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Impact of Earthquake Events on Regional 5G Telecommunication Infrastructure

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ABSTRACT

Telecommunication infrastructure (TI) offers a wide spectrum of critical communication services to connect people, businesses, and the built environment. The advent of the fifth generation (5G) TI introduces a paradigm shift owing to its ultra-high speed, ultra-low latency, and vast connectivity, enabling a plethora of advanced communication use cases and smart city applications such as Internet of Things, smart grid, connected autonomous vehicles, and telemedicine and remote surgery. Despite its increasing prevalence and importance, TI also has a long history of earthquake vulnerability. Sustained telecommunication services after earthquakes are vital to the affected population for timely information exchange, situational awareness, and emergency responses. The ongoing 5G rollout will lead to a drastic change in regional TI deployment landscape, with increased seismic hazard exposure particularly due to the densely deployed small cells. This study carries out a pioneering effort in quantifying the post-earthquake TI failures and functionality to better support risk mitigation decision-making. In this study, we propose a novel seismic risk assessment framework for regional 5G TI, by holistically integrating regional seismic hazard analysis, infrastructure seismic exposure data, electric power infrastructure seismic fragility modeling and network connectivity analysis, as well as wireless TI functionality modeling. The proposed framework is evaluated based on a hypothetical regional infrastructure testbed located in Memphis, Tennessee, subjected to several earthquake scenarios. The results indicate that significant performance degradation of 5G TI is expected especially after major earthquake events. Enabled by the proposed framework, we further compared the efficacy of several risk mitigation strategies and pertinent implications are provided.

Keywords: Regional seismic risk assessment, 5G telecommunication infrastructure, Electric power infrastructure, Physical vulnerability, Post-earthquake functionality.

INTRODUCTION

Telecommunication infrastructure (TI) has become one of the most important infrastructure in modern society, offering a wide spectrum of communication services to connect people, business, and the built environment. The revolutionary fifth generation (5G) TI introduces a paradigm shift because of its ultra-high speed, ultra-low latency, and vast connectivity, enabling a plethora of advanced communication use cases and smart city applications such as Internet of Things [1], smart grid [2], connected autonomous vehicles [3], and telemedicine and remote surgery [4]. Despite its increasing prevalence and importance, TI also has a long history of earthquake vulnerability. For example, after the 2010 Haiti Earthquake, 20% of the country's telecom capacity was lost due to failure of cell sites and base stations [5]; the 2011 Christchurch Earthquake revealed the lack of backup power supply for micro- and mini-cells [6]; During the 2011 Great Tohoku Earthquake and Tsunami, approximately 1000 of Nippon Telegraph and Telephone's 1800 buildings were affected [6]; and the 2020 Puerto Rico Earthquake knocked down 32% cell sites on the island. Given the increasing population and urbanization in earthquake prone regions around the world, sustained telecommunication services after earthquakes are vital to timely information exchange, situational awareness, and emergency responses (e.g., contacting family members and loved ones, evacuation, hazard warning, relief operation, and search and rescue).

5G TI deployment is envisioned to be heterogeneous with macro towers providing wide-area coverage of low/mid-band frequency signals, and densified small cells offering localized high-band frequency signal transmission [7]. However, such a heterogeneous TI deployment, especially the dramatic small cell densification can also lead to increased seismic hazard exposure, as TI typically lacks sufficient power backup and its functionality heavily relies on the condition of the supporting structures and infrastructure [8]. Given the ever-increasing reliance of future smart city applications on 5G TI, post-earthquake

TI failures may result in more significant consequences. Yet, there is a lack of research in how 5G TI will perform under seismic hazard impacts. The few existing studies on TI seismic vulnerability and resilience mostly focused on forensic post-earthquake analyses [6,9–11], with very limited focus on quantitative and physics-based seismic risk assessment. The HayWired Project lead by the United States Geological Survey (USGS) conducted a holistic high-level study to characterize the earthquake impact on physical vulnerability of TI in the San Francisco Bay region [12], yet without much focus on 5G TI and TI functionality. Leelardcharoen [13] and Talebiyan et al. [14] studied the seismic vulnerability of interdependent power and telecommunication networks, where traditional public switched telephone network (PSTN) was considered. Cardoni et al. [15] developed a methodology to quantify seismic vulnerability and post-earthquake functionality of wireless TI, where only the TI's physical dependence on the supporting building portfolio was considered.

