Simulation as a Tool: Towards Next Generation Crisis Management and Emergency Communication during Blackout Disasters

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ABSTRACT

Crisis teams and crisis management must always be able to respond efficiently to disasters. However, Blackout Disasters pose a significant challenge for crisis teams and the affected citizens. Their impact on mobile networks can leave people without any means of emergency communication for an indefinite period, putting them in danger. Therefore, crisis teams must be able to act quickly by assessing the extent to which a power outage affects cellular coverage in disaster-stricken areas. However, the necessary expertise for this is often lacking. This study examines how simulation can enhance crisis management in Blackout Disasters. In an integrative research approach the PPRR-crisis management model is extended with phase-specific simulation use cases. The study demonstrates how simulation, based on digital twins, can model mobile networks, predict failures, assess disaster impact, and support the restoration of authority managed emergency mobile communication networks. First simulation results on a Berlin dataset show that already minor disruptions within the power grid will lead to severe impacts on mobile networks. Knowing this impact before the disaster occurs is an important asset for crisis preparedness and response.

Keywords

Future Crisis Management, Public Safety Campus Networks, Blackout, Simulation, Digital Twins

INTRODUCTION

Large-scale blackout disasters have a massive impact on residents and critical infrastructure, making them a major challenge for crisis management. Interconnected power grids, spanning multiple regions and countries, carry the risk of cascading failures triggered by natural disasters. The consequences can paralyze entire metropolitan areas. Due to climate change, the likelihood of such events is increasing significantly. In addition, local disasters, human error, and cyberattacks on central components of critical infrastructure pose significant threats that may also lead to large-scale power outages. One particularly critical infrastructure that is highly vulnerable to power outages are mobile communication networks. While their functionality is essential for emergency-communication by citizens towards first responders and public safety communication under the responsibility of crisis management authorities, responsibility for their functioning infrastructure lies with mobile network operators (MNOs). Without functioning mobile networks, emergency calls become impossible, posing a severe risk to citizens and especially to vulnerable groups, during a disaster. Fixing damaged mobile network infrastructure to establish emergency and public safety communication does not belong to the domain of first responders or crisis management authorities, which is a severe disadvantage during disasters as it hinders rapid emergency communication within crisis response.

VISION ON FUTURE CRISIS MANAGEMENT

Our vision for future crisis management, disaster-response and resilient public safety communication for blackout disasters is therefore as follows:

> *Next Generation Crisis-Management teams, First Responders and Authorities should be independently able to assess the impact of a large-scale blackout on mobile networks. They should also be able to independently set up and operate own emergency mobile networks within disaster response, openly accessible for the public, before official mobile network and power grid operators arrive to repair the impacted infrastructure.*

The viability of this vision has been firstly proposed and discussed in (Lukau et al. 2023), where researchers show that mobile phones retain battery power for a certain period after a power outage and might connect to a rapidly deployed cellular network. However, this potential currently remains unused since the establishment of an authority-operated cellular network in a disaster-stricken is a rather disruptive solution for a non-trivial problem, challenging security, regulatory, legal and organizational frameworks.

Challenges and Problems: The Lack of Mobile Network Expertise in Crisis Management

The technical foundation of authority-operated cellular networks has been firstly presented in (Lukau et al. 2024). Here the researchers present container-based Public Safety Campus Networks (PSCN) that establishes a public emergency cellular network for voice and data transmission within disaster-stricken areas without cellular coverage. This provides operator-agnostic access to all means of public safety and emergency communication between citizens and authorities.

However, the primary challenge preventing crisis management and authorities from adopting this innovation is the high demand for expertise in mobile network technology. Deploying and managing such networks requires specialized technical knowledge, which is not necessarily present in crisis management staff. This issue becomes particularly critical when consultations between MNOs and crisis management staff during a disaster is delayed. In time-sensitive situations, the lack of expertise hinders a rapid and effective disaster response. Consequently, innovative solutions such as PSCN remain largely inaccessible as a viable solution within blackout disasters to authorities that mostly have no direct involvement with public mobile communication technology.

With respect to the lack of expertise on mobile networks in crisis management, this paper proposes the use of simulation as a tool to:

(I) provide critical insights into the impact of power outages on mobile networks in urban environments
(II) support decisions, actions and response made by crisis management staff.

Our goal is to demonstrate that authorities without immediate support from MNOs can obtain sufficient information, by using simulation-based expert knowledge, to assess the effects of a blackout and counteract them with appropriate technologies. Additionally, we envision that simulation is viable tool not only within a blackout disaster but also before and after the incident, for improved recovery and preparedness. To underline the vision and to motivate discussions, this paper presents a first approach on the holistic integration of simulation-based expert knowledge into crisis-management by extending the commonly known crisis-management cycle (Cronstedt, 2002 and Johansson, 2007) with phase-specific simulation use-cases targeting to blackout disasters and mobile communication. This paper further demonstrates how simulations on a digital twin can improve crisis response.

It is the first time that this kind of research and simulation is conducted on a realistic digital twin of a Berlin district including its critical-infrastructure, buildings and demographics. [1]

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[1] The simulations were conducted on real infrastructure and demographic data from the district Berlin Schöneberg within the Fraunhofer SIRIOS Project 2024 (https://www.sirios.fraunhofer.de). Unfortunately, no non-published or disclosed specific data points regarding route networks, the power grid and demographic details can be published due to their critical nature.

