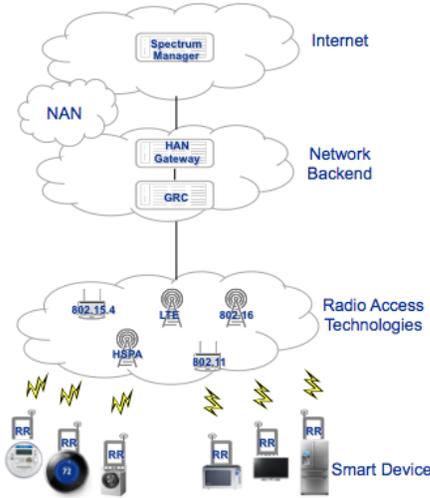


Figure 2. System Model

Each BS/AP can communicate with the Spectrum Manager to lease additional open spectrum. The spectrum leasing procedure is illustrated in Figure 3. The BS/AP can initiate a spectrum lease request in response to any of several triggers, such as, an increase in traffic demand, load balancing, an agreement with a primary spectrum owner for periodic use, etc. Once the Spectrum Manager receives the request, it evaluates spectrum availability and grants the spectrum to the requesting BS/AP if it is available. The spectrum is leased to the requesting BS/AP for a duration specified by Spectrum Lease Duration shown in Figure 3. Upon receiving, or relinquishing this additional spectrum, the BS/AP calculates the corresponding increase or decrease in RAT resources.

From an operational perspective, the RR first must sense RATs and register with the GRC before transmitting or receiving any data. We show the procedural flow example of this process in Figure 4. First, the RR senses and scans for available RATs and their utilization. Selecting one of the available RATs, the RR obtains an IP Network connection,

which it uses to communicate with external hosts. Next, the RR discovers, registers, and communicates with the GRC application server, which we assume uses standard discovery and registration procedures. After establishing a connection with the GRC, the RR delivers periodic sensing information about available RATs to GRC. Upon receiving this periodic sensing information from the RR, the GRC can calculate the RR-RAT mappings and the rate assignment per mapping. This information is then relayed to each RR, which uses it to tune its radios to the appropriate RATs, and HAN Gateway: the gateway in turn uses this information to forward the incoming traffic to the appropriate RATs.

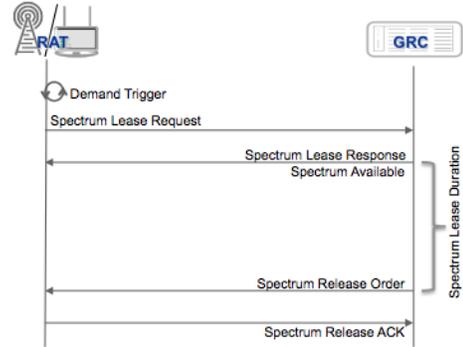


Figure 3. Spectrum Leasing Procedure

After each RR is configured according to the RR-RAT mapping, radio links are established with the associated RATs for data transmission and reception. The HAN gateway acts as an ingress/egress point for traffic sent to and received from smart devices. For incoming Smart Grid traffic, the NAN forwards the traffic intended for smart devices to the HAN gateway which passes it along to the appropriate RAT using connectivity information obtained from GRC. Outgoing traffic flows in the reverse direction from smart devices to the HAN gateway, which forwards the traffic to the NAN.

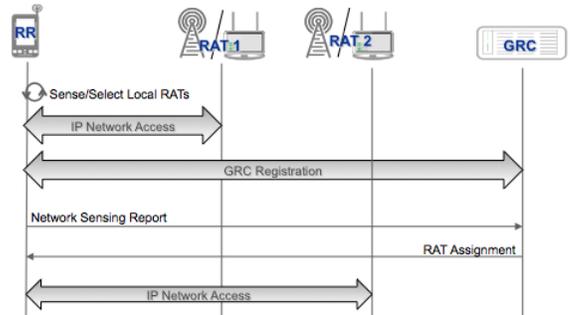


Figure 4. Resource Allocation Procedure

B. GRC Scheduling

The GRC implements a scheduler that assigns each smart device's RR to the most efficient RAT. The GRC scheduler determines these RR-RAT assignments periodically (every 1 second). For each 1-second interval, the scheduler tries to satisfy two types of Smart Grid traffic classes: (1) Real-Time traffic with strict delay requirements; and (2) Best-Effort traffic with no delay requirements. The real-time traffic supports applications such as ADR that can generate periodic traffic that

