Talking After Lights Out: An Ad Hoc Network for Electric Grid Recovery

Jan Janak*, Dana Chee†, Hema Retty‡, Artiom Baloian*, Henning Schulzrinne*
*Department of Computer Science, Columbia University, USA
†Perspecta Labs, USA
‡FAST Labs, BAE Systems, USA
Email: janakj@cs.columbia.edu, dchee@perspectalabs.com, hema.retty@baesystems.com, ab4659@columbia.edu

Abstract—When the electric grid in a region suffers a major outage, e.g., after a catastrophic cyber attack, a “black start” may be required, where the grid is slowly restarted, carefully and incrementally adding generating capacity and demand. To ensure safe and effective black start, the grid control center has to be able to communicate with field personnel and with supervisory control and data acquisition (SCADA) systems. Voice and text communication are particularly critical. As part of the Defense Advanced Research Projects Agency (DARPA) Rapid Attack Detection, Isolation, and Characterization Systems (RADICS) program, we designed, tested and evaluated a self-configuring mesh network architecture and prototype called the Phoenix Secure Emergency Network (PhoenixSEN). PhoenixSEN is designed as a drop-in replacement for primary communication networks, combines existing and new technologies, can work with a variety of link-layer protocols, emphasizes manageability and auto-configuration, and provides a core set of services and applications for coordination of people and devices including voice, text, and SCADA communication. The PhoenixSEN prototype was evaluated in the field through a series of DARPA-led exercises. The same system is also likely to support coordination of recovery efforts after large-scale natural disasters.

Index Terms—Ad hoc networks, network architecture, network security.

I. INTRODUCTION

Most electric power outages are locally-contained and recovery can rely on the public or utility-owned communications infrastructure to coordinate restoration and energizing parts of the electric grid. Large-scale electric power outages, a.k.a blackouts, are rare but do happen [1], [2]. Recovering from a large-scale outage typically follows a special procedure known as black start. “A total or partial shutdown of the national electricity transmission system (NETS) is an unlikely event. However, if it happens, we are obliged to make sure there are contingency arrangements in place to ensure electricity supplies can be restored in a timely and orderly way. Black start is a procedure to recover from such a shutdown.” [3]

In the United States (U.S.), the black start procedure is usually managed by regional transmission organizations (RTOs) that coordinate several electric utilities. For example, PJM, a large RTO, describes its black start operation as follows: “Black Start capability is necessary to restore the PJM transmission system following a blackout. Black Start Service shall enable PJM, in collaboration with the Transmission Owners, to designate specific generators whose location and capabilities are required to re-energize the transmission system.” [4]

Even if sufficient black start generating capability is available, a successful black start requires coordination of electricity supply and demand, typically by incrementally adding both generating capacity and load. Such coordination usually takes place either via phone calls to substation personnel, or via real-time control of supervisory control and data acquisition (SCADA) devices. Both cases require network connectivity. Grid operators often rely on internet service providers (ISPs) for network services [5]. If the ISPs are also impaired by the blackout, network connectivity may be difficult to guarantee.

If the blackout is caused by a network-based cyber attack, the attacker may also attempt to actively thwart or delay power restoration, making a bad situation worse. The Defense Advanced Research Projects Agency (DARPA) has recognized the danger network-based cyber attacks represent for the U.S. critical power grid infrastructure and launched the Rapid Attack Detection, Isolation, and Characterization Systems (RADICS) program [6]. The goal of the program is to create a set of tools that will aid the power distribution industry in recovering from a hypothetical large-scale blackout triggered by a network-based cyber attack.

In this paper, we present the design, prototype implementation, and experimental evaluation of the Phoenix Secure Emergency Network (PhoenixSEN) designed by BAE Systems and Columbia University as part of the DARPA RADICS tool set. PhoenixSEN consists of a hybrid, isolated, self-forming network and services specifically designed to enable the coordination of power restoration amidst an ongoing network-based cyber attack. It combines existing and new technologies, can work with a variety of link-layer protocols, and provides applications for rapid coordination of people and devices. The network is designed as a drop-in replacement for primary communication networks that are likely to be severely impaired during a large-scale blackout.

We begin by discussing the motivation and the problem
being addressed by our work (and the DARPA RADICS program in general) in Section II. Section III presents a simplified model of the U.S. electrical grid with an emphasis on networking infrastructure. We then discuss the general architecture and features of the Phoenix network and node in Section IV. The subsequent sections describe various building blocks, applications, and services in detail: naming and service discovery (Section V), voice and chat support (Section VI), network monitoring (Section VII), and insider attack mitigation (Section VIII). We conclude in Section X and discuss potential future work and applicability of PhoenixSEN to other scenarios, e.g., natural disaster response.

II. MOTIVATION & PROBLEM STATEMENT

Our work is primarily motivated by the need of the power distribution industry for backup network infrastructure that could be used to recover from a large-scale blackout caused by a network-based cyber attack [7]. We assume that the grid control SCADA devices, as well as the network infrastructure itself maybe be compromised and could act maliciously. Therefore, the backup infrastructure should provide a means to reconnect healthy devices and keep those isolated from potentially compromised or malicious devices. This would allow for an incremental approach where devices are connected to the temporary (isolated) network only after they have been inspected and deemed healthy.

Like most complex networked systems today, power grid infrastructure relies, at least partially, on networks managed by external ISPs for remote command, control, and coordination of both machines (SCADA) and operators (voice). It is likely that the network infrastructure itself will be severely affected in case of a large-scale blackout. This presents an interesting “chicken or the egg” dilemma. The network needs power to connect the grid, but the grid cannot operate without the network. Clearly, there needs to be infrastructure in place that will allow the grid to be temporarily self-sufficient, at least during the initial restart phase when the grid is not yet fully operational. We envision a mostly self-configuring network infrastructure that can take advantage of various existing link layer technologies and can be deployed to geographically dispersed sites used by the power grid infrastructure after the blackout. We assume the personnel setting up the infrastructure will have technical background, but not necessarily in computer or network engineering. The network would provide the minimum set of services and bandwidth necessary to black-start the power grid in a secure manner.

A recent series of large scale blackouts illustrates that such events are not merely a hypothetical possibility. The 2019 blackout in Argentina, Uruguay, and Paraguay left 48 million people without power [1]. For comparison, the Boston-Washington metropolitan area has 50 million inhabitants. In 2019, a large-scale power outage in England affected more than a million homes and severely disrupted the public transit system [2], [8].