Considering the important role of 5G TI in future smart city applications and post-hazard emergency responses, one research question yet to be answered is how earthquakes may impact regional 5G TI functionality. To this aim, this study will conduct probabilistic regional seismic risk assessment of post-earthquake functionality of heterogenous 5G TI, where the uncertainties and physical process of regional earthquake hazard, seismic vulnerability of the dependent electric power network, and functionality of wireless communication networks are holistically integrated.

METHODOLOGY

The overall modeling and risk assessment methodology for post-earthquake TI functionality is illustrated as follows, based on a regional testbed in Shelby County, TN.

Regional Seismic Hazard Modeling

For demonstration purposes, an earthquake scenario with a moment magnitude (M_w) of 6.7 is considered, and the epicenter is located at (35.3°N, 90.3°W) near the New Madrid Seismic Zone and the Memphis Metropolitan Area following Adachi and Ellingwood [16]. The fault mechanism is assumed to be strike-slip, and an average seismic shear wave velocity V_{S30} = 260 m/s is considered. For the ground motion random field simulation, the ground motion prediction equations by Hassani and Atkinson [17], and the intensity measure (IM) spatial correlation models by Goda and Atkinson [18] and Loth and Baker [19] are adopted. Given the earthquake scenario information, random realizations of the ground motion random field can then be generated based on the joint probability distribution of spatially distributed IMs to allow regional assessment of seismic impacts [20,21].

Power and Telecommunication Infrastructure Seismic Exposure Modeling

This study will focus on modeling the dependency of TI on the electric power network, which dictates the post-earthquake TI functionality. The power transmission network data and topology are adapted from Gonzalez et al. [22]. The geographical locations of the substations and their connectivity are shown in Figure 1. The gate stations (i.e., high-voltage substations) serve as the power sources in this network, and power can only be transmitted from gate stations to the mid-voltage/low-voltage substations, thereby forming a directed graph.

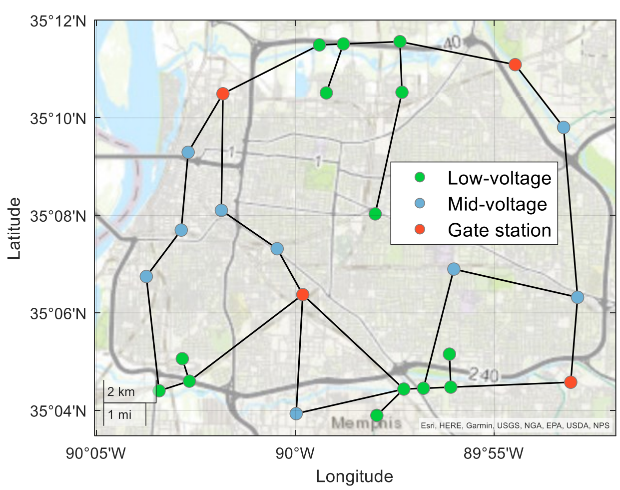

Figure 1. Spatial distribution of the power substations and power transmission network

As shown in Figure 2, for the TI exposure data, location of the existing macro tower sites is extracted from Tower Maps [23]. Due to the lack of small cell deployment data, the small cell sites are assumed to be uniformly distributed with a hexagon pattern [24] within the testbed region, and an inter-site distance of 200 m is considered to represent a dense urban small cell deployment. Due to the densified 5G small cell deployment, the number of small cell sites is much larger than the number of macro cell sites and power substations.