Scope of this Paper

The scope of this paper does not include the development or assessment of simulation-models for radio and signal processing, nor does it introduce newly created simulation models. Instead, this work demonstrates first results and the feasibility of simulations for crisis management. The work aims to show how scientifically validated mathematical models can already be leveraged to conduct simulations on digital twins with given tools and present realistic results that are already helpful for current blackout disaster response plans and towards empowered future crisis management

SIMULATION AS A TOOL WITHIN THE CRISIS MANAGEMENT CYCLE

As part of our research, we conducted expert interviews with crisis management staff, critical infrastructure operators as well as expert consultations with various security authorities, state officials and first responders. The objective was to gain an understanding of when simulations can be effectively utilized in blackout related crisis management operations. We identified use-cases and expectations towards simulation-assisted crisis management that should be integrated into the so called: *Prevention* (also mitigation), *Preparedness*, *Response* and *Recovery* crisis-management cycle (PPRR). This model is based on the Comprehensive Emergency Management Framework (CEM) that was firstly introduced in 1978. While criticized in literature (Cronstedt 2002) it is to this day internationally adopted (Johansson 2007, UNDRR 2016, FEMA 2024) in emergency and crisis management and also base of the German crisis-management procedure recommendations by the Federal Office of Civil Protection and Disaster Assistance (BBK 2025).

The integration of simulations into crisis management is not a new concept and has already been adopted, discussed, and presented in various studies (e.g., Paton et al., 2006, Ramírez et al., 2015). However, our consultations with crisis experts revealed a lack of guidelines and use-case-specific examples to better understand how simulations, particularly simulated expert knowledge, can support decision-making throughout all phases of crisis management.

By incorporating expert requirements and use cases, we developed an initial version of a holistic approach by strategically extending the PPRR model for simulation-assisted crisis management, specifically aligned with blackout disaster scenarios. This should motivated further research and discussion on this subject. Our phase-specific approach integrates simulation-based predictions, actions, and planning into each phase of the PPRR model, demonstrating how both pre- and post-disaster simulations can enhance crisis management (**Figure 1)**.

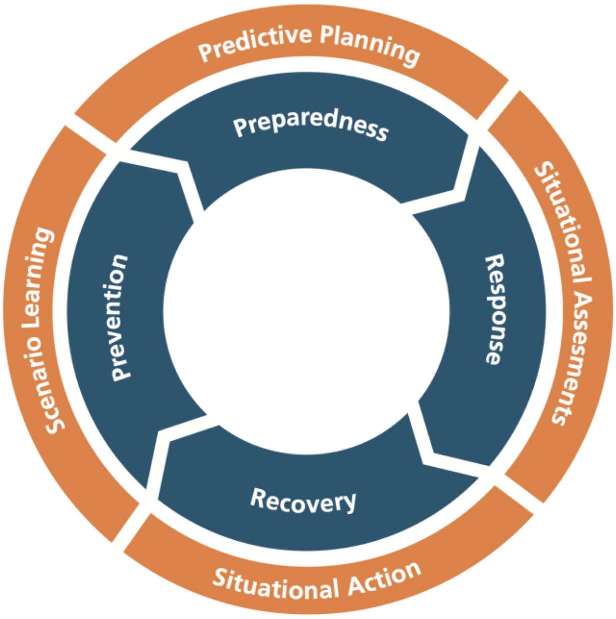

Figure 1. Simulation-Assisted PPRR Crisis Management Circle

Phase-Specific definition of simulation-assisted PPRR-Crisis Management Cycle

The following definitions for each phase are the result of an integrative research approach. Each phase is reconsidered by synthesizing existing knowledge from literature (UNDRR 2016, Johansson 2007, FEMA 2024, BBK 2025). Building on this foundation, the use cases identified in the crisis-expert consultations are incorporated to develop new visions and redefine the extended PPRR-phases:

1. **Prevention:** The prevention phase encompasses all actions and measures taken to reduce or eliminate risks to critical infrastructure and inhabitants before a crisis occurs. We introduce **Scenario Learning** as a simulation-related use case in this phase. Scenario Learning refers to all activities aimed at understanding and documenting commonly known or expected disaster impacts on critical infrastructure and inhabitants.
   This process involves collecting essential data (e.g., infrastructure data) and making public investments in programs and projects that generate standardized scenario descriptions, which can then serve as inputs for simulations. For example: Scenario Learning for a blackout-related disaster involves identifying the direct and indirect dependencies on power supply and accurately mapping the potential outage effects on infrastructure and residents.
   By systematically analyzing different scenarios, Scenario Learning helps identify critical weaknesses in infrastructure, enabling the implementation of targeted countermeasures to mitigate the negative impacts of a disaster.

2. **Preparedness**: The preparedness phase encompasses all actions and activities taken to ensure an effective crisis-management and emergency response. This includes the development of emergency-plans, definition of emergency-processes, public investments, resource management, and training.

   By extending this phase with **Predictive Planning** as a simulation-based use case, all actions within Preparedness benefit from simulations and predictions based on educated scenarios discovered and learned within Scenario Learning. Simulations based on educated scenario descriptions generate predictions that improve the development of new plans and processes. These predictive insights help identify critical areas where investments should be reprioritized and can also influence political decision-making.
   Additionally, restructuring staff and refining training programs based on simulation-driven predictions can lead to optimal resource allocation. These proactive measures not only enhance disaster resilience but also improve overall crisis response effectiveness while minimizing the likelihood of unintended consequences

3. **Response**: The disaster response phase encompasses all immediate actions taken to manage and mitigate a current disaster. These actions are carried out by crisis management teams, authorities, and first responders during the disaster or immediately after its impact. Decisions made in this phase are ideally based on preparedness and predictive planning, ensuring that disaster response measures are effective and well-coordinated. However, availability of in-situ data on the current disaster such as weather conditions, structural damage, current state of infrastructure and other situational factors can provide valuable real-time insights into the current situational state of the event.
   This allows for **Situational Assessment** as simulation-related use-case by using real-time data as input for re-simulations to refine predictions. If these simulations can be executed quickly, they allow for real-time verification of previous assumptions, identifying whether initial response strategies remain valid or require adjustments. This adaptive approach supports educated decision-making and enables crisis management to proactively switch to alternative solutions as new data emerges.