is up to 100 Kbps/node [1]. The best-effort traffic supports applications such as AMI that do not have strict delay requirements. To support each traffic type, the scheduler follows a two-step approach. Because the scheduler operates on a 1-second frequency, it identifies the minimum throughput requirement for real-time traffic of each smart device per scheduling interval through the network sensing report procedure described earlier and illustrated in Figure 4. In this network sensing report, the RR also relays information about the Modulation and Coding Scheme (MCS) that it can use to connect to any available RAT. In addition, the network sensing report includes the number of Resource Blocks (RBs) that each RAT possesses for a 1-second interval. In the first scheduling step, using the network sensing report information, the scheduler follows a greedy bin packing approach to satisfy the minimum required throughput of each smart device by assigning each RR to the RAT to which it can connect using the highest MCS in a sorted fashion. In the second step, the scheduler distributes unused RBs of each RAT to RRs using Proportional Fair (PF) scheduling. For best-effort traffic, PF is an accepted compromise to obtain high throughput vs. fairness tradeoff [23]. The overall order of allocation begins with RATs that have the most allocation resources (RBs) and proceeds to RATs that have the fewest allocation resources. The pseudo-code for the algorithm implemented by the scheduler is presented in Algorithm 1.

Algorithm 1. GRC Scheduler Pseudo-Code

```

% Initialization
1. avg_throughput_all_RR = 1
2. for each time unit t
3.   sortedlist = sort each RR according to MCS
4.   for each RAT in descending order
% Step 1: Real-Time Support
5.   i = 1
6.   while (rt_support_any_RR == false &&
           rem_RB_any_RAT > 0)
7.     if (rem_RB(sortedlist(i).RAT(j)) ≥ req_RB(i))
8.       sortedlist(i).RR = assign(RAT(j))
9.       i.assigned_RB = req_RB(i)
10.      sortedlist(i).rt_support = true
11.      rem_RB(RAT(j)) = rem_RB(RAT(j)) - req_RB(i)
12.     end if
13.     i = i + 1;
14.   end while
% Step 2: Best-Effort Support
15.  for each RAT j
16.    if (rem_RB(j)) > 0)
17.      i = RR with highest inst_to_avg
           throughput ratio using RAT j
18.      i.assigned_RB = i.assigned_RB + rem_RB(j)
19.    end if
20.  end for
21.  for each RR i
22.    avg_throughput(i) =
        0.9 * avg_throughput(i) for time t - 1 +
        0.1 * throughput(i) for time t
23.  end for
24. end for each time unit t

```

C. Simulation Description

We developed a MATLAB-based simulation model with sufficient fidelity to demonstrate the properties of our proposed heterogeneous wireless system for Smart Grid communication. We consider the presence of a HAN in a 200 * 200 m² area that uses multiple RATs. We use four RATs in our experiments; each RAT manages 20 MHz spectrum. The APs/BSs of these RATs are placed on four different corners of the grid. We assume a Wi-Fi like coverage area for each RAT. In addition, each RAT supports adaptive MCS. We placed 100 smart devices randomly in the grid. Based on the location of the smart device in the topology, the RRs on these devices can connect to any of the four RATs using one of the supported MCSs provided in Table 1. The closer the RR is to a BS/AP, the better the signal reception the RR experiences at that location. This translates into a better MCS mapping for the RR to connect to the particular RAT under consideration. The overall simulation topology is presented in Figure 5. Simulation parameters are summarized in Table 1.

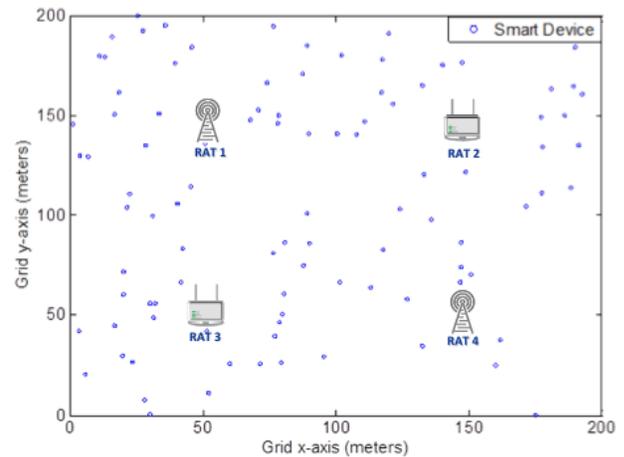


Figure 5. Coverage of the simulation topology

TABLE 1. SIMULATION PARAMETERS

Simulation Parameter	Value
Smart Devices	100
Number of RATs	4
RAT Spectrum	20 MHz
RAT RBs/sec	12,000
RAT MCS	BPSK 1/2, BPSK 3/4, QPSK 1/2, QPSK 3/4, 16-QAM 1/2, 16-QAM 3/4, 64-QAM 1/2, 64-QAM 3/4
RAT Coverage	200 m
Open Spectrum Bands	4
Open Spectrum Channels	4 * 5 MHz
Real-Time Traffic	100 kbps/device
Simulation Duration	10,000 seconds