Network-based cyber attacks on critical power grid infrastructure can potentially have even more disastrous and long-lasting consequences, leaving tens of millions of people in large metropolitan areas without power for extended periods of time. An ongoing cyber attack on power grid systems may attempt to thwart any restart attempts, leaving a large number of people without power for days or weeks. Depending on the state of the power grid infrastructure, a full black-start recovery after a cyber attack may also take a long time, e.g., days or weeks, depending on the sophistication of the attack.

While some of the critical grid infrastructure may be temporarily powered by on-site backup diesel generators, the situation will get progressively worse as those generators begin malfunctioning or start running out of fuel. Communication networks stop working, potentially bringing down other critical services such as the Global Positioning System (GPS). Water and gas systems, hospitals, nursing homes, and waste treatment facilities will soon begin shutting down, transportation infrastructure can be severely affected. The situation gets progressively worse as more critical services shut down [9].

In a large-scale catastrophic scenario like this, with a substantial and prolonged disruption of electric power, time is of the essence. The operation of the electrical grid must be restored within a few days to prevent other critical facilities from shutting down. A full black-start recovery of the electric grid requires communication and coordination. However, communication networks are unlikely to remain operational after a substantial power disruption event.

While the main use case for the work presented in this paper is black-start recovery of the power grid, a similar architecture could also be used to create temporary isolated networks for emergency communications in various disaster relief scenarios, e.g., the hurricanes that ravaged Puerto Rico in 2017 [10]. Similar technology is being used by some disaster relief organizations such as the Red Cross [11].

III. ARCHITECTURAL MODEL OF U.S. ELECTRICAL GRID

The U.S. electrical grid is a complex, heterogeneous, geographically dispersed system that combines physical infrastructure for producing and delivering electric power with computer-based monitoring, management, and control. As essential infrastructure that has been evolving for more than a century and is subject to extensive government regulation, the grid has seen incremental upgrades and organic growth, resulting in considerable variability across geographical and political boundaries. The grid’s architecture is moving from a model with a small number of vertically-integrated utility monopolies towards an interconnected model with a multitude of utility and non-utility companies coordinating to use shared transmission infrastructure. In the interconnected model, networking infrastructure plays an increasingly important role and is critical for reliable grid operation.

In the U.S., hundreds of companies participate in the production and transmission of electric power. To ensure reliable grid operation, the Federal Energy Regulation Commission

1 A vertically-integrated utility controls all stages of electric power supply chain, from generation to distribution among consumers.
(a) Distributed grid model where electricity market participants use shared transmission infrastructure coordinated by a regional transmission operator (RTO) or independent system operator (ISO).

(FERC) has designated the North American Electric Reliability Corporation (NERC) to develop and enforce operational standards. Regional system operators coordinate the generation, transmission, and distribution of electric power. In some regions the system operator is affiliated with a particular utility company. In other regions the system operator is an independent entity known as the RTO that coordinates multiple utilities. Some regions have an independent system operator (ISO) instead with a similar role. The differences are subtle and beyond the scope of this paper. The RTO/ISO operates a wholesale electricity market, guarantees non-discriminatory access to shared grid infrastructure, and ensures reliable grid operation and compliance with NERC standards. The actual electric power generation, distribution, metering, and billing is provided by utility and non-utility companies coordinated by the RTO/ISO.

The major elements of an electric grid are the devices that produce and transmit electric power, information technology (IT), industrial control systems (ICSs), and the underlying network infrastructure. Since electric power is generated and consumed almost instantaneously, the grid must be coordinated to match power generation with demand in real-time. Fig. 1 provides a simplified architectural model of the U.S. grid with a focus on the communications infrastructure.

NERC operational standards provide high-level guidance primarily aimed at ensuring reliable grid operation. The actual implementation details of power grid systems are left to the RTOs/ISOs and utilities. As a result, existing grid systems are heterogeneous and often use a multitude of devices that communicate with mutually incompatible protocols. Early substation automation devices communicated using proprietary protocols over industry-specific buses or serial links. Modern-day substation systems tend to use standardized process automation protocols and reuse existing wired and wireless network technologies.

The flow of electric power through the grid is managed by an energy management system (EMS) program. The primary purpose of the EMS to keep the grid operational and reliable in response to varying conditions such as the available generator pool, transmission capacity, and instantaneous load. Ideally, a single instance of the EMS with the ability to remotely control critical grid devices would be provided by the RTO/ISO for the entire region. In practice, individual transmission operators typically run their own EMS to monitor and protect their assets.

The EMS obtains the data about available generation resources and transmission capacity for its scheduling and planning algorithms from the Open Access Same-Time Information System (OASIS), a standardized web-based management system [12] that serves as an interface between electricity market participants, transmission providers, and the RTO/ISO. FERC requires that each RTO/ISO must provide an OASIS node. Clients typically interact with the OASIS system by invoking Hypertext Transfer Protocol (HTTP) application programming interfaces (APIs) over the internet.

The operators of infrastructure deemed critical for the reliability of the grid by the RTO/ISO are required to provide the RTO/ISO with remote access to selected components for monitoring and control purposes. This is accomplished by integrating the RTO/ISO’s and the operator’s SCADA and synchrophasor subsystems over a redundant wide area network (WAN) provided for this purpose by the RTO/ISO. The data obtained from these subsystems is used by the EMS to build a global view of the state of the grid. Furthermore, the EMS can use SCADA to remotely control grid devices in the field, e.g., circuit breakers. Not all grid participants need to be SCADA-capable and connected to the RTO/ISO WAN. Smaller entities sometimes rely on the internet for all communication with the RTO/ISO.

From the previous paragraphs it follows that many different types of data networks are involved in managing the flow of electricity through the grid. The RTO/ISO operates a
A substation with connected devices (e.g., SCADA) must with stricter latency and bandwidth guarantees. The typical RTO/ISO WAN is a redundant Multiprotocol Label Switching (MPLS) network based on links leased from several external ISPs. The synchrophasor subsystem, if deemed critical for future grid systems, will most likely use a dedicated WAN with stricter latency and bandwidth guarantees.

