Towards efficient Post-Blackout Emergency Communication based on Citizens' Smartphone State of Charge

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ABSTRACT

Effective emergency communication between citizens and authorities after a power outage can be a challenging task. In such situations, citizens may be in danger and need to contact authorities in case of an emergency. However, overloaded cellular networks and failing network infrastructure can severely hamper citizens' ability to communicate with authorities, even if their smartphones are still functioning. Addressing these challenges requires the development of effective post-blackout communication systems that can operate in a range of emergency scenarios. In this work we investigate smartphone state of charge during the day in order to evaluate the impact of a power outage on the citizens ability to communicate in a post-blackout scenario. The results are then used to propose future-proof communication networks that are suitable for post-blackout emergency communication especially after cellular network infrastructure has failed. We introduce two post-blackout communication phases named communication-burst and communication-void. Our study indicates that a significant amount of smartphones remain usable even after a long-lasting blackout and communication infrastructure failure. Not utilizing these devices could lead to missed opportunities for emergency communication.

Keywords

Smartphone, State-of-Charge, MESM, Emergency, Future Proof, Post-Blackout, Emergency Communication, Communication-Burst, Communication-Void

INTRODUCTION

Post-Disaster Communication between authorities and citizens in disaster-struck areas is a cumbersome challenge. While recent research was always capable to present improving solutions on technological and organizational levels, there are still several difficulties to overcome. One of the biggest challenges for all applied communication-technologies that enable the communication with endangered citizens is the emergency communication after a power outage or *Post-Blackout Emergency Communication.*

Major blackouts not only occur due to power supply issues, human error or targeted destruction, but also as a direct consequence of major environmental disasters such as earthquakes or floods which are always situations with a very high probability of casualties and people in need. Since most modern emergency communication between authorities and citizens (i.e. Phone, Internet) uses electricity, a blackout is always critical. Matters are aggravated for vulnerable persons trying to contact authorities (C-to-A communication) as well as for first responders on evacuation or search and rescue missions for endangered citizens (A-to-C communication). This research aims to investigate A-to-C and C-to-A Emergency Communication in critical situations during a blackout and especially during the mobile network radio silence period we refer to as the *Communication-Void.* The goal is to propose future-proof and sustainable concepts that include most recent findings from ICT-research and public-safety research that may be used by citizens and authorities equally in a post blackout emergency. Especially the newest technological developments and improvements specified by standardization bodies such as

3GPP or ETSI regarding public safety communications and mobile network communications have lots of potential that may give citizens the tools and systems in the future to increase resilience within these kinds of situations. In this context, our contribution represents first research findings that layout the foundation for our future work.

THE ROLE OF SMARTPHONES WITHIN POST-BLACKOUT EMERGENCY COMMUNICATION

After power outage, it is expected that most emergency communication will be done via smartphone since remaining battery power and remaining mobile network capacities will enable the smartphones to still function for a certain period.

To gain a better understanding of the smartphone usage before, within and after a blackout the general all-day battery level - also known as *Smartphones State of Charge* (SoC) (Tarkoma et. al., 2014) - over multiple citizens may be investigated. We therefore conducted a study based on a *Mobile Experience Sampling Method* (MESM). The study involved multiple participants that hourly uploaded their current battery level. The results of the study are expected to provide first insights and allow us to make first assumptions regarding research questions such as:

- What is the general SoC of smartphones throughout the day?
- Is there a specific hour or period within one day that can be considered as *most critical* point of time for a blackout regarding the overall SoC?
- Which emergency-communication service should be provided to affected citizens according to the expected post-blackout SoC?

Furthermore, we propose a strategical concept of communication technologies to overcome various post-blackout phases from the beginning of the blackout until partially or complete recovery of mobile communication networks. The information about smartphone SoC gained from the study may provide a first guidance about the order in which the proposed ICT innovations might be implemented to provide trivially (or easily) accessible emergency communication for people in need. This might be used as investigative guideline of technologies and concepts that should be considered in future work.