Because each RAT is a part of existing communication infrastructure at a consumer’s residence, the RAT not only supports Smart Grid traffic, but it also supports other Internet traffic. As a result, we introduce an experimental parameter, *network outage*, that models the support for other Internet traffic. Network outage represents the percentage of time each RAT is unavailable to the smart devices. An outage might

IV. RESULTS AND ANALYSIS

occur for various reasons, including congestion that results from an increase in Internet traffic, time-varying channel impairment caused by multipath or RF interference, AP/BS malfunctions or software upgrades, or even network attacks such as Denial of Service. The network outage experimental parameter controls the percentage of a RAT's RBs that are effectively not available to Smart Grid traffic. We vary the outage percentage from 0% to 80% in increments of 5% in our simulation. Each RAT suffers independent random outages with the probability determined by the network outage percentage. As a result of these outages, it becomes crucial for the heterogeneous wireless system to adapt by reconfiguring devices to use a different spectrum.

In our simulation, we assume that the DSA capability has been integrated into the BS/AP of each RAT. In addition to the 20-MHz band managed by each RAT, the BS/AP of each RAT can access four bands of open spectrum. For simplicity, we assign one open band to each BS/AP. Each band of spectrum has four available channels of 5 MHz each. The channel availability (which depends on the duty cycle of the channel use) of each open band is modeled by the work described in [24]. Wellens, in [24], developed this model by using energy detection of 200 KHz-wide channels for one-second intervals in residential and office area settings. The bands were considered to be in use if the measured energy on the channel was above -107 dBm; otherwise, the bands were considered unused and available. Based on the results, Wellens et al proposed a modified beta distribution probability density function to model channel duty cycle, namely:

$$f_{m\beta}(x; \alpha, \beta) = p_{DC=0} \cdot \delta(x) + (1 - p_{DC=0} - p_{DC=1}) \cdot f_b(x; \alpha, \beta) + p_{DC=1} \cdot \delta(x - 1),$$

where $x \in [0,1]$, $p_{DC=0}$ and $p_{DC=1}$ are parameters used to characterize the duty cycle, $\delta(x)$ is the Dirac delta-function and $f_b(x; \alpha, \beta)$ is the probability density function for the beta distribution, specified by:

$$f_b(x; \alpha, \beta) = \frac{1}{\mathcal{B}} x^{\alpha-1} \cdot (1-x)^{\beta-1},$$

and where \mathcal{B} , the beta function, is:

$$\mathcal{B}(\alpha, \beta) = \int_0^1 t^{\alpha-1} \cdot (-t)^{\beta-1} dt$$

TABLE 2. CHANNEL DUTY CYCLE PARAMETERS [24]

Band Descriptor	$p_{DC=0}$	$p_{DC=1}$	α	β
TV 770 MHz AB	0.189	0.342	0.414	1.103
GSM 1800 DL AB	0.193	0.616	0.716	1.202
DECT 1900 MHz AB	0.073	0.0	1.688	4.927
ISM 2.4 GHz AB	0.144	0.0	0.84	5.947

The corresponding parameters associated with the four open bands used in the simulation are presented in Table 2. Following the channel duty cycle distribution, the BS/AP of each RAT obtains additional spectrum in the four open bands that translates to additional RBs for the corresponding RAT in our simulation. We set the Spectrum Lease Duration value to 1 second.

We study three simulation scenarios that capture the trends of radios expected to be used in smart devices over time. The main obstacle in equipping each device with a completely reconfigurable radio is energy consumption. In an analysis we performed in our earlier work [25], we showed that a completely reconfigurable radio can achieve over 500% increase in spectral efficiency, but at the same time it will consume more than 600X more energy using the existing reconfigurable radio fabric. So, the transition to completely reconfigurable radios is expected to be gradual. Hence, we consider the following three scenarios:

- *Scenario 1*: Represents the situation today. Each smart device is equipped with a static radio that supports only one RAT. So in our simulation, using random device-RAT assignments, 25 devices use RAT 1, 25 use RAT 2, 25 use RAT 3, and 25 use RAT 4.
- *Scenario 2*: Represents the use of static multi-modal radios such as those present in many mobile phones today. Each smart device is equipped with four different radios to support all four RATs. The GRC instructs the smart device to use a specific RAT at any particular time. However, these devices cannot use any open spectrum.
- *Scenario 3*: Represents the use of completely reconfigurable devices. These devices can use any of the four RATs and also the additional open spectrum obtained by the BS/AP, because these radios can tune to any spectrum band as required.