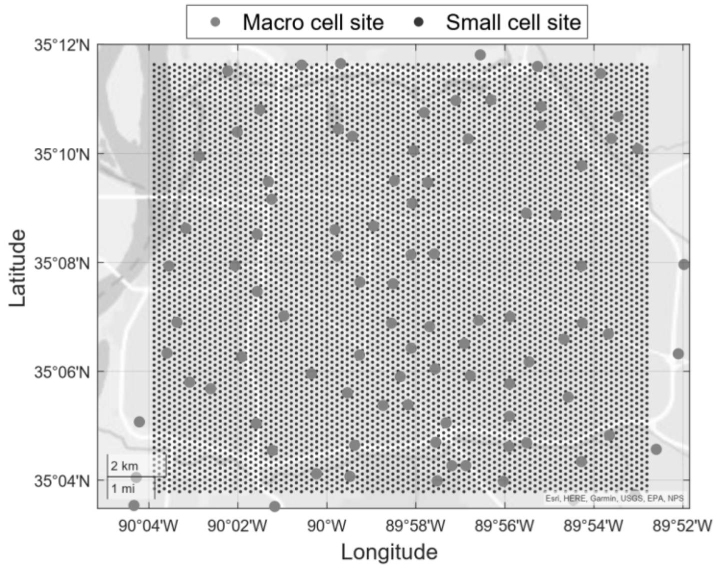

Figure 2. Spatial distribution of the macro and small cell sites

Seismic Vulnerability Modeling of Electric Power Network

We will adopt existing seismic fragility models to estimate the seismic damage states of power network infrastructure. As for the power transmission network, only seismic damages to substations (e.g., gate station, mid-voltage, and low-voltage) are considered. The classic lognormal fragility functional form as shown in Equation (1) is adopted to quantify the probability of a substation exceeding a given damage state (DS) conditioned on the IM:

$$P(DS|IM) = \Phi\left(\frac{\log IM - \log IM_{med}}{\beta}\right) \tag{1}$$

where: Φ is the standard Gaussian cumulative distribution function. IM_{med} is the median IM level, and β is the lognormal standard deviation, and their values are adopted from HAZUS [25] as shown in Table 2 for the three types of substations. In the present study, the substations are assumed to be fully functional for any damage state below extensive, and are deemed fully out-of-service if reaching or exceeding the extensive damage state [26]. By coupling the simulated ground motion IM field with the fragility models, the functionality of each substation can be determined. Moreover, since the substations are also interconnected within the power transmission network, network-level cascading failures should also be considered. As such, the power networks connectivity is formulated as an adjacency matrix based on graph theory. Graph networks consist of nodes and links, where nodes represent critical infrastructure components such as transmission substations and distribution nodes (i.e., the cell sites), while links represent power transmission/distribution lines that connect the infrastructure components [27]. This network representation can easily allow network reconfiguration to reflect various network-level damages or failures. By performing connectivity analyses via the shortest path algorithm [28], electric power availability from power source (i.e., the gate stations) to a TI cell site can be determined. Finally, the failure of a cell site can be linked to the loss of power at the nearest power supply node, as loss of power is considered as the sole TI failure mode in this study.

Table 2. Lognormal fragility model parameters for power transmission substations

Damage state		Low voltage	Medium voltage	Gate station
Slight	Median *PGA* (g)	0.15	0.15	0.11
	β	0.7	0.6	0.5
Moderate	Median *PGA* (g)	0.29	0.25	0.15
	β	0.55	0.5	0.45
Extensive	Median *PGA* (g)	0.45	0.35	0.2
	β	0.45	0.4	0.35
Complete	Median *PGA* (g)	0.9	0.7	0.47
	β	0.45	0.4	0.4