STATE OF TECHNOLOGY AND CONTRIBUTIONS OF THIS RESEARCH TO SMARTPHONE BASED POST-BLACKOUT COMMUNICATION

The field of disaster communication has been extensively researched. Post-blackout communication can be seen as a subcategory within disaster or post-disaster communication. Several research results and concepts within these areas have already reached at least practitioner level. However, most of the solutions that reached practitioner level focus on the communication within authorities or first responders, making them more resilient by enabling them to work during communication system failures. In (Reuter et al., 2013) and (Reuter et al., 2014) the authors' contributions to blackout communication are noteworthy. The concepts presented by the authors describe how information can be effectively communicated to citizens in situations between a blackout and communication infrastructure failure. Many disaster communication solutions presented in research, such as those mentioned rely on the use of smartphones, often requiring internet connection and the installation of an app. Since emergency communication over cellular networks uses licensed spectrum, most post-disaster communication solutions presented in research rely on ad-hoc Wi-Fi networks for enabling mobile apps and web solutions (Matracia et al., 2022).

The research conducted by us focuses on exploring technological innovations in both Wi-Fi and Cellular networks to enable mobile phone-based emergency communication between citizens and authorities following a blackout, particularly in situations where cellular communication infrastructure has failed. Furthermore, we discourage the reliance on preinstalled mobile applications for emergency communication in post-blackout scenarios. Our aim is to explore future-proof communication-systems that enable mobile phone-based emergency communication services 'out-of-the-box' within post-blackout scenarios and without pre-installed mobile apps. This research goal is rooted in the fact that Crisis preparedness is not widespread in society, especially among vulnerable individuals (Dominianni et al., 2018; Breuer et al., 2021). Our work encourages research on readily available mobile phone-based emergency services for citizens, such as information, emergency, crowdsourcing and warning services that can be trivially accessed in the event of a disaster, without requiring additional preparation or the need to download an app in advance.

The IEEE Public Safety Technology Gaps and Opportunities White Paper (Ulema et al., 2021) underlines the relevance of complementary network technologies in disaster-struck areas. According to the paper, it is important that future government officials and non-governmental organizations are enabled to restore public services in disaster-struck areas. This includes telecommunications service infrastructure that may have been either damaged or nonfunctional. The white paper proposes, among other solutions, the restoration of telecommunication services using various technologies and innovations such as the installation of locally restricted cellular networks in affected areas. Our research aims to contribute into the same direction by evaluating the selection of specific post-disaster communication-technology that may be used for restoration of communication networks. Some of the evaluated technologies are mentioned in a comprehensive survey on post-disaster communication technology and architectures by (Matracia et. al., 2022)

The MESM study conducted in our research hourly collects the current battery level of multiple smartphone users over several weeks. Our goal is to be able to predict the overall smartphone state of charge over the course of a day. This might provide new insights that may enable us to better estimate the duration and ability of citizens to communicate in a post-blackout situation. A comparable study has been conducted by (Oliver et.al., 2010). Their measurement study focuses on: "understanding how smartphone users interact with their devices and how they consume and replenish energy". The study is grounded on a dataset of phone usage and energy consumption of a large sample 15500 smartphone users. The study is also restricted to only BlackBerry phones that were released since 2006. The core algorithm of their study is an event-driven BlackBerry application that continuously runs as background service on the phone. Once installed it receives various user interactions with the phone as event such as backlight activity. Upon receiving an event the current battery level is logged. While the approach and data used in the study produced impressive results, they may not be directly applicable to future-proof research on selective post-blackout communication based on battery level. However, BlackBerry phones are no longer in common use and the way people use smartphones has significantly evolved over the past decade. The evolution of smartphone technology has brought about significant changes to the CPUs, operating systems, and battery management, to support advanced services such as streaming, mobile gaming, social media, artificial intelligence, remote work, and more. Additionally, mobile network standards like LTE and 5G have introduced new effects on energy consumption, which are markedly different from ten years ago. In addition, the use of constantly running background applications that log data can consume device resources, resulting in a degraded battery lifetime and user experience. Therefore, Android and iOS operating systems have implemented strict limitations to prevent such practices. To address these limitations, we devised a new approach for our study that is in line with the constraints imposed by device operating systems. Our work in this involved implementing this approach on iOS devices as a first step and proof of work. A study containing the data based on Android smartphones has been scheduled for future work, due to the higher complexity of the existence of various device types, device models and operating system versions compared to the rather homogenous device models provided by Apple.