4. **Recovery**: The recovery phase encompasses all actions taken to return to a normal or a desired state, whether restoring pre-disaster conditions or establishing a more resilient infrastructure. In contrast to the response phase, decision-making during recovery can be less time-sensitive and targets all measures after the immediate disaster-response. This allows for long-term planning, the evaluation of multiple solutions, and strategic decision-making tailored to specific situations. By leveraging **Situational Actions**, simulations can be used to assess the effects of different recovery-actions, as needed by the effects of the disaster, compare their outcomes, and determine the most effective approach. In-situ simulations can also uncover unintended side effects of parallel recovery missions, helping to optimize resource allocation and suggest prioritizations for planned recovery activities.

DIGITAL TWINS IN SIMULATION-ASSISTED FUTURE CRISIS MANAGEMENT

Digital twins are becoming increasingly important in future crisis management. They are particularly essential for critical infrastructures, cities and municipalities as well as simulations and analysis to efficiently manage infrastructure and improve crisis preparedness and disaster response. The most recent comprehensive work on Digital Twins in general, its idea and definitions have been conducted by (Trauer et.al 2020). They derived the definition of Digital Twins in the context of Industries as: "*virtual dynamic representation of a physical system" that is "connected to it over the entire lifecycle for bidirectional data exchange*". This definition can freely be transferred into the context of simulations for crisis management. In Germany, a standardization for Digital Twins specifically for cities and municipalities has been established through *DIN SPEC 91607*, which defines the requirements for digital twins. The standard defines Digital Twins for cities and municipalities as a: "*digital representation of municipal reality with systematic reality synchronization*". This means that various digital resources must be integrated and combined to create an accurate and realistic digital model of a municipality. The intention is more efficient management of critical infrastructure and targeted disaster management measures.

Data Integration and Simulation of Cellular Coverage

The integration of simulations as an information system for future crisis management is a feasible task. Our approach presents the technical fundamentals on which the simulation on top of a digital twin provides authorities with expert knowledge on mobile network coverage in target area. The objective is to understand the coverage created by mobile network within a selected target district.

To conduct simulations on top of the digital twin of the given area of interest in Berlin, real-world infrastructure data must be collected and transformed into a virtualized digital representation. To realize this, we use an integrated reimplementation of the NS3-Network-Simulator (Carneiro et.al 2010) to simulate the cellular network and calculate the network coverage. The reimplementation of NS3 allows to create network scenarios based on localized mobile base stations. To be more specific: we use a dataset of LTE-Base Stations (eNB) installed in Berlin to simulate the LTE-Network and mirroring the coverage. This dataset is based on crowdsourced data (CellMapper 2025) and publicly available information on installed eNBs in Germany, provided by the Federal Network Agency (BnetzA 2024).

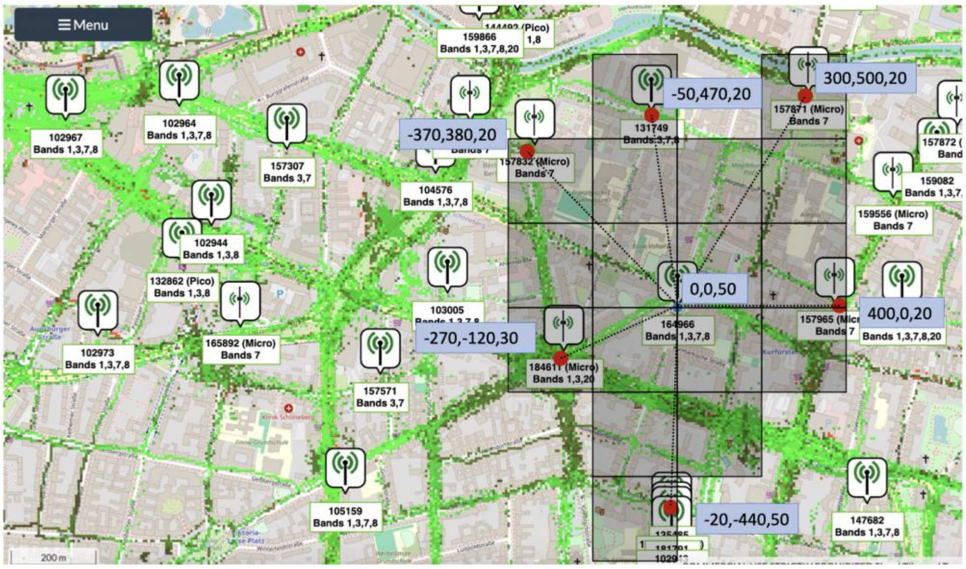

Figure 2. Screenshot of the crowdsourced eNBs within the target area as presented on cellmapper.net. (as of February 25, 2025)

Figure 2 presents a visualization of crowdsourced eNBs within the target district on as presented on cellmapper.com. The eNBs that are selected are highlighted with a red dot. The visualized grey squares help to better rasterize the positions of the eNBs within the NS-3 simulation environment.

The retrieved and combined data from the sources are used to create a simulation database of eNBs with the following attributes: *Geolocation (Latitude, Longitude), Antenna Height, Building Height, Azimuth (Orientation),* *Operating Bands and Protocols and Frequencies.* Since NS-3 does not support generic MIMO antenna models yet, we use MIMO-aware PHY models, beamforming and spatial multiplexing. This ensures close to realistic cell simulated ranges. In addition to the information on base stations we integrate geolocated building information, since the eNBs are typically installed on rooftops. This information is obtained by the Berlin *ALKIS* database, published by Berlin Senate Department for Urban Development, Construction and Housing. By extending the eNB-Data with geolocated building information a highly accurate digital representation of each base station, including its spatial and operational parameters, can be constructed and integrated into the virtual topology within NS3 while preserving real-world positioning and configurations.