The use of the public switched telephone network (PSTN) for human-to-human voice communications between the RTO/ISO and utility personnel is required by NERC. Despite an overall increase in remote instrumentation capabilities across the electrical grid, human-to-human voice communication remains the most important communication modality in emergency situations, e.g., after a blackout. To meet NERC’s strict reliability requirements, the phone system typically uses cellular or satellite phones as backup.

Each utility also operates a dedicated WAN spanning its (sometimes large) service area that connects the utility’s control center with all substations. The typical utility WAN is Internet Protocol-based (IP) and uses a combination of public (ISP-owned) and non-public (utility-owned) network infrastructure. A substation with connected devices (e.g., SCADA) must also provide a field area network (FAN). The FAN connects substation automation devices as well as any remote devices (metering, data collection) within the substation’s service area, e.g., a neighborhood. Due to the large variety in deployed automation devices, the FAN is perhaps the most heterogeneous network type and is typically based on a combination of wired and wireless technologies. The public internet (not pictured) is typically used for other communication, e.g., to access the RTO/ISO’s OASIS portal, or to transfer metering or billing information between the utility and its customers.

SCADA interactions at utility control centers, which in turn communicate with remote terminal units (RTUs) deployed at substations. The synchrophasor subsystem is based on a hierarchy of phasor data concentrators (PDCs) that aggregate and process IEEE C37.118 data streams coming from phasor measurement units (PMUs) deployed across the grid.

IV. Phoenix Secure Emergency Network

The PhoenixSEN is a self-configuring ad hoc network architecture designed to provide a drop-in replacement for the grid’s primary (ISP) communication networks. The network requires minimal deployment configuration and offers essential services for human-to-human (voice, text) and device-to-device (SCADA) coordination. Uniform hardware and software architecture allows rapid deployment from a storage facility to substations. Nodes are designed for compatibility with a variety of link technologies, e.g., radio, fiber, or powerline. Fig. 2a illustrates the overall network architecture.

PhoenixSEN consists of a designated control center (CC) and Phoenix nodes deployed to substations or relay points. The nodes are interconnected with short-distance and long-distance links. Some of the links can be provided by third-parties, e.g., the National Guard. PhoenixSEN is designed to be deployed into geographic areas served by multiple utility companies. The network provides an isolated virtual network to each utility on top of shared physical infrastructure. The virtual network spans all utility’s substations. Each Phoenix node connect its substation local area networks (LANs) to the appropriate virtual network and also route packets for virtual networks of other utilities. The CC provides additional equipment and services to facilitate network monitoring and management, and to support one-way broadcast communication across the deployment area.

Each Phoenix node provides multiple virtual LANs (VLANs) to its substation. Typically, there will be one VLAN for SCADA devices and another VLAN for IT (backend) systems. The addressing architecture of each VLAN is configurable, allowing it to match the original ISP network in order to minimize the need to reconfigure existing equipment. Each Phoenix node also provides essential network services locally to enable
communication within the substation even when disconnected from PhoenixSEN. These services include, among others, Domain Name System (DNS), Dynamic Host Configuration Protocol (DHCP), Network Time Protocol (NTP), and Voice over IP (VoIP) signaling.

The primary purpose of PhoenixSEN is to restore connectivity in a grid under network-based cyber attack. We assume the grid’s devices (SCADA and IT) might be compromised and may contribute to the attack. For this reason, Phoenix nodes provide a dedicated access port for a forensic team and services through which portions of the network or individual devices can be isolated from the rest of the network. PhoenixSEN also comes with a built-in intrusion detection system (IDS) that attempts to automatically mitigate certain types of insider attacks.

A. Phoenix Node

The Phoenix node is designed to be deployed from a storage facility to substations by ground transportation or via air lift shortly after a blackout. All hardware comes in a weather-resistant enclosure which contains all essential components such as Intel Next Unit of Computing (NUC), Ethernet switches and cables, GPS, Wi-Fi access points, and VoIP clients. All Phoenix nodes use a uniform hardware and software architecture to simplify deployment and installation. Fig. 2b illustrates the hardware architecture, Fig. 3 provides an overview of the software architecture. Fig. 9 shows a small-scale prototype built for field evaluations.

The Phoenix node is based on the Intel NUC small form-factor computer. The operating system (OS) is Ubuntu Linux 16.04 in a minimal configuration. All custom software for PhoenixSEN is pre-installed in the form of Docker containers. The containers are built from source code and are specifically designed to support re-building in the field without internet access, e.g., after modifications to fix critical bugs or vulnerabilities.

A newly deployed Phoenix node starts in a minimal configuration. In this state, the node starts only a deployment manager process and a management VLAN. Utility and substation specific services are not yet provided. The deployment manager provides a user interface (UI) for the substation crew to perform one-time deployment configuration, i.e., to enter the utility name and substation number. The management VLAN can be used by the CC for remote support, configuration, or maintenance.

The configuration for utility and substation specific services is generated by a custom configuration synthesis program out of a model of the whole PhoenixSEN. The model contains parameters such as number of utilities, number of substations per utility, desired IP addressing architecture, types of VLANs and links, etc. In most cases the model can be created prior to PhoenixSEN deployment based on information collected from utilities in the deployment region. In that case, the generated configuration library can be pre-loaded onto each Phoenix node. If the model is unavailable prior to deployment, the synthesis can be performed at the CC and the generated configuration library can be distributed to substations on a Universal Serial Bus (USB) memory card, or the CC can run the synthesis program on Phoenix nodes remotely over the management network.

Upon receiving the utility name and substation number, the node selects the appropriate configuration from the configuration library and starts utility and substation specific services and VLANs. A fully configured Phoenix node runs one or more isolated virtual network environments. The purpose of the network environment is to emulate the primary ISP network that connected the substation to the internet before blackout. Nodes with multiple links also serve as transparent routers for other utilities sharing the PhoenixSEN. The virtual network environments are configured for a particular substation and typically correspond to the substation’s VLANs, e.g., IT systems, VoIP devices (phones), and SCADA. Each environment is connected to a subset of the ports on the Ethernet switch. One port connects to the substation LAN, the other ports connect to link modems or radios. The network environments are implemented using the Linux networking namespace capability with services provided by Docker containers.