Mobile Experience Sampling Method to track Smartphone State of Charge

We conducted the Mobile Experience Sampling Method (MESM) based study to collect information about the overall battery state of charge during a day. Our objective is to gain a better understanding of the typical state of charge of smartphones throughout the day, as well as identifying the most critical time periods during which a blackout would have the greatest impact on citizens´ communication capabilities. We also aimed to assess the effectiveness of the MESM approach similar to the approach by (Restel et. al. 2022) as a tool for gathering smartphone-related SoC information. We decided to use this methodology since we see the necessity to accompany the closely participants throughout the day and the study. We expected to receive more data with an automatic data sampling approach integrated into the daily live of the participant rather than repeatedly asking participants for information, especially while participants are busy.

The study had overall 131 anonymous participants that installed the MESM app on their iPhones. The implemented MESM-App was designed to record the current battery level and send it automatically to our backend services on an hourly basis. Due to immense technical and privacy-related restrictions set by the iPhone operating system and its developer framework, a higher upload frequency of energy related data that is tracked and uploaded in a background process was not possible. Rather than utilizing a long-running background service on the smartphone that is resource-intensive, we opted for a backend-driven approach. In this approach, the apps are contacted by the backend service through a silent push notification, thereby avoiding the need for a constant running of the app. The remote wake-up call activates the app in the background with a limited time window granted by the operating system to quickly record the data, send it to the backend, and then terminate its activity. To ensure a frequent and consistent update of the data, the system has been designed to request the data only once every hour. However, to provide more flexibility for the study participants, the app also provided a manual upload option, allowing users to donate their information more frequently if they chose to opt out of the automatic upload schedule. The app has further been designed to accompany the participants for at least one week. After this first week, users had the option to repeat the study for a consecutive week.

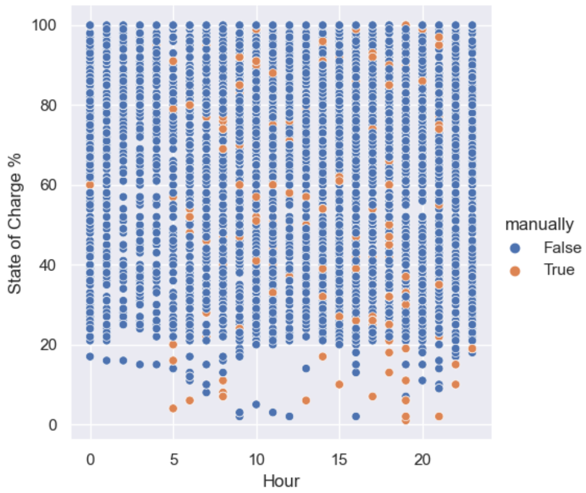

Figure 1. Overview of manually vs automatically submitted data points

The study was conducted over a 12-week period, during which we were able to collect approximately 8,200 data points related to users battery information. As demonstrated in Figure 1, the silent-push approach allowed us to collect a significantly larger amount of data over an extended period of the study compared to the manual upload approach. In fact, the data collected through the silent-push approach surpassed that of the manual upload approach by an order of magnitude.

Each collected datapoint included a timestamp, the current state of charge, the current charging state (unplugged/charging/full), and device model. To put the results into perspective we used the device model information to determine the age of the participating phones. Figure 2 illustrates distribution of ages of the phones used by the study participants. We calculated the maximum age of each model based on its initial release year. On average, the participating phones were 4.29 years old. This information is important to consider in order to understand any potential battery-age related biases that may have affected the phones' discharge behavior. Assuming that batteries had not been replaced, our analysis revealed that the participating phones were not too old or too new, which is relevant for the interpretation of our results.