To model realistic cellular network coverage in relation to human presence inside buildings, the virtual network topology is combined with virtual buildings of varying heights according to the provided building data. Pathloss and signal penetration is calculated using NS-3's *Hybrid Buildings Pathloss Model* (Bugarcic 2021) which allows for accurate network simulation, including different wall types with or without windows. To represent signal attenuation realistically and close to real world conditions, the virtual buildings are created and randomly to assigned different wall types and evenly distributed within the virtualized topology. To measure the signal a receiving device (i.e. a Smartphone) is need. Therefore, the virtual topology adds cellphones or "*User Equipment*" (UE) as probes into the scenario to measure the signal strength. These cellphones are positioned within virtual buildings and outside. The signal strength between each UE and eNB is determined based on Received Signal Strength (RSRP) and Signal-to-Noise Ratio (SINR). **Figure 3** illustrates the network topology, where yellow dots represent evenly distributed UEs and blue dots indicate localized eNBs.

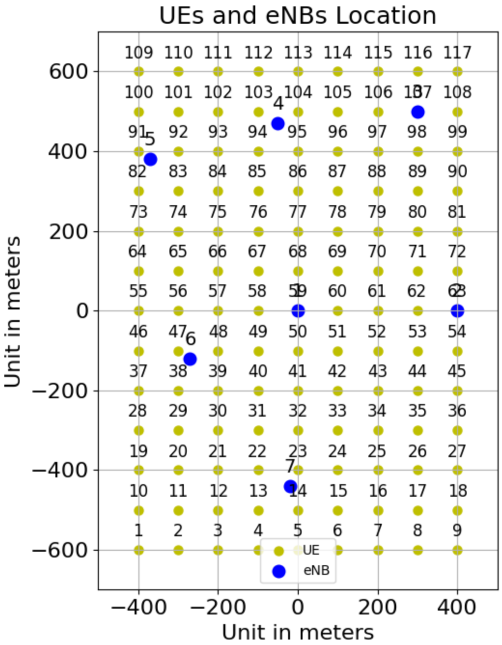

Figure 3. Point Plot presenting the virtualized cellular network Topology

Simulation-Results and Learnings for Crisis Management

The simulations calculate the received signal strength at each UE. The eNB in range with the strongest signal is selected by the UE if the received signal strength is sufficient, initiating the cell connection process. **Figure 4** illustrates the relationship between each UE and its connected eNB, visualizing the resulting network coverage. Here each eNB represents a cell and is plotted with a specific color. The illustration shows which of the UEs is connected to which eNB effectively creating the cell coverage. Since the base stations have differing configurations in frequencies bands and transmission power, as well as in height and attenuation the cell sizes also differ in range and size.

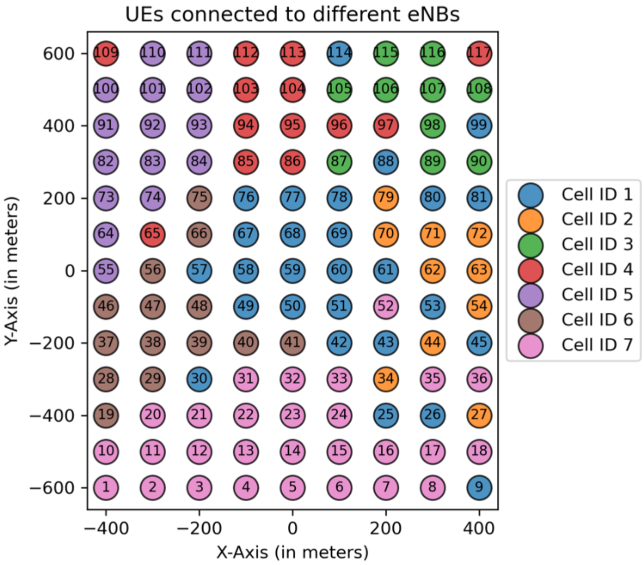

Figure 4. Point Plot of each UE connected to an eNB with colors depicting the coverage of each eNB

It can also be seen that some UEs seem to establish connections with more distant eNBs due to signal strength fluctuations. This indicates that cells may also overlap each other. This phenomenon can be better presented through a polygon-based visualization of the network cells, as shown in **Figure 5**. Each polygon represents a cell based on UE connections. This representation highlights differences in cell size and signal distribution. The plot highlights the dominance of more powerful base stations, whose coverage extends over weaker or smaller cells. It clearly indicates that Cells 1, 4, and 7 are the most dominant within the target area. A failure of these eNBs would likely have a more significant impact on overall coverage compared to the failure of other eNBs. However, the plot also demonstrates the resilience of the mobile network in the area. The failure of individual eNBs may not necessarily cause major coverage gaps, as neighboring eNBs could still provide sufficient signal strength, ensuring continued connectivity and mitigating the impact of potential outages.

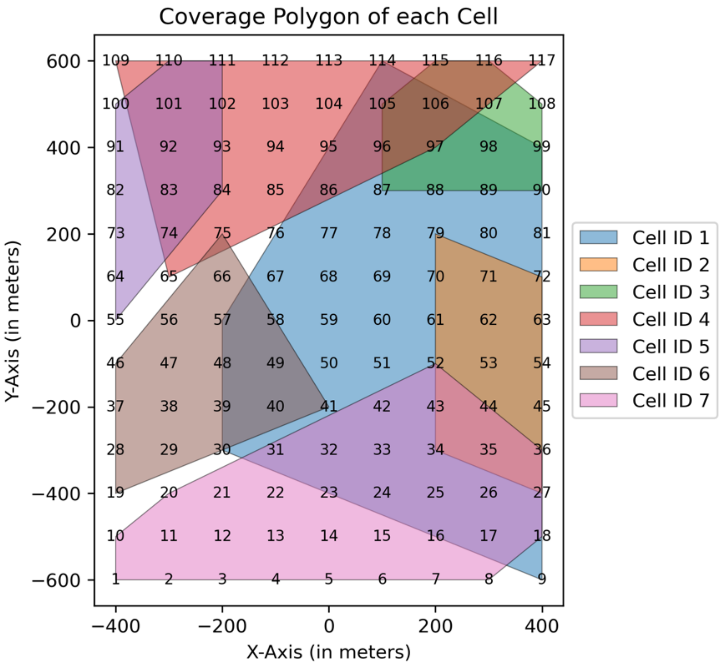

Figure 5. Plot of each polygon presenting the simulated cell coverage of each eNB

