Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2023) 5324-5333

ECCOMAS Proceedia

COMPDYN 2023
9th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Athens, Greece, 12-14 June 2023

METRICS FOR EVALUATING THE SEISMIC VULNERABILITY OF TELECOMMUNICATION NETWORKS

Alessandro Cardoni[1], **Gian Paolo Cimellaro**[1]

[1] Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Turin, Italy
e-mail: {alessandro.cardoni,gianpaolo.cimellaro}@polito.it

Abstract

Urban communities have been massively relying on telecommunication infrastructures for everyday activities in the past decade. Their importance is also crucial during emergencies to enable communication among users and first responders. This paper presents a methodology to model and assess the seismic vulnerability of wireless telecommunication networks on the urban scale. The case study is a virtual testbed that is representative of a typical European city. The information to model the infrastructure has been collected from a crowdsourced database and satellite imagery. Since most of the telecommunication network components are located on the roof and inside buildings, the vulnerability of the network has been linked to the damages caused by a given earthquake scenario to the built environment. Different simulations allowed to estimate the failed towers, the available throughput, and the number of users served by each base station after the seismic event. These results have been used to formulate three vulnerability metrics that can be used for detailed resilience analyses.

Keywords: telecommunication infrastructure, seismic vulnerability assessment, wireless mobile network, physical interdependencies, seismic damage simulation.

Peer-review under responsibility of the organizing committee of COMPDYN 2023.
doi: 10.7712/120123.10803.21407

1 INTRODUCTION

Telecommunication networks are among the most critical infrastructures for urban communities as they are essential both to daily activities and in case of emergencies such as earthquakes. The design and seismic performance of telecommunication infrastructure have improved after the investigation of the effects of past earthquakes.

In the literature, few studies tackling the vulnerability of this type of network can be found. In the HAZUS methodology, FEMA proposed seismic fragility curves of telecommunication facilities for different damage states [1]. Following the 2011 Great East Japan earthquake, Nemoto and Hamaguchi [2] discussed strategies to improve the robustness of wireless networks, such as prompt recovery using mobile equipment, an information distribution platform to collect data for decision-making, a mesh network that bridges communication among satellites and unmanned aerial vehicles. Gomes, et al. [3] discussed approaches to improve the robustness and resilience of communication systems against natural disasters. They also pointed out that the number of failures is still high compared to other infrastructures, mainly because of poor design. Overall, methods to quantify the vulnerability and the resilience on a large-scale are still lacking.

This paper proposed a physical-based procedure for a preliminary vulnerability analysis of urban telecommunication networks. The case study is the *Ideal City* virtual environment, which is inspired by the city of Turin, Italy [4]. The network was modeled through a crowdsourced database and satellite imagery inspection. To define the connectivity among the base station controllers (BSCs) a hierarchical three-layer topology was chosen, while base station transceivers (BTSs) were connected to BSCs according to a star scheme.

The performance of the infrastructure was assessed in terms of throughput under a simulated seismic scenario. In this analysis, the dependence relationship with the building portfolio was considered by associating the vulnerability of the network to the collapse of the buildings. Two metrics were proposed to assess the networks' performance. The first one is based on the physical damage to the towers, while the second on the performance in terms of throughput.