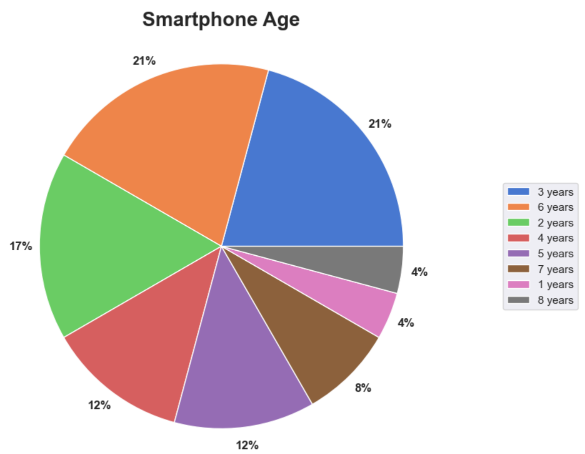

Figure 2. Distribution of Smartphone Age

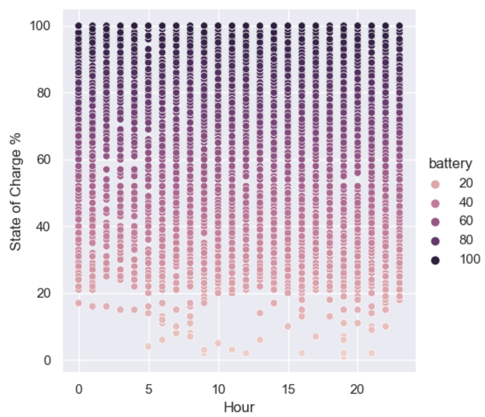

Figure 3. Overview of all SoC data points received

Our analysis of the received data reveals that there is a similar battery usage behavior among all participants and devices. As shown in Figure 3, each data point received in the study contains the current SoC and hour, with no significant accumulation of phones that have less than 20% SoC within a specific hour throughout the day. This suggests that users tend to charge their phone as soon as it hits 20%, resulting in an accumulation of SoC above 20% throughout the day. One possible explanation for the consistent battery usage behavior among participants and devices is that iPhones remind their users with a visible alert to either charge their phones or switch to battery saving mode as soon as the SoC hits 20%. This insight provides a better understanding of the impact of a blackout following a disaster on users' communication ability. The data suggest that there may be a lower probability of a large number of participants experiencing power outages with less than 20% SoC, making them more resilient in terms of communication than previously anticipated. This is an interesting insight that helps to understand the actual impact of a blackout following a disaster on the users’ ability to communicate.

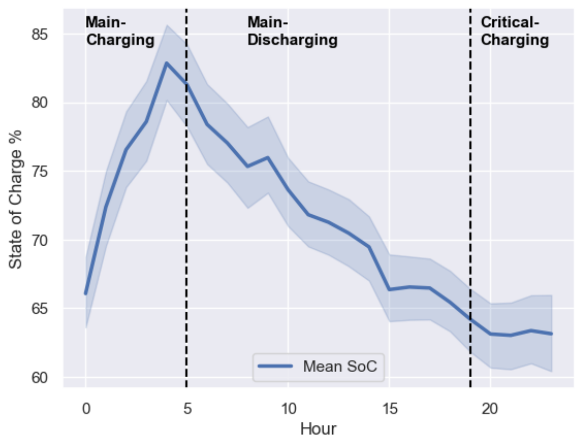

Figure 4. Overall Mean Smartphone State of Charge over the course of a day

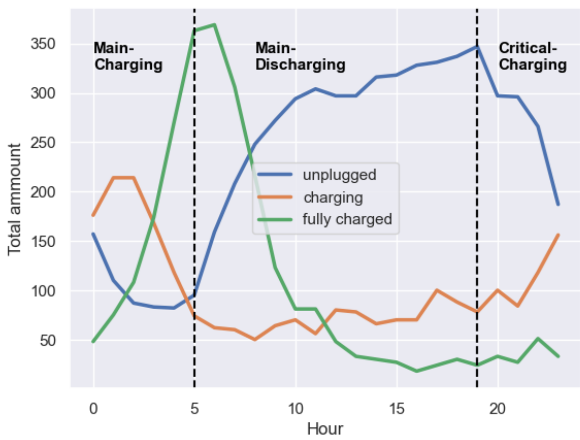

Figure 5. The total amount of datapoints per hour, ordered by charging-state

Furthermore, we have investigated the pattern of SoC during the day, which can provide insights into the potential impact of a blackout or communication infrastructure failure at a particular time of day. To achieve this, we aggregated all the received datapoints for each hour of the day, resulting in a graph that visualizes the course of SoC throughout the day for all participants (see Figure 4). The graph shows the mean SoC over all participants as a blue line, and the average SoC as deviation. It again reveals the consistently similar battery usage behavior of the participants such as illustrated in Figure 3. However, this time with a typical overnight charging behavior and daytime discharge behavior. Notably, there is a lack of very low SoC levels, which suggests that participants charge their phones before reaching the critical level. This trend explains the average SoC over the day being above 60%, as depicted by the graph.