Discussion: Dealing with Uncertainty in Mobile Network Simulations for Crisis Management

It is important to note that basic simulations conducted using NS3's integrated Hybrid Buildings Model might also introduce minor uncertainties that cannot be directly compared to industry-level simulations used by MNOs. Additionally, alternative path loss models, may yield different results depending on specific conditions, topology, and scenarios. Further This simulation does not support MIMO for special multiplexing, however compared the ranges of the cells with the crowdsourced data we can see similar cell sizes and do not expect drastic changes if MIMO is considered und thus for this use-case more than sufficient. Signal propagation is inherently complex, which is one reason why many authorities and crisis management teams tend to avoid engaging with it in detail. However, it is essential to discuss whether the relevance of uncertainty in cellular network simulations depends more on the specific requirements and intended use case of the simulation. For instance, MNOs prioritize highly optimized, robust, and high-performance mobile networks, where precision in coverage and performance is crucial. In contrast, crisis management, first responders and authorities have different priorities. They might prioritize to geographically locate coverage gaps, evaluating their size and impact as well as assessing the number of people potentially affected with a lack of emergency communication. Especially within blackout related disaster-response, it is rather crucial to quickly provide fundamental insights into network functionality, coverage reach, and potential outage impact without requiring fine-tuned optimizations. Our simulation results provide sufficient evidence to reasonably assume that cellular network simulation approaches, based on scientifically validated models as presented here, deliver adequate information for crisis management and authorities to assess the impact of an outage, even if precise coverage boundaries cannot be determined down to the meter. However, environmental factors such as high-rise buildings, glass facades, parks, rivers, underground structures, and weather conditions like heavy rain or fog further contribute to signal variations and introduce additional uncertainties that always must be considered.

BERLIN BLACKOUT CO-SIMULATION AND MOBILE NETWORK DISASTER IMPACT ASSESSEMENT

If simulating a mobile network can create a digital twin of cellular coverage, it can also be used to test and predict various failure scenarios. Therefore, we integrate the mobile network simulation system into a coupled simulation architecture, linking it with a power grid simulator to model a digital twin-based power outage scenario within the target district. We therefore implemented a co-simulation infrastructure, allowing for coupled simulations of various domain-specific simulation modules (Restel, 2023 and Restel et.al 2025). Therefore, this presented simulation demonstrates the feasibility of simulation-assisted crisis management and its usefulness for disaster-response and disaster-preparation in blackout-disasters. The co-simulation system runs blackout disaster simulations on a digital twin by enabling the manipulation of critical components within the power grid. The system then calculates the impact on the cellular network and estimates the expected number of affected citizens.

The connected power grid simulator (Gerold et.al 2023) simulates the state of the power supply in the target area. The data obtained for the dataset enabling a power-grid digital twin has been received data-portals on electricity networks in Berlin. The data include geographically accurate points of common coupling, transformers, substations as well as high/medium and low-transmission powerlines. The data is sufficient to mirror a virtualized digital twin of the power grid within the target area. The mobile network simulator is equally used as described before. Additionally, it also incorporates information from cable routes, as some of these cables, not only supply power to the base stations on rooftops but also connect them to the providers internet network.

We define the interfaces, or "*points of common coupling"*, between the power grid and the communication network at locations where a stable power supply is essential for operation. This applies either when base stations lose power due to a building-wide electricity outage or when outdoor internet distribution cabinets, housing critical amplifiers and signal converters, lose their power supply and cease functioning. **Figure 6** shows connected distribution cabinets. Located outside they couple electricity and data networks. realizing the interconnection between electricity-network elements and internet-network.

Figure 6. Distribution Cabinets connecting electricity network and data networks

Simulation Step 1: Simulation of Pre-Blackout Mobile Network Coverage

In the first simulation step, we simulate the fully functional mobile network in the target area and predict the resulting coverage within the target area. To visualize the simulation results in a situational picture for crisis management, we use the electronic situation dashboard for civil protection based on ELD-BS (Hellmann et.al 2022). **Figure 7** shows the predicted mobile network coverage with complete coverage and no impairments. For better visualization for non-experts, it should be noted that coverage area of each base station is represented as hexagon, based on the simulators predicted cell size compared to the visualized simulation of cells as illustrated in **Figure 5**. Furthermore, for this experimental setup, it must also be considered that base stations outside the target area are initially treated as non-existent to better analyze the functionality of the simulator. However, it is highly likely that adjacent base stations significantly influence coverage within the test area, which is why excluding base stations should not be done in real-world scenarios.