Each network environment runs its own instance of the Optimized Link State Routing Protocol (OLSR) agent which publishes the environment’s IP subnet information to PhoenixSEN. This information is exchanged only with OLSR agents that belong to the same utility and environment type (e.g., SCADA). For example, utility A’s SCADA environment on one Phoenix node connects to utility A’s SCADA environments on all other Phoenix nodes, but not to utility B’s SCADA environments.

The utilities served by the same PhoenixSEN can use conflicting or overlapping IP subnets (e.g., 192.168.x.y). Supporting such scenarios natively would require VLAN support on all PhoenixSEN links. In order to stay compatible with a wide variety of link layer technologies (including IP-only point-to-point links), the node does not require VLAN support on links. Instead, it passes all traffic through a Virtual Extensible LAN (VxLAN) [17] gateway which encapsulates Ethernet frames in User Datagram Protocol (UDP) packets prior to transmission. A unique VxLAN virtual network identifier (VNI) is generated for each utility-VLAN combination during configuration synthesis.
Each network environment provides fully isolated elementary network services to the corresponding substation VLAN such as DHCP, DNS, or NTP. The DNS service is described in Section V. Each environment also runs a custom Netmon agent to discover and identify devices connected to the substation LAN. The Netmon service is described in more detail in Section VII.

The type of the network environment determines what additional network services are created. For example, the VoIP environment provides a Session Initiation Protocol (SIP) [18] server on each Phoenix node to keep the substation’s phones operational and to provide a means of communication between the substation personnel and the CC. Please refer to Section VI for more detail. The SCADA environment provides additional services for intrusion detection and mitigating insider attacks by compromised devices (Section VIII).

B. Deployment & Network Formation

The deployment of PhoenixSEN begins with the deployment of the CC. The CC then coordinates the deployment of the rest of the network and provides remote assistance to substations while they are setting up Phoenix nodes. During the initial deployment phase, the CC may only have one-way broadcast capability, e.g., a high-power high frequency (HF) radio with voice or low-speed data support. The CC crew can use the broadcast channel to transmit substation-specific setup instructions, just enough to get the substation connected. Once the substation is connected, the CC crew can help configure the substation’s Phoenix node remotely.

Upon Phoenix node delivery, the substation crew begins setting up the node. We assume the crew has technical background (e.g., in electric grid engineering), but not necessarily in IT, communications, or networking. The node includes a playbook and detailed installation instructions. All parts and connectors are clearly labeled. The instructions are detailed enough to allow the crew to independently setup the Phoenix node in a minimal configuration with a low-bandwidth control connection to the CC. To facilitate this critical first step, the node enclosure may include a pre-configured HF receiver to receive broadcast communication from the CC.

When powered on, the Phoenix node begins to search for other Phoenix nodes on its link interfaces. Each interface has an instance of the OLSR daemon configured to automatically discover other OLSR-enabled [19] nodes reachable over the interface. Gradually, Phoenix nodes form an OLSR-based mobile ad hoc network (MANET) that eventually spans all substations and the CC. Once the network is formed, the CC can further configure and coordinate deployed Phoenix nodes over the network.

While forming, PhoenixSEN provides connectivity in phases, gradually providing additional modes of communication as the system transitions from one phase to another. The phases are as follows.

1) Low-speed, broadcast-only communication from the CC to substations in the process of deploying a Phoenix node.

2) Low-speed command and control connection between the CC and each substation. The connection provides just enough bandwidth for the CC crew to configure the Phoenix node remotely.

3) The Phoenix node is fully connected to the network, but the overlay may not have yet fully formed or the node may be in the process of resolving an addressing conflict. The substation may not be able to reach all other substations of the same utility yet.

4) The node is fully connected and provides VoIP and text communication between the CC and the substation crew. Finally, the substation or CC crew perform one-time deployment configuration by entering the utility name and substation number into the node. This step can be performed locally at the substation or remotely over the network. The node uses the entered information to create utility and substation specific services and VLANs. The process is described in more detail in Section IV-A.

V. Naming and Service Discovery

For compatibility with existing devices and applications, PhoenixSEN provides naming and service discovery services based on the DNS. The requirements outlined in Section II and the fact that PhoenixSEN must remain usable when disconnected from the internet make the traditional DNS architecture with a single authoritative master server difficult to use in an ad hoc network. In PhoenixSEN, each node should be able to independently contribute its own records into a flat namespace based on a DNS zone shared by all nodes. In this section, we describe the design of a hybrid peer-to-peer DNS system used in PhoenixSEN.

The two primary use-cases for DNS in PhoenixSEN are discovering services offered by Phoenix nodes and supporting third-party tools with pre-existing Transport Layer Security (TLS) certificates. The first use-case is implemented in the VoIP and chat service, as described in Section VI, which uses DNS service discovery to map phone numbers to Phoenix nodes in a distributed manner. The second case refers to forensic and cyber-security activities performed with third-party tools. During live exercises, external participants often needed to be able to connect their tools with mandatory TLS server certificate validation to PhoenixSEN. The DNS service allows registering domain names that match pre-existing TLS certificates on a first-come first-serve basis and resolving those names across PhoenixSEN.

The DNS service takes advantage of the following: 1) a weak eventual consistency model is sufficient for DNS; 2) in a network like PhoenixSEN, the impact of conflicts and inconsistencies can be minimized network-wide through design. Point 1) expands the range of protocols that could be used for DNS database replication to gossip (epidemic), flooding, and multicast-based protocols. Point 2) means that if applications and devices are configured appropriately, the probability of conflicts due to a weak consistency model will be negligible.

PhoenixSEN provides such DNS subsystem, with no dedicated master server and without any single point of failure. The
A DNS-based service discovery mechanism allows the reuse of higher layer protocols and services, e.g., TLS server certificate validation.

Fig. 4 illustrates the architecture of the DNS subsystem. Each Phoenix node runs the full set of services that make up the DNS subsystem for service discovery. Custom-made blocks are highlighted in blue. Communication via proprietary protocols is highlighted in purple.

The VoIP clients at a substation register with the nearest DNS server, the VoIP clients usually register with the SIP at their substation’s Phoenix node. To discover the SIP server, a VoIP client performs the standard procedure described in [22]. The SIP server, the VoIP clients usually register with the SIP at their substation’s Phoenix node. To discover the SIP server, a VoIP client performs the standard procedure described in [22]. The SIP server, the VoIP clients usually register with the SIP at their substation’s Phoenix node. To discover the SIP server, a VoIP client performs the standard procedure described in [22].