We also analyzed the users' charging behavior. Each collected data point reported not only the state of charge, but also whether the phone was currently plugged-in and charging, plugged-in and fully charged, or unplugged. Figure 5 aggregates the total amount of data points (or responses) that have been send by each phone throughout the timespan of the study for each hour. This gives us the information how often phones have been either charging, fully charged or unplugged within a day over the 12-week study timespan. The graphs within this figure show that between 0:00 and 5:00, most phones reported a charging state. Within this time there is also a notably drastic increase in the number of phones that were fully charged compared to the rest of the day, with the highest amount of fully charged phones between the hours of 5:00, 6:00, and 7:00. The statistics also reveal that the number of unplugged phones is highest during the day between 6:00 and 19:00, which is also the time with the fewest fully charged phones. Additionally, the graphs for unplugged phones and charging phones show a rather symmetric change of slope at 19:00. The steeply increasing slope of the graph for currently charging phones suggests a critical period during which users perceive the need to charge their phones for the first time.

Blackout impact within SoC related charging phases and post-blackout related phases

Based on the results of the study, we can determine three SoC related phases throughout the day: *Main-Charging Phase*, *Main-Discharging Phase* and *Critical-Charging Phase*.

The main-charging phase, which is the period where most users tend to charge their phones, typically occurs overnight in order to start the day with a fully charged phone. Based on the observations of mean SoC and charging state, this phase can be considered to take place between 0:00 and 5:00. We assume that a blackout just before this phase is critical. Citizens that are used to reload their phone overnight would face the blackout with remaining battery life of the passed day. However, a blackout shortly after the Main-Charging Phase can be assumed as most-resilient. The results show that around 5:00 and 7:00 most smartphones are either fully charged (see Figure 5) or at least around 85% indicated by the mean SoC (see Figure 4). Therefore, most citizens would face the blackout with nearly maximum battery capacity.

The main-discharging phase occurs between 5:00 and 19:00. It is the period where the most smartphones are unplugged, resulting in a constantly decreasing SoC. The data suggests that most citizens are either away from home, at work, or on the move during this phase. It also indicates that there are always smartphones that need to be charged from time to time during this period. Therefore, we assume that a blackout during the main-discharging phase would be most critical for phones that require multiple recharges throughout the day.

Based on the data, we have identified the early-evening to late-evening time as the critical-charging phase. Starting from 19:00, the number of plugged phones noticeably increases, while the number of unplugged phones decreases accordingly. These numbers reveal the urgency of most users to charge their phones compared to the previous hours of the day. This is consistent with the fact that the lowest SoC of the day appears in the evening. Therefore, we assume that a blackout occurring in the evening would be very critical for citizens. Most citizens would face the blackout with a low battery level if they had not charged their phone before.

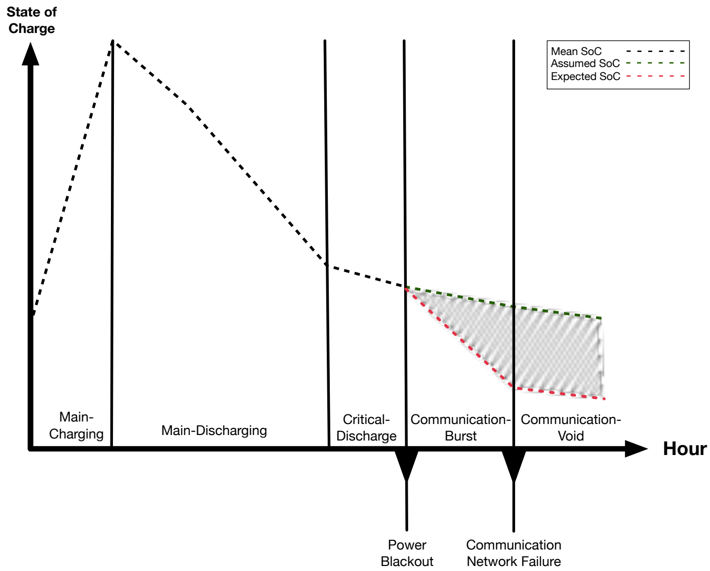

Figure 7. Expected state of charge over the course of multiple phases

Emergency Communication within Post-Blackout Phases

The findings from this study, including the classification of citizens' battery levels based on average SoC and Charging-Phase, provide valuable insights into the impact of a blackout on people's ability to communicate.