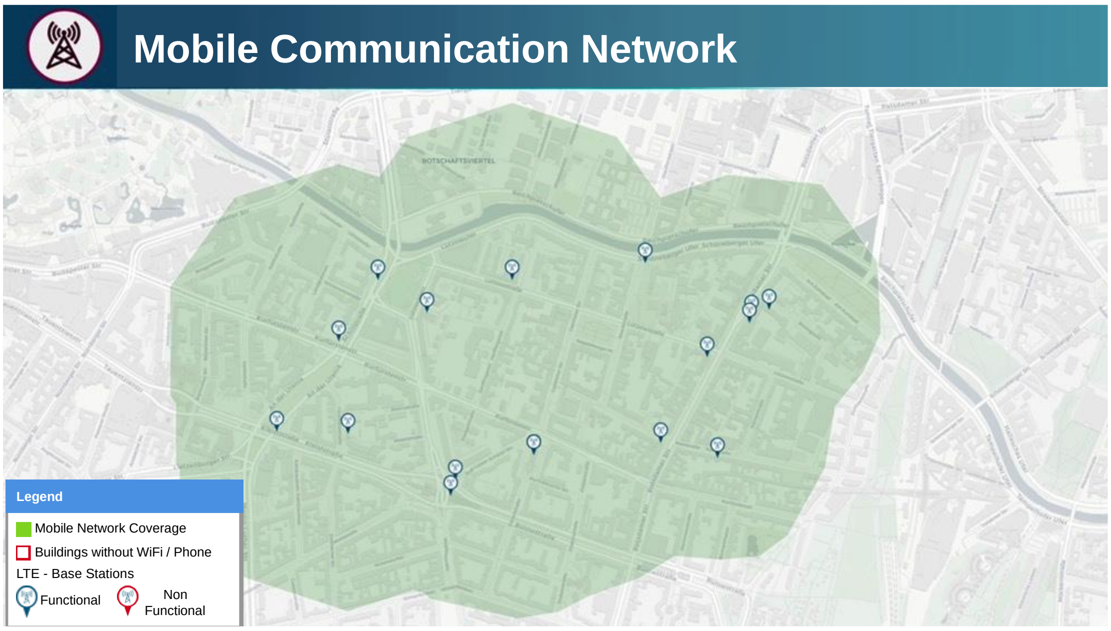

Figure 7. Common Operating Picture: Simulation Results predicting the mobile coverage pre-blackout, visualized in a situation dashboard based on ELD-BS (Hellman et.al. 2022)

Simulation Step 2: Simulation of Blackout impact on Mobile Network Coverage

In a second simulation step, a local critical power outage in the test area is simulated. The failure is initiated by deactivating a critical local distribution substation, responsible for the transformation of medium voltage for local electricity distribution. In a real-world scenario, such a failure could be caused by vandalism, cyberattacks, or environmental disasters. As a result of the failure, the power grid simulator calculates the change in power distribution and outputs a new state of the power grid. This information is transferred to the network simulator, allowing conclusions about which buildings and distribution cabinets are affected by the outage and, consequently, which base stations are impacted. Based on this event, a modification of the topological network architecture is performed, which serves as the basis for calculating the resulting loss of mobile network coverage. This recalculation considers changes such as the reduction of transmission power in base stations, the overload of adjacent base stations, and even the complete deactivation of affected base stations. Additionally, the simulator outputs information on which households are left without internet or telephone access due to either a lack of power or disrupted data transmission, meaning they no longer have access to home-based emergency communication.

Figure 8 shows the predicted impacts of the outage as calculated by the simulators. Buildings without power supply, and thus without any possibility of emergency communication, are highlighted in red. Additionally, the failed base stations are marked. It is clearly visible how significantly mobile network coverage is reduced, with nearly one-third of the previous coverage lost.

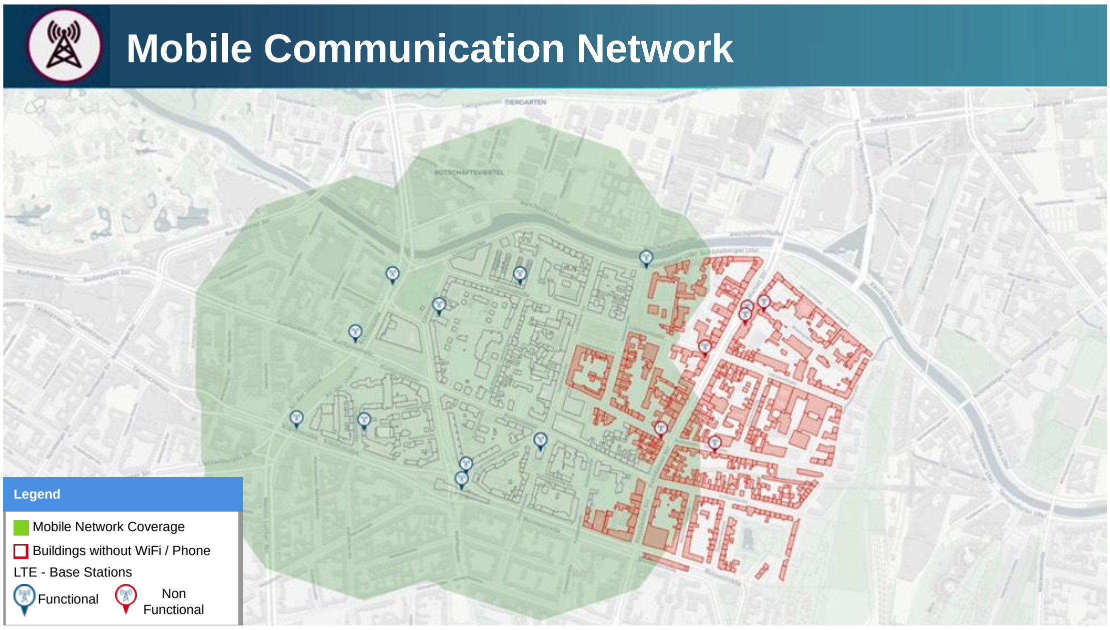

Figure 8. Common Operating Picture: Simulation Results predicting the impacted mobile network while-blackout, visualized in a situation dashboard based on ELD-BS (Hellman et.al. 2022)

Simulation Results and Learnings for Crisis Management

To the best of our knowledge, such a coupled simulation of a partial power outage with direct impact on mobile communications networks, fabricating a realistic result based on a digital twin of a district in the city of Berlin, has not yet been published. The results are therefore first of their kind for the city of Berlin and will serve as an input for further discussions and plans regarding increased resilience, empowered disaster management and the cities blackout disaster preparedness.