Such a device is freeze-framed by a custom program called “Avahi Publisher”. The program behaves as a secondary DNS server for the shared zone. When the zone is updated, Knot sends a DNS NOTIFY request to the program. The program issues a DNS zone transfer to Knot to download all records and publishes those records via Avahi’s DNS-SD API. Thus, LAN clients that resolve DNS records via Unbound receive records not only from the local Knot DNS server, but also from all DNS servers found anywhere in the network.

A. Service Discovery Example

PhoenixSEN provides a SIP-based decentralized VoIP service (highlighted in gray in Fig. 4) designed to help substation personnel coordinate during a black-start recovery. The service relies on the PhoenixSEN DNS subsystem for network-wide service discovery. We discuss how the VoIP service uses the DNS subsystem in this section.

The VoIP clients at a substation register with the nearest SIP server. Since each Phoenix node runs a dedicated SIP server, the VoIP clients usually register with the SIP at their substation’s Phoenix node. To discover the SIP server, a VoIP client performs the standard procedure described in [22]. The DNS queries issued by the VoIP client will be forwarded by Unbound to the local Knot DNS server. The DNS server has those records via Avahi’s DNS-SD API. Thus, LAN clients that resolve DNS records via Unbound receive records not only from the local Knot DNS server, but also from all DNS servers found anywhere in the network.

Devices that obtain an IP address via DHCP are automatically assigned hostnames by the DHCP server. The DHCP server uses the standard dynamic DNS (DNS UPDATE) protocol to publish records to the local DNS server. For example, a DHCP client with the name “foo” will be assigned the hostname foo.phxnet.org. Having an automatically generated hostname for each device has two main benefits: 1) the device can be reached by its chosen name across the network; 2) services running on the device can use TLS certificates with a wild-card certificate issued by Let’s Encrypt.

Unbound, because its behavior can be customized with an external Python program. We use that feature to resolve ordinary DNS queries via multicast DNS (mDNS) [20] (described later).

Unbound first forwards the query to a local authoritative DNS server implemented with Knot DNS server. The DNS server is authoritative for the domain phxnet.org and for a portion of the in-addr.arpa space corresponding to the IP subnet allocated to the Phoenix node. The domain phxnet.org represents a namespace shared by all Phoenix nodes. Any node can register a record in the shared namespace. If multiple nodes register the same record, all such records are merged when a client attempts to resolve the record. It is left up to the application to resolve the potential conflict.

If no record is found, Unbound forwards the query to an external Python module. The module attempts to resolve the query via mDNS using a local Avahi daemon instance. The Python module and Avahi daemon communicate via a D-Bus API.

In a typical configuration, the Avahi daemon multicasts DNS queries over LAN interfaces, e.g., local Ethernet or Wi-Fi interfaces. Since multicast DNS packets are not forwarded by layer 3 routers, only nodes connected to the same link can be reached this way. PhoenixSEN is, however, a routed network managed by an OLSR [19] daemon running on each node. The daemon includes the Basic Multicast Forwarding (BMF) plugin that enables multicast communication for the overlay network. We use the plugin to propagate Avahi’s mDNS packets across the OLSR network. The BMF plugin forwards multicast packets along a spanning tree covering the entire network, i.e., all Phoenix nodes.

The Avahi daemon on each Phoenix node publishes all DNS records from the local DNS server via mDNS. This is accomplished with a custom program called “Avahi Publisher”. The program behaves as a secondary DNS server for the shared zone. When the zone is updated, Knot sends a DNS NOTIFY request to the program. The program issues a DNS zone transfer to Knot to download all records and publishes those records via Avahi’s D-BUS API. Thus, LAN clients that resolve DNS records via Unbound receive records not only from the local Knot DNS server, but also from all DNS servers found anywhere in the network.

Dynamic service discovery improves robustness in scenarios where the network is impaired or only partially formed. A DNS-based service discovery mechanism allows the reuse of higher layer protocols and services, e.g., TLS server certificate validation.

Devices that obtain an IP address via DHCP are automatically assigned hostnames by the DHCP server. The DHCP server uses the standard dynamic DNS (DNS UPDATE) protocol to publish records to the local DNS server. For example, a DHCP client with the name “foo” will be assigned the hostname foo.phxnet.org. Having an automatically generated hostname for each device has two main benefits: 1) the device can be reached by its chosen name across the network; 2) services running on the device can use TLS certificates with a wild-card certificate issued by Let’s Encrypt.
The VoIP subsystem has been designed to support a variety of VoIP clients. IP digital enhanced cordless communications (DECT) phone represents VoIP clients that come bundled with the Phoenix node hardware. Each Phoenix node comes with a couple of IP DECT phones pre-configured for use with the network. The client labeled as “PC with a web browser” could be any tablet, laptop, or a PC with a recent web-browser with Web Real-Time Communication (WebRTC) support. The SIP server includes a JavaScript WebRTC application that can turn any such device into a fully-featured VoIP and chat client without the need to install any software. The desk phone icon represents VoIP clients that had existed at the substation before the Phoenix node was installed. The smartphone VoIP client represents mobile Android devices with a SIP client application installed. The mobile clients are connected via a Wi-Fi network created by the Phoenix node and can roam between substations while keeping the same number.

The VoIP and chat subsystem uses a simple four-number dialing plan where each substation is allocated a fixed prefix. The substation’s VoIP clients are assigned numbers from that prefix. Each Phoenix node runs a full set of VoIP services (SIP and WebRTC servers, conference server, chat server). The clients register at the nearest SIP server, typically the one located on the Phoenix node installed in the client’s substation. Having a full set of VoIP services on each Phoenix node allows the node to function in isolation. Even if the node is disconnected from PhoenixSEN, calls and chats within its substation should remain possible.

The subsystem supports ordinary two-way calls between any two VoIP clients, multi-party conference calls with conference rooms created on demand, peer-to-peer chat on compatible devices (Android clients), and a web-based group chat service accessible through the JavaScript WebRTC client. The VoIP service supports persistent logging and archiving of conversations (both voice and text), if needed. The SIP server on each Phoenix node performs transparent media transcoding and enforces authentication and encryption on calls that traverse the whole network can have identical configuration and can, in case of smartphones, roam between substations.