The study data sheds light on how the timing of a power outage could affect citizens depending on the hour of impact. Specifically, the state of charge of smartphones after the blackout can serve as an indicator of how long citizens may remain reachable. When authorities and first responders assess how to provide emergency communication post-blackout, they may find the information on remaining battery life on citizens' smartphones to be particularly useful. However, the citizens' usage of smartphones changes significantly after a blackout incident. Furthermore, authorities should expect communication network failures to occur soon after a blackout (Birkmann et al., 2010; Reuter et al,. 2013).

To develop future-proof and efficient post-blackout emergency communication strategies for citizens, first responders and authorities, it is important to consider these circumstances of post-blackout scenarios. This includes the expected SoC of citizens' smartphones and the availability of communication infrastructure. To aid in this process, we propose the definition of two additional phases closely related to the post-blackout period: the *Communication-Burst* phase and the *Communication-Void* phase. The data from our study highlights the importance of such distinctions, as the timing of a power outage can have a significant impact on the reachability of users in emergency situations, with post-blackout SoC levels likely to be lower than typical for a given time period, as illustrated in Figure 7.

The Communication-Burst Phase

In our research we refer to the timespan between the impact of the blackout to the collapse of cellular communication as communication-burst phase. This is when increased network usage and decreased network capacity causes the failure of cellular network connectivity (Reuter et al., 2014).

We anticipate that the average SoC during the communication-burst phase will be considerably lower than the average SoC observed in our study during the charging phase that was impacted by the power outage. This is since citizens will be uncertain about how long the blackout will last and may try to connect with authorities by repeatedly attempting phone calls, reloading web pages, and restarting unresponsive apps. Such increased phone and data usage during a high-stress situation can result in higher energy consumption than usual for the same time of the day. Authorities should therefore be aware that the SoC data collected during normal conditions may not fully capture the battery usage patterns during post-blackout emergency situations.

Research literature on recent post-blackout incidents such as (Breuer et al., 2021) as well as reports on recent post-blackout operations on the field such as (Schmersal et al., 2020) notable mention the drastic increase of phone calls and data traffic closely after the incident confirming the assumption that after a blackout, citizens tend to use their phones more intensively. They may try to call emergency services, authorities, friends, and family, or seek information from the internet or blackout related communication services. According to the authors of both works the impact of increased phone usage led to collapsed emergency phone lines due to an overwhelming number of calls from citizens from either within the affected area or from the outside into the affected area.

The increased network load not only puts more pressure on the infrastructure, but all smartphone traffic that were previously handled by local Wi-Fi networks is also suddenly redirected to the cellular network. This is because all Wi-Fi routers stop functioning immediately after a power outage. Furthermore, base stations that are intended to optimize network coverage may also stop working, leading to a decrease in network capacity just as the network load is increasing (Reuter et. al., 2014). The first signs of collapsing cellular networks can be recognized as early as 15 minutes after a blackout, according to the reports by (Breuer et al., 2021). This is due to the increasingly challenging conditions for cellular communication infrastructure after a blackout, as described in previous studies by (Birkmann et al., 2010 and Petermann et al., and Reuter et al., 2014). Overloaded cellular networks in an affected area, may not be immediately obvious to authorities. Since they may not be caused by technical malfunctions of base stations, but rather since citizens are unable to make or receive phone calls, send or receive messages, or access any services (apps or web) that rely on internet connectivity due to overloading.

The Communication-Void Phase

The communication-void is a phase in which the communication infrastructure has suffered severe damage, and as such, it is a phase that must be considered by authorities. During this phase, there is complete radio-silence within the disaster-struck area, meaning there is an absence of public cellular network communication within licensed spectrum. The communication-void phase may result from an extended communication-burst phase with failing infrastructure, but can also appear as a direct result of disasters that have a tremendous impact on critical infrastructure. In fact, the communication infrastructure within the communication-void is not only non-functional or overloaded, but rather technically disconnected, malfunctioning, or destroyed, preventing all forms of mobile communication by citizens.