2 NETWORK MODEL

2.1 Data collection

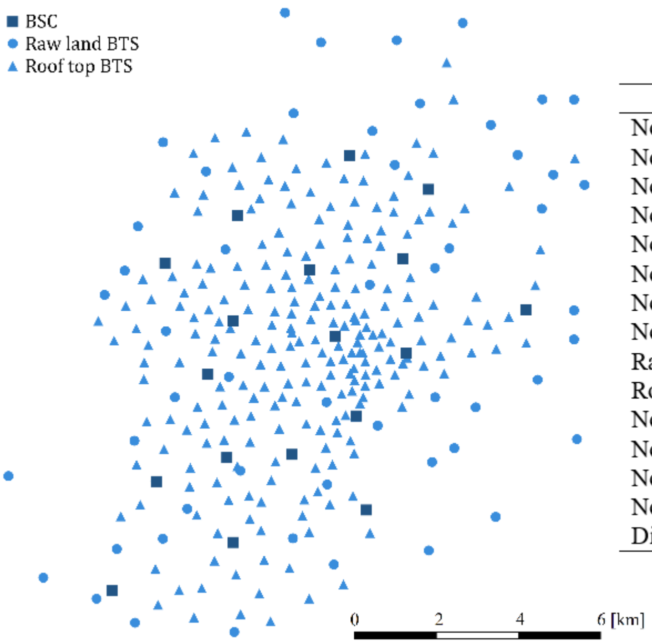
The elements of wireless telecommunication networks are: (i) mobile switching center (MSC), which handles communications at a regional/state level; (ii) base station controller (BSC), which manages urban communications; (iii) base transceiver station (BTS), typically a steel structure where antennas are installed and other devices located within in a structure at the base; (iv) user equipment (UE), i.e., mobile devices.

Most of the information to model the network was obtained through the crowd-sourced website CellMapper, [5]. Since the virtual case study *Ideal City* is based off the city of Turin, Italy, the available data for that city, such as coordinates of antennas, frequency bands, bandwidth, was used. The three largest MNOs were identified, however, for the purpose of this work, only the largest (MNO_1) was analyzed. MNO_1 serves 35.4% of the population, which is about 900,000 people. The information provided by CellMapper was double-checked and integrated using the GIS map of Turin [6] and satellite imagery from Google Maps [7]. The latter operation was also fundamental to distinguish BSCs. It was possible to identify 387 BTSs and 18 BSCs, which is a reasonable number since each BSC usually manages between 10 and 20 BTSs [8]. All the collected information was structured in a database. Examples of database records for each antenna are the following.

- Coordinates: both in geographical and geometrical format.

- Band: either 3 or 20.
- Frequency: 800 MHz for band 3 and 1,800 MHz for band 20.
- Type of cell: 800MHz BTSs serve macro cells, 1,800MHz BTSs serve micro cells.

Figure 1 illustrates the location of BSCs and BTSs and some characteristics of the network.



	MNO_1
No. of BTS	387
No. of Towers	304
No. of Raw land towers	57
No. of Rooftop towers	247
No. of Raw land macro cells	33
No. of Raw land micro cells	50
No. of Rooftop macro cells	70
No. of Rooftop micro cells	234
Raw land towers height	25 – 45m
Rooftop towers height	2.5 – 7m
No. of Raw land posts	35
No. of Raw land masts	22
No. of Rooftop posts	186
No. of Rooftop masts	61
Distribution of customers	35.4%

Figure 1: Characteristics of the network.

2.2 Topology

A hybrid topology was implemented where BTSs are connected to BSCs through a star topology. The main criterion used for the connections was the shortest distance. It was supposed that all connections are made via underground cables. This topology has many advantages: (i) when a BTS node fails the rest of the network is still functional; (ii) the system can be easily expanded by adding more connections and nodes; (iii) it allows heavy data transfer. However, some negative aspects are that it can be expensive due to the length of the connections and the failure of a BSC causes the failure of all BTSs downstream.

The BSCs were structured in a hierarchy of three layers, namely core, aggregation, and edge, like in a fat tree. The proposed topology consists of two core nodes, both connected to four aggregation nodes. Each of these has six connections to the edge nodes which guarantees that each edge node is connected to two different aggregation nodes.

Based on geographic location and size of the facilities, BSCs were divided into core, aggregation, edge nodes. The most internal BSCs are assumed to be core nodes, then the closest ones were assumed aggregation nodes. The remaining are the edge nodes. Figure 2 shows the topology of the network.