Functionality Modeling of Regional 5G TI

Signal transmission and telecommunication signal coverage are important metrics for TI functionality quantification. For the case study, two carrier frequencies are considered, including a 2.5 GHz mid-band frequency (band n41) for macro cells and a 28 GHz high-band frequency (band n261) for small cells to represent a heterogeneous 5G deployment scenario. When there are obstacles blocking signals between the cell transmitter and user equipment (UE), higher signal path loss can be expected. As such, the path loss for line-of-sight (LOS) and non-line-of-sight (NLOS) conditions can be significantly different. The LOS probability for the macro and small cells are estimated according to the International Telecommunication Union (ITU) guidelines [29], where the LOS probability reduces with increasing separation distance between the transmitter site and UE. The close-in path loss model parameters for the macro and small cells under LOS and NLOS conditions are adopted according to Sun et al. [30]. Tri-sectored cells (i.e., 3 cell antennas, each covering 120° of angle) are considered for each macro and small cell site. The transmitter and UE receiver antenna parameters for the macro and small cells are listed in Table 1 as per the ITU guidelines [29] and 3GPP [31], and the wireless network simulation is carried out via the MATLAB Antenna Toolbox [32].

Table 1. 5G antenna and UE parameters for the macro and small cells

Parameters	**Macro cells**	**Small cells**
Carrier frequency (GHz)	2.5 (band n41)	28 (band n261)
Antenna height (m)	25	10
Transmit power (dBm)	44	40
Channel bandwidth (MHz)	20	100
Mechanical down tilt (°)	5	10
Duplex mode	TDD	TDD
UE noise figure (dB)	7	10
UE antenna gain (dBi)	0	5
UE height (m)	1.5	1.5
Thermal noise level	-174 dBm/Hz	-174 dBm/Hz

Wireless signal quality perceived by a UE is commonly characterized by the signal to interference and noise ratio (SINR) as shown in Equation (2):

$$SINR = \frac{S}{I+N} \tag{2}$$

where: *S* denotes the signal power from the main transmitter; *I* denotes the interference signal power, which is the aggregated signal power from all the other transmitters that operate on the same frequency as the main transmitter; and *N* is the noise power. Note that SINR is commonly expressed in decibels (dB), and a higher SINR indicates better signal quality.

RESULTS AND DISCUSSIONS

For the given earthquake scenario, 1000 random realizations are performed to propagate the uncertainties from spatial ground intensities, fragilities, and TI functionality modeling to yield probabilistic estimates of the regional TI seismic vulnerability.

Post-Earthquake Power Availability

As the TI failure is assumed to be dictated by power availability, power network seismic vulnerability is first examined. Figure 3 and 4 visualize the probability of physical seismic damage and functional failure (i.e., no power supply) for the power substations for the M_w 6.7 earthquake scenario. It is first noticed that the physical seismic damage potential of the substations agrees with the fragility model parameters, with the gate stations being the most vulnerable followed by the mid-voltage substations and low-voltage substations. Moreover, for substations of the same tier, the closer the substations are to the epicenter, the higher seismic damage probability they are expected to experience. On the other hand, a different failure pattern is observed when it comes to the substation functional failure probability, due to the directed graph network topology of the power transmission network, where the power is supposed to flow from the gate stations to the downstream mid-voltage and low-voltage substations. As a compound effect of the physical seismic damage and network topology, those substations that are closer to the epicenter or separated by larger number of hops from the gate stations generally experience higher chances of functional failure.

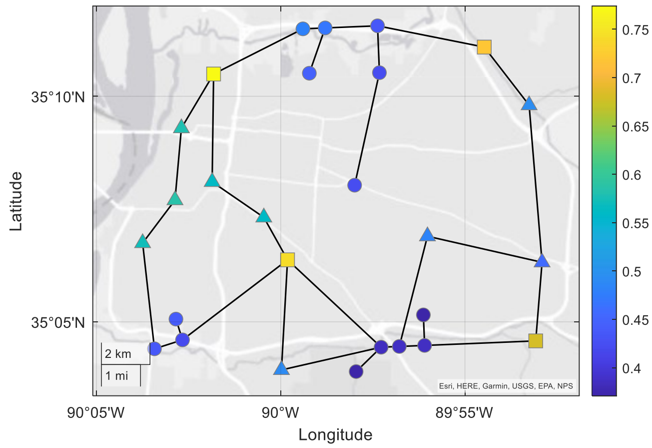

Figure 3. Substation physical seismic damage probability (extensive damage state) for the M_w 6.7 earthquake scenario