Upon VoIP client registration, the SIP server publishes a custom DNS record mapping the VoIP client’s number to the hostname of the SIP server where it has registered, for example 4822._voip.phxnet.org. IN CNAME voip-phx23.phxnet.org, where 4822 is a VoIP client’s phone number and voip-phx23.phxnet.org is the hostname of the Phoenix node where the client is registered. A custom program called “DNS Publisher” (Fig. 4) publishes the record to the local DNS server via DNS UPDATE and the record is subsequently disseminated across the network with multicast DNS.

When a remote SIP server receives a SIP INVITE [18] for the VoIP client, it extracts the called number from the Request-URI and constructs a domain name from the number within the _voip.phxnet.org suffix. The SIP server then queries the DNS for the corresponding CNAME record. If a match is found, the call is forwarded to the SIP identified by the record.

Note that the multicast DNS subsystem is configured to pro-actively disseminate the requests across the network. Thus, for existing (registered) numbers, the query will usually be answered by the local DNS server from its cache fast. Queries for non-existing (unregistered) numbers take a few seconds until multicast DNS times out.

Both VoIP clients and servers rely on the DNS service discovery feature to locate each other. This helps make the VoIP architecture fully decentralized and scalable, allows (mobile) VoIP clients to roam between Phoenix nodes, and makes swapping hardware components, e.g., VoIP clients, easy in the case of compromise or malfunction.

VI. VOICE AND CHAT

One of the purposes of PhoenixSEN is to facilitate the coordination of people during an emergency. To that end, the network provides built-in support for SIP-based [18] real-time voice and text communication. The service supports the following modalities: two-party calls, multi-party conferencing, text messaging, and multi-party group chat (with a persistent log). Fig. 5 shows the internal architecture of the subsystem.

Fig. 5. Internal architecture of the VoIP and chat subsystem. The subsystem can integrate a variety of SIP (red) and WebRTC (green) based VoIP clients. Each Phoenix node runs a full set of services. VoIP clients register at the nearest node. Communication sessions that traverse slow links (blue) are optionally transcoded and compressed. VoIP clients and servers rely on DNS-SD for server federation and client discovery. IP multicast (used by DNS-SD) helps make the subsystem fully decentralized and with no single point of failure.
VoIP subsystem has important benefits: 1) Phoenix nodes VoIP client is registered. Section V-A describes in detail how VoIP clients, and to discover the SIP server where a particular (LAN) devices using active network scanning. It also provides (long-haul) links and improves robustness of calls traversing such links.

A simple four-digit dialing plan with prefixes allocated to substations was used during live exercises, however, the VoIP subsystem has no fixed dialing plan hard-coded. Instead, it relies on DNS-SD to discover available SIP servers and VoIP clients, and to discover the SIP server where a particular VoIP client is registered. Section V-A describes in detail how the VoIP subsystem uses DNS-SD. Having a fully dynamic VoIP subsystem has important benefits: 1) Phoenix nodes have uniform hardware and software configuration and are interchangeable; 2) mobile VoIP clients roaming from one substation to another are supported; and 3) the subsystem is fully decentralized with no single point of failure.

VII. Network Monitoring

In a geographically distributed ad hoc network architecture such as PhoenixSEN, real-time network monitoring and situation awareness is key for successful deployment and operation. In this section, we describe Netmon, a network monitoring service designed and developed for PhoenixSEN. Netmon provides near real-time information about the state of the network through a web-based UI. The UI lets the control center see the topology of the formed OLSR network and provides alerts when it detects security-related events and incidents. Fig. 6 shows the UI displaying the network topology graph of a PhoenixSEN prototype during a live exercise.

The internal architecture of Netmon is shown in Fig. 7. Every Phoenix node runs a custom Netmon agent process. The agent collects data about the state of the node using OS-level instrumentation and about directly attached substation (LAN) devices using active network scanning. It also provides an API for other processes on the same node, e.g., an IDS. The collected data includes statistics from selected network interfaces, the state of the node’s OLSR links, and information about discovered devices.

To discover devices attached to the node’s substation LAN interfaces, the agent periodically issues Address Resolution Protocol (ARP) requests for all IP addresses that belong to the interface’s configured IP subnet. A device that responds to the ARP request is recorded and will be displayed in the network topology graph, as shown in Fig. 6. Once a LAN device has been discovered, it is periodically contacted to determine the device’s reachability. The agent also probes the state of selected UDP and Transmission Control Protocol (TCP) ports on all discovered LAN devices to see what services might be offered by the device.

A separate IDS process, running on the same Phoenix node, provides additional data to the Netmon agent. The data represents potential intrusion detection incidents and security threats. Netmon transmits the data to the backend where it is then presented to the network operator by the frontend (UI).

Each agent maintains a persistent WebSocket [23] connection to an agent server discovered via DNS SRV. The control center Phoenix node provides one agent server instance for each VLAN. As long as the agent is connected to the server, data is streamed to the agent server in near real-time. When an agent gets disconnected from the server, it temporarily stores the collected data in a local cache. All locally cached data will be uploaded to the server later once the agent has reconnected.

The agent server stores all the data from all connected agents in a persistent database. The data is processed and indexed to allow time-based addressing and aggregation, i.e., retrieving the state of the network at a particular time. This feature allows debugging or post-mortem analysis after an exercise when the physical network infrastructure is no longer operational. A backend server, also running on the control center Phoenix node, serves the data to the frontend (UI) via a RESTful and WebSocket based API. The API allows the frontend code to retrieve any data generated by the agents, and to receive asynchronous (push) updates as new data becomes available.

The UI is a JavaScript application running in a web browser on a laptop in the control center. The application is specifically designed to always show the most recent network state without the need to reload the browser window. The UI is automatically
updated based on push notifications received from the backend server. The UI provides a quick “at a glance” overview of the entire network, as well as detailed information about individual network components. The operator can use the UI to quickly scan the network for faulty (red) nodes and links, or see which parts of the network require immediate attention.

The Netmon agent is implemented in Python, uses Scapy for network probing and device discovery, and SQLite for the local cache. The agent and backend servers are both implemented in JavaScript running in NodeJS. All collected data is stored in a MongoDB database on the control center Phoenix node. The frontend is a JavaScript application implemented with Vue.js and running in a web browser.