Scenario 1 uses simulation parameters presented in Table 1. For Scenarios 2 and 3, because each smart device communicates with the GRC to determine which RAT to use at any particular time, 25% of the RBs (presented in Table 1) available per RAT are deducted to account for this overhead.

Each simulation scenario runs for 10,000 seconds. We show the support for both real-time (100 Kbps) and best-effort Smart Grid traffic in Figures 6 and 7 respectively. From these figures, it is clear that reconfigurable devices are capable of supporting any amount of demand levels because they can operate over any open spectrum that is acquired on an as-needed basis. When the available RATs are highly congested (80% network outage), Scenario 3 (which uses completely reconfigurable smart devices) can support 80% more real-time Smart Grid traffic than Scenario 1 (which uses a single static radio); and Scenario 3 can support 40% more real-time Smart Grid traffic than Scenario 2 (which uses static multi-modal radios). For the same network outage setting, in addition to this gain in real-time traffic support, the gain in best-effort traffic support for Scenario 3 ranges from 220% (117.17 Kbps to 375.36 Kbps) to 726% (117.17 Kbps to 968.46 Kbps) as compared to Scenarios 1 and 2, depending on the number of open channels used by Scenario 3 (1-4 channels). Also, the trend in Figure 7 clearly shows that by obtaining more open channels, an additional increase in Smart Grid traffic support can be achieved, thus indicating that the solution is highly scalable.

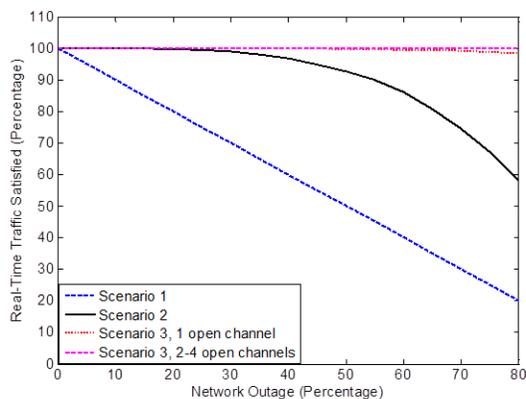


Figure 6. Percentage of Real-Time Traffic Supported

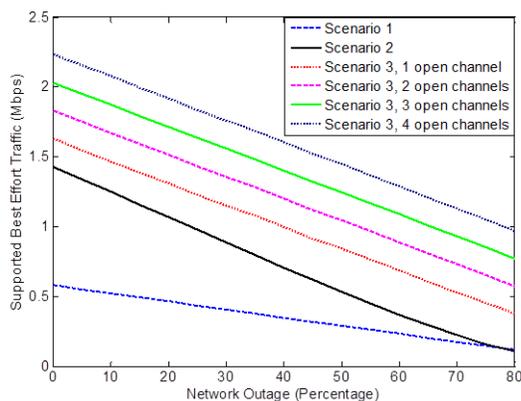


Figure 7. Supported Best-Effort Traffic

V. CONCLUSIONS AND FUTURE WORK

We presented a Smart Grid HAN communication infrastructure solution based on future heterogeneous wireless systems that incorporates:

- 1) the use of co-operative networking paradigms such as Dynamic Spectrum Access
- 2) a centralized resource controller that is involved in resource allocation process at the global level; and
- 3) the use of reconfigurable smart devices.

Using a two-step scheduling solution suitable for supporting real-time and best-effort traffic classes and an open spectrum access method supported by actual measurement studies, we showed up to 80% increase in real-time traffic support and 726% increase in best-effort traffic support in a scenario that uses reconfigurable radios (compared to the static radios used today by most smart devices).

In this study, we restricted our simulation scenario to HANs in which we assumed several wireless RATs exist that are subscribed to by the user. For NAN and WAN networks, the same concepts used in this paper are applicable; however, the cost of operating and using RATs also must be considered when selecting one of the access networks from several available RATs. As a part of future work, we intend to incorporate the cost parameter in our GRC scheduling algorithm that selects the access network for smart devices, thus making our solution applicable for NANs and WANs.

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