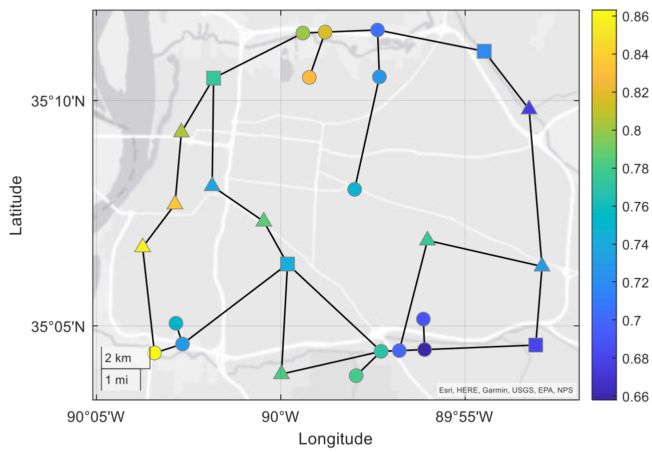

Figure 4. Substation functional failure probability for the M_w 6.7 earthquake scenario

Post-Earthquake Telecommunication Signal Coverage

The signal coverage (i.e., SINR > -5 dB) probability maps for the macro cell, small cell, and combined coverage are shown in Figure 5. Note that the combined coverage is defined as having signal coverage from at least one of the macro or small cell tiers. The probability contours are derived from the average coverage probabilities of the 1000 random realizations for 900 uniformly distributed UE sites across the studied region. Under a major earthquake event, the small cells, due to their short signal coverage range, experience significant coverage reduction. Macro cells, owing to their larger signal coverage capability, can offer better regional wireless signal coverage, which is crucial to emergency information dissemination to the affected population and rapid post-earthquake situational awareness. Table 2 compares the regional average signal coverage probabilities before and after the earthquake. The average combined coverage probability drops from almost 100% in the pre-earthquake condition to 35% after the M_w 6.7 earthquake scenario. We also observe that small cells tend to experience higher coverage losses compared to the macro cells. Although not considered in this study, usually there will be backup generators and fuels deployed at the macro cell sites (if not all of them), and the macro cells can remain functioning for an extended amount of time. However, backup power supply for small cells may not yet be commonly available.

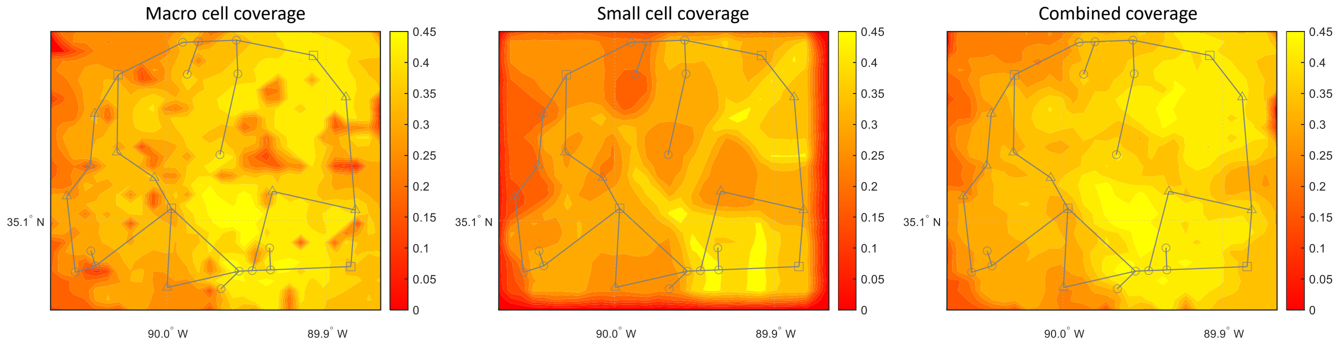

Figure 5. Signal coverage probability map for the M_w 6.7 earthquake scenario

Table 2. Comparison of regional average signal coverage probabilities

Scenarios	**Pre-EQ**	**M_w 6.7**
Macro cell only	0.92	0.33
Small cell only	0.87	0.24
Combined	0.99	0.35