VIII. MITIGATING INSIDER ATTACKS

Insider attacks are of particular concern in large physical infrastructures such as the electric grid. An attacker could use compromised devices in a substation LAN to attempt to thwart recovery attempts. If the attacker also gains physical access to the substation, they could plant a malicious device in the substation’s network (“device-in-a-closet”) [24] and use the device to launch man-in-the-middle (MITM) attacks. Lack of Ethernet security combined with ever shrinking form factor of embedded devices makes such attacks practical and very hard to discover.

To help mitigate the risk of network-based insider attacks, we designed and built a prototype device called EtherShield. EtherShield is a “bump in the wire” embedded device with two Ethernet ports: internal and external. The internal port is connected to a trusted (not compromised) SCADA device, preferably, as close to the SCADA device as possible to minimize the risk of malicious actors getting access to that segment of the network. The external port is connected to the untrusted substation LAN. Until activated, the device operates as a regular Ethernet switch. Once activated from the nearest Phoenix node, the device transparently authenticates all communication between the SCADA device and the network.

Fig. 8 shows the architecture of the EtherShield subsystem.

Each EtherShield device will have been paired with the nearest Phoenix node via a MITM-resistant USB connection prior to deployment into the LAN. During pairing, the EtherShield device and the Phoenix node generate the cryptographic material for secure communication over an untrusted LAN. Until activated, the EtherShield device passes all traffic between its two ports unmodified. Once a SCADA device protected with an EtherShield is deemed secure, the network operator can activate a secure mode in the EtherShield to isolate the SCADA device from potentially malicious traffic. In a secure mode, the EtherShield transparently authenticates all packets to the SCADA device, the nearest Phoenix node, and (optionally) other devices within the substation LAN.

The authentication is based on either IEEE 802.1X [25] or IPsec [26]. The EtherShield can be configured to only let authenticated traffic through to the SCADA device, or to allow traffic from other LAN devices not protected by an EtherShield device. This gives the network operator some flexibility while incrementally securing the substation SCADA network. Critical SCADA devices can be incrementally protected and isolated from malicious traffic without disrupting the operation of the rest of the substation LAN.

We built a prototype EtherShield device based on the Raspberry Pi running Open vSwitch. In the default “open” mode of operation, Open vSwitch is configured to function as a simple learning Ethernet switch. When switched into a secure mode, the device starts either an IEEE 802.1X supplicant or an IPsec tunnel and re-configures Open vSwitch to redirect a portion of the traffic to those services. For example, in the IEEE 802.1X mode only Extensible Authentication Protocol over LAN (EAPoL) frames are redirected to the supplicant process. Frames received from the protected device are transparently augmented with an authentication header (IEEE 802.1X or IPsec authentication header) as they pass through the switch.

A frame received from the untrusted LAN for the protected device is first authenticated before the frame is forwarded to the SCADA device. A custom controller application provides a secure HTTP API. This API can be used to configure and control the device from the nearest Phoenix node.

The Phoenix node provides a standards-based set of services to support the EtherShield subsystem. The cryptographic material generated during pairing is kept in a PostgreSQL database, along with account information. The node provides an IEEE 802.1X authenticator to the substation LAN based on the Remote Authentication Dial-In User Service (RADIUS) protocol [27]. The authentication is implemented with FreeRADIUS. An IPsec-based authenticator based on strongSwan is also provided.

IX. RELATED WORK

Disaster Communications. The critical role of communication in the aftermath of a large-scale disaster event became apparent after hurricane Katrina in 2005 [28], hurricane Irene in 2011, and during the 2017 Atlantic hurricane season [29]. In Puerto Rico, over 9 million people lost electricity for 11 days in the largest blackout in U.S. history [30]. These events rendered existing communication networks across large geographic areas unusable [10], [31]. Additionally, significant
challenges caused by non-interoperable communication systems were reported [9], limiting situational awareness and preventing communication across jurisdictions and organizations [32], [33]. A 2016 National Institute of Standards and Technology (NIST) report [34] found communication failures to be a major obstacle in all recent disaster recovery efforts.

**Industrial Control Systems.** Modern industrial control systems, including the power grid, require communication to function. As critical infrastructure, such systems are increasingly targets of cyber attacks [35], [36]. A 2011 vulnerability analysis performed by the Idaho National Laboratory found that applying traditional IT system protective measures to real-time energy delivery control systems is inadequate and could lead to a power disruption [7]. The Stuxnet worm [37] and the Maroochy water breach [38] incidents illustrate the danger network-based cyber attacks pose for industrial control systems. Even ordinary planned upgrades can have devastating consequences in systems that control physical processes [39].

**Network Architectures.** A network architecture suitable for emergency scenarios will inevitably be ad hoc and temporary [11]. Such architectures have been the subject of active research for decades and many promising ideas have been proposed including peer-to-peer, mesh, mobile, delay-tolerant, opportunistic, and hybrid network architectures [40]–[42]. Despite the wide range of communication architectures, basic interoperability between organizations is still a problem. There have been attempts to repurpose existing technology to provide services where communication networks are unavailable. The Village Telco project [43] designed and built a do it yourself (DIY) toolkit for voice and text communications based on wireless mesh networking and VoIP. The Osmocom project [44] provides the essential building blocks for temporary cellular network infrastructures.

**Disaster Management Systems.** Recently, specialized disaster management systems have been gaining interest. Several organizations specializing in emergency response have made their solutions available [11], [45]–[47]. The core functionality of these systems centers around crowd-sourced field data gathering, incident tracking, and visualization. Such systems typically place no special requirements on the underlying communication networks. There have been attempts to use advanced technology in emergencies, for example, Panacea Glass proposes to use Google Glass and cloud computing for situation awareness and effective triage of patients [48], [49].

**Network Monitoring Systems.** The ad hoc nature of temporary emergency networks calls for some form of real-time monitoring for topology discovery, bandwidth estimation, intrusion detection, and troubleshooting in the field. A vast number of network measurement and monitoring tools have been developed [50]. The tools can be broadly classified into passive, active, and hybrid (a combination of active and passive) [51].

Passive monitoring relies on packet capture [52], [53], OS instrumentation [54], or sampling [55] to perform measurements. Passive methods require existing network traffic to function, the ability to observe data flows within the network, and are generally less intrusive than active methods [56]. Notable passive monitoring tools include CoralReef [57], Bro [58], Wireshark [59], Snort [60], and sFlow [61].