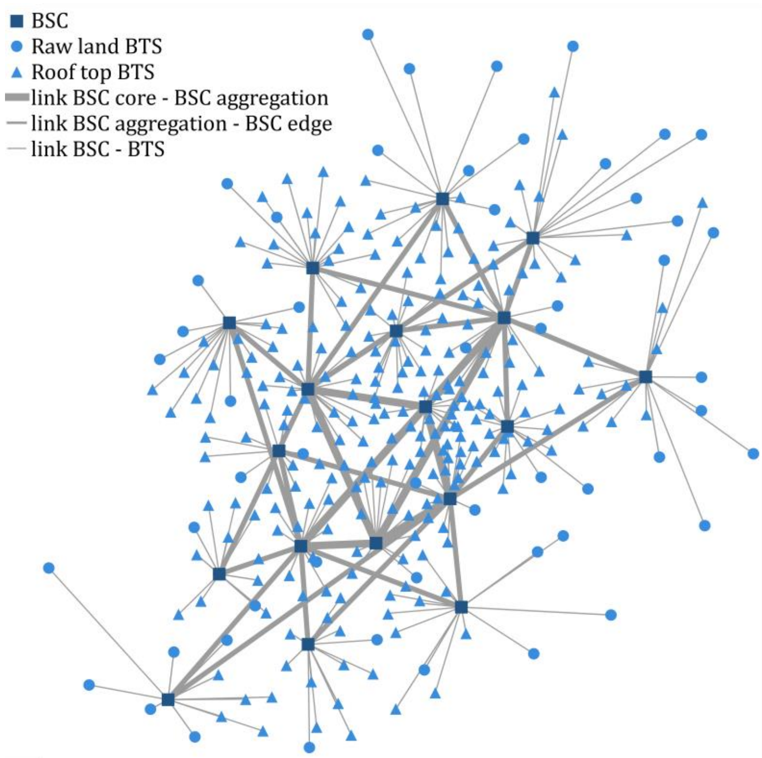


Figure 2: Network topology.

3 PERFORMANCE OF THE NETWORK

3.1 Signal to interference plus noise ratio (SINR)

The performance of the network was measured in terms of throughput, which is the rate of successfully delivered data per time unit [9]. Obviously, this parameter should be maximized to increase the quality of the service. It can be calculated from the signal to interference plus noise ratio (SINR) through a mapping procedure. The SINR is defined as per Equation 1:

$$SINR = \frac{P}{I + N} \tag{1}$$

where P is the received signal power equal to the difference between the transmission power (PT) and the path loss (PL); I is the interference; N is the background noise. It was assumed a transmission power PT of 43dBm and 30dBm for macro and micro cells, respectively [10, 11]. The path loss models for macro and micro cells developed by the International Telecom Union were adopted [12].

To calculate the interference, it was assumed that the network has a frequency reuse factor equal to 1. This implies that BTSs can use all the available frequencies, which is a conservative hypothesis. Therefore, the interference can be defined as the difference between the sum of the received power P of all BTSs and the P of the BTS for which the SINR is being calculated. Moreover, since the frequency reuse factor is equal to 1, the interference is so high that including the noise N would not be relevant.

For a faster calculation and better visualization, the population was divided in user clusters corresponding to the occupants in each building. Figure 3 shows an example of the SINR for one user cluster with respect to the macro and micro cells.