According to demographic information, which is also part of the digital twin data retrieved from the ALKIS database, the affected area with no means of mobile communication is expected to include between 8 and 9,000 residents in 55 buildings. Of these, approximately 2,000 individuals can be classified as vulnerable, being either over 65 or under 6 years of age. Also, a hospital as well as a Kindergarten is affected. This information is now available either before the crisis and can be integrated into plans, or if conducted within the crisis, available for any decision within disaster-response.

This approach introduces a valuable method for assessing the impact of disasters on mobile networks, that is in crisis-management not possible without consulting MNOs during a crisis. It enables precise conclusions about affected individuals and vulnerable groups that might not have any chance of emergency communication. This information is essential for optimizing disaster response efforts and emergency communication strategies.

SIMULATION-ASSISTED DEPLOYMENT OF PUBLIC SAFETY CAMPUS NETWORKS

In the previous chapters, we demonstrated the valuable role of simulation as a tool improving crisis management. Beyond this, we present how simulation-based expert knowledge enables authorities to adopt future-proof innovations. The PSCN concept is a crisis-communication innovation that enables rapid deployment of authority-managed emergency cellular networks in disaster areas. PSCN containers, utilizing edge computing power, can locally host public safety services such as emergency websites, warning systems, emergency VoIP services, emergency-chatbots, and assistance platforms, making them publicly accessible via emergency mobile networks within the disaster areas.

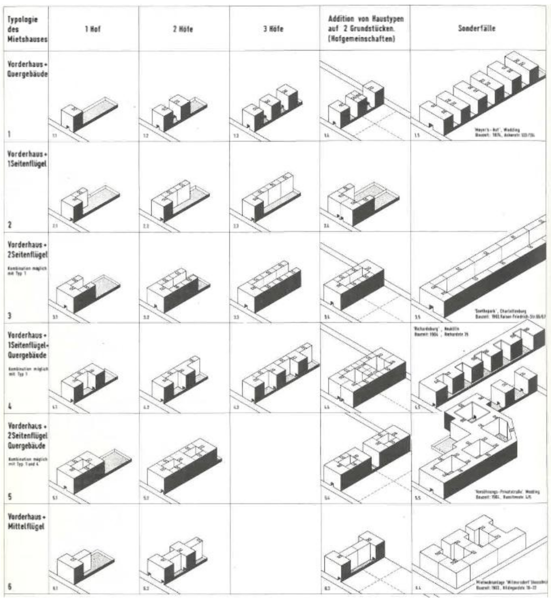

Figure 9. Overview of the complex architectures of Berlin Apartment Buildings (Geist et al. 1984)

A key challenge for authorities is the lack of expert knowledge to determine the optimal number, placement and radio-configuration of PSCN-containers for maximum coverage, particularly in urban environments where deep in-house service is required. In Berlin, architectural factors such as large inner courtyards in high-rise buildings (see **Figure 9**) further complicate signal propagation, making it difficult to provide reception in rear buildings. Without this knowledge, authorities cannot efficiently deploy emergency networks.

Our vision for next generation crisis management is for authorities to use simulation as a tool, controlled by intelligent algorithms to overcome these challenges. The simulations should provide authorities with the best possible recommendations for deploying PSCN containers in disaster situations for best possible emergency coverage.

Simulation and prediction of the PSCN-Container generated coverage into buildings

In the first step, we demonstrate how simulation can be used to calculate the expected network coverage extending deep into the apartments of complex architectural structures. This knowledge is essential for effectively coordinating multiple PSCN containers in large-scale scenarios to optimize network coverage. The architectural structure under consideration is a perimeter block building, which is typical for Berlin (**Figure 10**). This consists of a large, continuous building complex with an inner courtyard at its center. The simulated building is 200 meters long and comprises 22 interconnected buildings, each with three floors, where each floor contains four apartments of 100 square meters each.

As in the previous experiment, we place a UE in each apartment, representing a smartphone receiving the LTE signal. The simulation models an LTE antenna positioned on a container located 50 meters away from the building. The antenna model used in ns-3 is the 3GPPAntennaModel, which is integrated with the LTE module. For path loss calculation, the *HybridBuildingsPropagationLossModel* is applied.

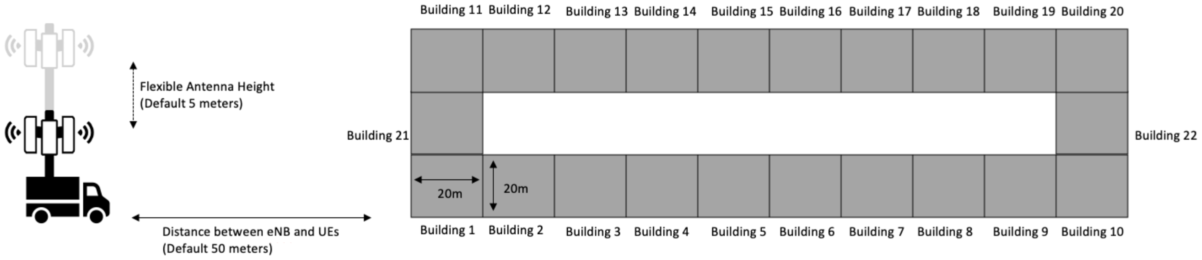

Figure 10. Simulation Scenario of a PSCN-Container serving a Perimeter Block Building with courtyard

Figure 11 presents the first simulation result in the form of a heatmap, which visualizes the signal quality received by the UEs. Areas with poor signal quality appear in blue, while red to green indicate very good signal quality. The results show that the LTE antenna provides strong coverage across almost the entire building, reaching a depth of at least 200 meters with a good signal. It is likely that apartments in the rear sections also receive a signal, albeit with reduced quality. This suggests that, for this building, the coverage provided by a single PSCN container is largely sufficient.