Active monitoring estimates network properties by observing the handling of special-purpose data injected into the network by the monitoring tool. Active methods are generally intrusive, generate variable amounts of artificial network load, and may interfere with application traffic. Existing active methods rely on IP options (Internet Control Message Protocol (ICMP) echo [62], traceroute [63]), TCP congestion control (iPerf [64]), bandwidth and transmission time probing (BWPing [65]), or packet dispersion measurements [66], [67]. Scapy [68] is a popular packet manipulation tool for active network discovery and monitoring.

An important aspect of any network monitoring system is its data processing architecture. The architecture determines the number and locations of collection points, types of collected data, collection protocols, and data processing algorithms. If data collection takes place over the network being monitored, care must be taken to minimize the generated overhead and its impact on the monitored network. Well-known monitoring data collection protocols include Cisco NetFlow [69], the IPFix protocol [70], and Simple Network Monitoring Protocol (SNMP) [71]. SNMP is widely supported by existing networking equipment. The following monitoring tools inspired Netmon, the monitoring tool presented in this paper: Moloch [72], MRTG [73], OpenNMS [74], Cacti [75], and Zabbix [76].

**X. Conclusion**

We presented the design and prototype implementation of PhoenixSEN, an ad hoc network architecture specifically designed to enable real-time coordination of people and (SCADA) devices during an emergency, while the primary network infrastructure may be inoperable. Our network architecture is designed with sufficient flexibility to be used a drop-in replacement for network infrastructure and services typically provided by third-party ISPs. Our work is primarily motivated by the needs of the power distribution industry during a hypothetical large-scale blackout triggered by a network-based cyber attack. We believe PhoenixSEN has the potential to speed up power grid recovery and service restoration, in particular during a cyber attack that is persistent and ongoing.

Several iterations of the PhoenixSEN prototype described in this paper were tested and evaluated through a series of DARPA-led cyber security exercises on Plum Island, NY [77]. During the exercise, PhoenixSEN was used together with a variety of power grid recovery tools contributed by other exercise participant to assess the readiness of the infrastructure to recover from a simulated large-scale cyber attack on the electrical grid. Photos in Fig. 9 show the evaluated PhoenixSEN prototype.

This paper describes the most recent iteration of PhoenixSEN. Some of the features described in this paper ended up not being evaluated in live exercises. The EtherShield prototype device described in Section VIII was developed and tested in a lab at Columbia University. The hardware deployed on
Recent advances in automated speech-to-text and text-to-speech technologies might provide a means to automatically transcribe and index emergency voice communications. In addition, such technologies might provide better support for voice communication over long-haul and slow links such as HF band links, satellite links, and power line communication (PLC) systems. A combination of Robust Header Compression (RoHC) [78], PTT, transcoding, and voice-to-text could be potentially used to design a near real-time, highly robust, and resilient communication system suitable for very challenged communication networks and scenarios.

We plan to continue developing the Netmon software with features specifically designed for mobile ad hoc networks. We believe that no other existing network monitoring solution supports ad hoc or highly dynamic networks well. In a future version of Netmon, we plan to remove the restriction to have only one instance of backend services per network. We will aim to make Netmon fully decentralized, with the backend services and data sharded across all Phoenix nodes. To build a global view of the network, Netmon will obtain and merge data obtained from all Phoenix nodes.

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REFERENCES

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Plum Island did not have GPS receivers since the precise location of each Phoenix node was known in advance. One-time deployment configuration (Section IV-A) was performed from a laptop attached to the Phoenix node via an Ethernet port. The configuration synthesis approach was only tested on a Columbia University testbed. The chat feature (Section VI), which was originally developed to support team coordination during the exercise, was eventually replaced with a third-party application the participants were already familiar with.

A. Future Work

Although the design of PhoenixSEN was primarily motivated by specific needs of the power distribution industry, we believe the resulting architecture is more general and flexible, and might be suitable for other emergency scenarios as well. As part of future work, PhoenixSEN could be extended with features and services for first responders, disaster recovery, and other emergency scenarios where communication and coordination is critical even if the primary communication networks are not operational. We envision supporting a variety of common emergency and disaster scenarios on top a general-purpose hardware and software architecture with interchangeable service profiles. Each profile will activate services designed to meet the needs of a particular emergency scenario, e.g., incident management, ticketing, collaborative document editing, and others.

The VoIP subsystem in PhoenixSEN provides all the usual modes of real-time communication: two-way calls, multi-party conference calls, direct chat, and group chat. It is likely that PhoenixSEN might get deployed in challenging scenarios where ordinary calls and chats may not be the most efficient means of communication. As part of an effort to support more emergency scenarios, further research into alternative means of (near) real-time communication might be warranted. Specifically, good support for push-to-talk (PTT) communication seems to be a promising direction for first responder communication systems.

Recent advances in automated speech-to-text and text-to-speech technologies might provide a means to automatically transcribe and index emergency voice communications. In addition, such technologies might provide better support for voice communication over long-haul and slow links such as HF band links, satellite links, and power line communication (PLC) systems. A combination of Robust Header Compression (RoHC) [78], PTT, transcoding, and voice-to-text could be potentially used to design a near real-time, highly robust, and resilient communication system suitable for very challenged communication networks and scenarios.

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[2] BBC. (2019, Aug.) Major power failure affects homes and transport. [Online]. Available: https://www.bbc.com/news/uk-49300025
[3] National Grid ESO. Black start. [Online]. Available: https://www.nationalgrideso.com/balancing-services/system-security-services/black-start
[4] PJM. PJM manual 12: Balancing operations. [Online]. Available: https://www.pjm.com/~/media/documents/manuals/m12.ashx

Fig. 9. Photos of the PhoenixSEN prototype evaluated through DARPA-led exercises. Left to right: Phoenix node components (Intel NUC, POE switch, Yealink W52P phone), Phoenix node in weather-resistant enclosure (Intel NUC, Yealink W52P phone, Netgear Ethernet switch, Tripp Lite UPS), small-scale Phoenix SEN prototype installation in a lab. The photos were taken by Hema Retty at the University of Illinois at Urbana-Champaign in September 2018.

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REFERENCES

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[2] BBC. (2019, Aug.) Major power failure affects homes and transport. [Online]. Available: https://www.bbc.com/news/uk-49300025
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