Efficacy of Different Mitigation Strategies

All the above results are for the reference power transmission network and 5G TI deployment scenario, where the power substations are considered non-functional when exceeding the extensive seismic damage state, and no power backup is considered for the 5G TI. In this section, the effectiveness of several risk mitigation strategies is further compared. Three mitigation strategies are considered based on the reference deployment scenario, including:

(1) Gate stations retrofitted: As gate stations are the least resistant to earthquake excitations (as reflected by the fragility models in Table 1) and they act as power sources for the power transmission network, in this scenario, only the gate stations are seismically retrofitted such that the gate stations will remain functional until reaching the Complete damage state.

(2) All substations retrofitted: In this scenario, all power transmission substations are seismically retrofitted such that they will remain functional until reaching the Complete damage state.

(3) Macro cells power backup: In this scenario, sufficient backup power is assumed to be available to support sustained operation of all the macro cells, which means the macro cells will remain functional regardless of the power accessibility to the power transmission substations.

Table 3 compares the regional average coverage probability among the above-mentioned mitigation strategies and the reference scenario. In terms of improving the post-earthquake telecommunication signal coverage, offering sufficient power backup to all the substations is the most effective approach. In practice, those macro stations that are most vulnerable to seismic impact can be prioritized for power backup. Retrofitting all substations ranks the second in improving post-earthquake coverage, followed by retrofitting only the gate stations. For actual applications, a mixed usage of the above mitigation strategies can be considered to more strategically improve the post-earthquake coverage. Moreover, life-cycle cost analysis can be carried out to quantify the long-term cost-benefit ratio for the above mitigation strategies.

Table 3. Comparison of regional average coverage probability for different risk mitigation strategies

Mitigation strategies	**Coverage Probability**
Reference scenario	0.35
Gate stations retrofitted	0.54
All substations retrofitted	0.68
Macro cells power backup	0.98

CONCLUSION

The ongoing 5G rollout will lead to a drastically changing TI deployment landscape, while increasing seismic hazard exposure. As TI is known to be vulnerable to seismic hazard impacts, particularly due to post-earthquake power outages, this study carries out a pioneering effort in quantifying the post-earthquake TI functionality to better support risk mitigation. A novel seismic risk assessment framework for regional 5G TI is proposed, by holistically integrating regional seismic hazard analysis, infrastructure seismic exposure data, electric power infrastructure seismic fragility modeling and network connectivity analysis, and wireless TI functionality modeling. The proposed method is evaluated based on a hypothetical regional infrastructure testbed located in Memphis, Tennessee, under a given earthquake scenario.

Based on the large-scale regional testbed, seismic damage and functionality failure potential of power transmission network is examined. Power gate stations are found to be most vulnerable to physical seismic damages, while the downstream low/medium-voltage substations are more prone to functionality failures (i.e., disconnection from power sources). As the survivability of TI is assumed to be solely dependent on the power accessibility, the TI failure pattern is similar to that of the electric power network. Based on the survivability of cell sites, post-earthquake regional TI functionality in terms of signal coverage is evaluated. It is noticed that macro cells can offer better signal coverage than small cells. The TI coverage will undergo significant performance degradation after earthquake events. The above observations highlight the need for proactive risk mitigation planning so that the TI can be more resilient to earthquake hazards. Enabled by the proposed framework, we further compared the efficacy of several risk mitigation strategies and pertinent implications are provided.

It should be noted that all the above findings are based the following simplifications and assumptions, where the survivability of TI was assumed to solely rely on the power accessibility while the physical seismic damage potential of TI was not considered, which may underestimate the TI failures. Future research should develop seismic fragility models for 5G TI components and incorporate them into the risk assessment framework. Although the present study mainly focused on the supply side performance, post-earthquake population mobility and communication demand should be considered for more realistic assessment.

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