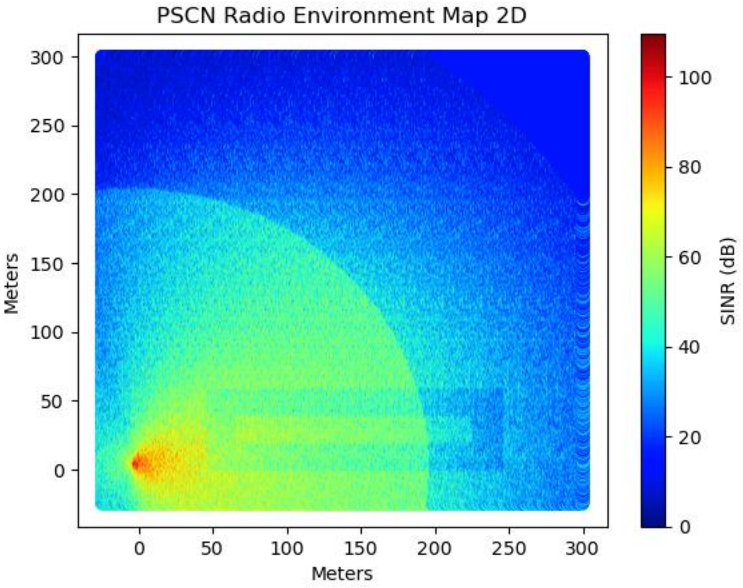

Figure 11. Simulation Result: Calculated Deep-Range of a LTE PSCN-Container, covering the Perimeter Block Building

Discussion: Simulation Challenges, Uncertainty and Promising applicability

Considering that this is merely an initial and relatively simple simulation scenario, the approach appears promising. These calculations, when embedded in dynamic simulations for large scale disasters, could enable authorities to precisely determine how many containers are needed and exactly where they should be positioned. However, it must be acknowledged that, as criticized in literature (Zugno et.al 2019), the available antenna models within NS-3 do not always allow for an optimal configuration of LTE base station within complex urban scenarios. Especially since typical LTE-Base Stations consists of panel-antennas, that are not explicitly implemented as model within NS-3. We therefore rely on the 3GPP Antenna model that is a variation of a parabolic model defined in 3GPP TR 38.901 v15.0.0. Therefore, it is expected that different simulation configurations in NS-3 may yield varying results. Nonetheless, we do not anticipate these differences to be so drastic that they would call into question the overall applicability of either the simulation technique nor the PSCN technology. That said, the issue of handling uncertainty must be further explored, as in this use case, a few meters in coverage could lead to gaps in connectivity when deploying PSCN containers.

From the perspective of simulation-assisted crisis management, it is important to highlight that this simulation can serve two key purposes. First, during the preparation phase, it enables the pre-planned deployment of PSCN containers based on different scenarios. Second, in the disaster response phase, it allows for rapid, spontaneous decision-making based on simulator recommendations, ensuring that coverage gaps are closed until MNOs restore conventional networks.

CONCLUSION

This work proposes the use of simulation as a tool to provide critical insights into the impact of blackouts on mobile networks and to support decisions and actions made by crisis management. First a new crisis management model is presented, that extends the PPRR-Model with simulation related phase-specific use-cases. Additionally, simulations are presented that predict the impact of power outages on mobile network. The first simulation (a co-simulation of electricity and mobile-network simulators) revealed that already small power grid failure led to massive impact on mobile networks. These predictions can already be done before the disaster. The second simulation presents supports crisis management by suggestions an towards the strategic deployment of authority managed (PSCN) emergency networks.

Both simulation techniques enhance decision-making in two specific phases which we defined within the simulation-assisted PPRR model. In the **Disaster Response** phase, the co-simulation, as presented, enables crisis managers to conduct a *Situational Assessment* of the current impact of a blackout on communication networks. This supports informed decisions about which immediate response actions need to be taken. For example, the size and location of expected mobile network outages directly influence evacuation strategies and crisis communication capabilities.

In both the **Disaster Response** and **Disaster Recovery** phases, the second simulation, as presented, provides concrete information that support *Situational Actions* to crisis management teams. It does so not only by providing suggestions on the number of PSCN containers required for deployment, but also by offering expert knowledge on how to optimally position PSCN Base Stations to maximize emergency communication coverage. The ability to evaluate and prepare situational actions based on simulation outcomes, combined with expert input, significantly improves the effectiveness and efficiency of recovery efforts.

NEXT STEPS AND FUTURE WORK

The exemplary simulations and results show how simulations as a tool can help to leverage authorities and first responders towards future crisis-management, enabling them to efficiently use next generation solutions.

The newly developed simulation-assisted PPRR-Model offers an innovative foundation for requirements engineering and requirements analysis within the context of crisis management simulations. However, it still requires further in-depth investigation. It is essential to examine the varying roles, perspectives, and needs of different stakeholders (i.e.: crisis managers, first responders, authorities) across all phases of the crisis management cycle to further refine and specify the model. Therefore, the next steps will include a comprehensive analysis aimed at providing additional insights into how simulation as a tool can concretely inform and enhance decision-making processes throughout the entire crisis management cycle. This will ensure that the model can be introduced on a sound scientific basis.

The simulation approaches presented in this work require further investigation and validation. While the results are promising, different models within NS-3 must be analyzed and their outcomes verified, particularly in simulations of mobile network coverage. Additionally, the accuracy of these results must be assessed by comparing them with real-world conditions. As a next step, these approaches will be integrated into a comprehensive architecture that enables control through intelligent agents. These will then be able to provide authorities with predictions and recommendations based on the disasters impact.

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