We see future research into the communication-void phase as critical and very important as there may be unused potential to establish emergency networks. As our study has shown since some citizens may still have functioning smartphones within the disaster-struck area after the blackout destroyed cellular infrastructure does not necessarily mean that mobile communication is impossible. Furthermore, the SoC of citizens within the communication-void phase is closely linked with the SoC phase they experienced during the blackout. For instance, a blackout that occurs soon after a main-charging phase will result in citizens entering the void phase with maximum battery capacity, while a blackout during the critical-charging phase will result in citizens having less battery charge during the void phase and being less likely to communicate or use their phones for emergency services.

EFFECTIVE STRATEGIES AND TECHNOLOGIES FOR SMARTPHONE RELATED EFFICIENT POST-BLACKOUT EMERGENCY COMMUNICATION

With an understanding of the expected SoC before and after a blackout, as well as during the communication-burst and communication-void phases, authorities can consider new technologies and innovations to establish reliable and easily accessible emergency communication systems for citizens within a disaster.

Recent research and standardization activity in the area of disaster-communication have already uncovered a variety of innovations that can be considered for scenarios that involve either rebuilding of failed infrastructure or building urgent replacement infrastructures and network architectures. These solutions may prove useful since the loss of communication infrastructure does not necessarily imply the inability to communicate via cell phone. According to our study results, we can now assume the overall SoC to be at least sufficient after a blackout such that some phones within the affected area would still be functional. In fact, our results presume that even if the blackout occurs during the critical-charging phase (early or late evening), people would still be able to use their phones for a few hours even after the communication-burst phase, assuming an average SoC of around 50%. These phones would then be able to be used for emergency communication if there is a functioning emergency-network they could easily connect to.

The next steps in this research will be to analyze communication technologies, standards and network infrastructures presented in research and literature. Suitable strategies should be used as foundation for post-blackout citizen-to-authority emergency communication, especially within the communication-void phase. There is also a need for a firm requirements analysis of the technologies that come into consideration in communication-burst and communication-void.

As a first step towards this research, we present a first approach in categorizing communication concepts based on three Tier Levels: *Void-Emergency-Communication Services, Blackout Emergency-Communication Services and Public Safety Services*. In the provided table we explain the concepts briefly with examples and recommend the suitable SoC-related phases in which these concepts should be implemented to establish efficient emergency communication.

Strategies and Services to apply depending on the occurrence of a blackout or disaster until recovery of cellular mobile networks
Tier 1: Void Emergency-Communication Service
Description: Quickly installed Cellular Emergency-Communication Infrastructure within the disaster struck area enabling trivially (easily) accessible emergency communication for citizens.
Technology: Locally deployed aerial or stationary nomadic cellular (LTE/5G-Core) networks reconnecting still working smartphones (vendor neutral).
Services: • A-to-C Emergency Communication via (areal) Cell-Broadcast, • C-to-A Emergency Phone Call • C-to-A / A-to-C Emergency SMS-based communication (rescue, localization, information) • A-to-C active smartphone location tracking
Examples: • Evacuation announcement/coordination via cell broadcast • Receive/Send Emergency Information via SMS • Warning/Information via Broadcast / Cell-SMS • Localization of vulnerable persons with working Phones.
Recommended Phases: • Void, Critical-Discharge, Main-Charging
Tier 2: Blackout Emergency-Communication Service
Description: Strengthened Disaster Network that cover the disaster struck area, offering heterogenous network protocols on top of next generation network innovations for Post-Disaster/Blackout Emergency Services. Cellular Services may be offered via still working or rebuild base stations.
Technology: Next Generation Network innovations such as Mobile Edge Computing are used to deploy and host service applications within the disaster struck area. WIFI Access Points and Areal Network Hubs, offer access to Edge-Hosted Services.
Services: • WIFI-Access Points offered by fixed Access Points, Drones and Vehicles, • Access to edge hosted emergency web applications (locally-restricted-web) • Recruitment of First Responders / Volunteers via Web-Interface • C-to-A Video / Image Transfer • Extended Messaging / Chatbots
Examples: • Authorities offer Web-Services with authenticated Information for citizens within the disaster struck area. • Volunteers and Citizens can use WIFI to upload images and videos to first responders

• First Responders host Web-Services • Additional wifi-hotspots can be built up to strengthen the upcoming date for public safety services
Recommended Phases: • Main-Charging, Main-Discharging, Critical-Discharge, Communication-Burst
Tier 3: Public Safety and Crisis Communication Services
Description: Robust and Energy-efficient communication possibilities and fixed community hotspots for citizens and authorities within the disaster struck area. Connectivity to the world-wide-web until reconstruction of communication Infrastructure.
Technology: Extended IP-connectivity to world-wide-web and cloud services through either Satellite connection or adjacent non-struck areas with working internet connected infrastructure
Services: • sophisticated information centers offering information and access to the internet for citizens. • mobile applications
Examples: • Authorities offer central information locations and hot spots to citizens. • Citizens are enabled to recharge their phones within information location
Recommended Phases: • Main-Charging, Main-Discharging, Critical-Discharge, Communication-Burst

CONCLUSION

We conducted a MESM study to understand the citizens' state of charge throughout the day and to evaluate the impact of a blackout depending on the time of occurrence. The study results allowed us to define three distinct phases during the day when smartphones are either charged or discharged (main-charging, main-discharging, critical-charging). Our results did not indicate any hour in which most smartphone battery levels were critically low. Instead, we found that users tend to charge their phones at or before reaching 20%, resulting in an average overall state of charge of 60%. Our study revealed that citizens are more resilient than expected when it comes to smartphone energy management. Even after a blackout and communication infrastructure failure, some smartphones may still be usable.

We identified specific periods in which a blackout can be considered most critical, occurring just before the main-charging phase or during the critical-charging phase (between 19:00 and 23:00). In preparation for future investigations, we defined two post-blackout phases (communication-burst and communication-void) that describe post-blackout communication circumstances. These five periods can now be used as a reference framework for selecting emergency communication technologies based on the impact of the blackout and expected smartphone state of charge. Based on our provided strategies we propose the investigation of communication strategies that can be applied within the void-communication period such as nomadic-cellular networks. These may help to connect still active smartphones within the disaster-struck area and make users directly reachable via messaging and phone.

The MESM approach proved to be a suitable method for retrieving real-time battery level information and charging behavior from multiple participants over an extended period of time. However, the approach used in this study should be considered a preliminary approach that is not yet fully developed and has its limitations. The hourly state of charge and charging behavior of the participants obtained by this method appear to be generalizable within a target group that is similarly socialized. The graphs generated based on the received data can be interpreted as indicators of the work and sleep cycles of users. However, this may vary if the socialization of the target group differs. For example, individuals who work late or who live in different areas may have different sleep and work cycles or charging behaviors, and therefore, they would not be accurately represented by our study. To address this issue, future studies should consider the demographics of the users to prevent ambiguities.

However, we were able to ascertain that a significant number of phones may still be working after a power outage. This is essential to consider when planning post-blackout emergency communication scenarios. Failing to utilize the potential of these devices could lead to missed opportunities to establish communication with citizens in need. Therefore, it is crucial to consider these devices in emergency communication strategies to ensure effective communication during crises.

RESEARCH PERSPECTIVES / FUTURE WORK

In our future work, we plan to undertake several important tasks. Firstly, we will conduct a complementary MESM-study with Android phones, to gain a more comprehensive understanding of battery usage behavior across different devices. Additionally, we will investigate whether a machine learning model that can predict the post-blackout state of charge can be trained based on the data. This will however need a large-scale study in order to address a critical mass of data. A trained model might be useful in estimating how long citizens are reachable in case of a power outage. Another key task will be to investigate reference architectures for Tier 1 Void Emergency-Communication Service Architectures and Applications, with the aim of identifying the most effective strategies for enabling post-blackout communication via locally deployed cellular networks. We see potential in trivial accessible emergency services that are provided via SMS, Cell-Broadcast and phone, without the need of internet connection. Finally, we plan to build a framework for post-blackout communication systems that will help guide the development and usage of post-emergency communication technologies in the future.

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