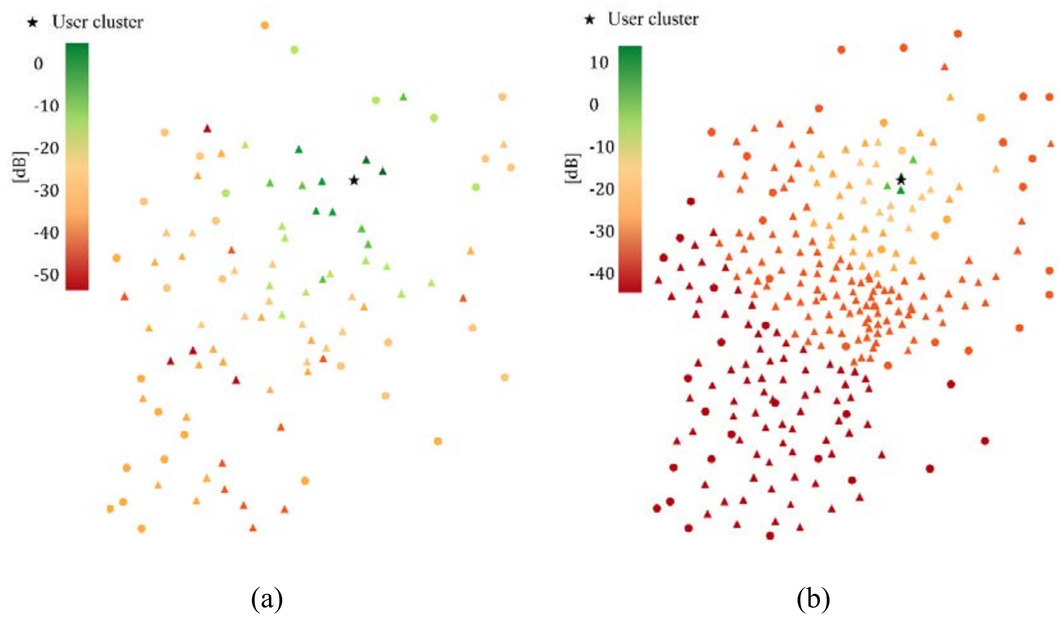


Figure 3: SINR experienced by a user cluster for (a) macro and (b) micro cells.

Depending on the BTS operating band, different BWs are available. Table 1 summarizes characteristics of bands 3 and 20, those of Ideal City's BTSs. This information was extracted from the "E-UTRA Operating Bands" and "E-UTRA Channel Bandwidth" documentation [13].

Band	**Duplex mode**	**Frequency [MHz]**	**Uplink [MHz]**	**Downlink [MHz]**	**Channel bandwidths [MHz]**
3	FDD	1,800	1,710 - 1,785	1,805 - 1,880	1.4, 3, 5, 10, 15, 20
20	FDD	800	832 - 862	791 - 821	5, 10, 15, 20

Table 1: Characteristics of the selected frequency bands.

Given the lack of data, it was assumed a 10 MHz BW for both bands, which is cautious for modern networks. Therefore, for each BW, 50 resource blocks (RBs) are available. The adopted duplex mode was the frequency division duplex (FDD), which ensures the full BW capacity in uplink and downlink.

After defining the modulation coding scheme (MCS) [14], the BTS selects the transport block size (TBS). Given the TBS and the number of RBs, the number of bits that can be transmitted is calculated [15]. To increase the throughput, a 2x2 multiple-input-multiple-output scheme was adopted [16].

The SINR-throughput relation is modulation specific, as discussed by Olmos, et al. [17]. Mühleisen, et al. [18] mapped the SINR to 13 MCSs for a 20 MHz BW. In this work, a subset of 14 MCSs with a different coding rate for a 10MHz BW defined by the LTE standard was used. The linear envelop curve was then generated from the calculated functions (Figure 4). This represents an ideal situation because users would get the best modulation. However, this is balanced by the fact that using a frequency reuse factor equal to 1 generates large interference that has the effect of lowering the SINR.

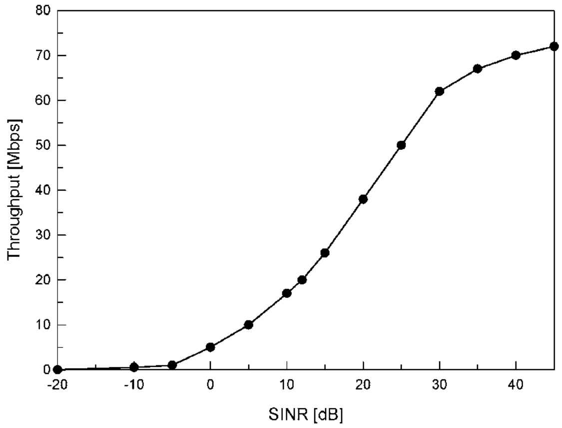


Figure 4: SINR vs. throughput.

3.2 Vulnerability of the network

In the literature, few studies can be found related to this endeavor, mainly because networks are privately managed. Masts and monopoles are the most common structures used to install antennas. While FEMA [1] provided fragility curves for telecommunication facilities, few studies can be found on the seismic vulnerability of telecommunication towers, especially at the large-scale network level. Given that these networks are privately managed, and data are confidential, detailed seismic damage simulations cannot be easily performed and many assumptions about section dimensions, types of elements, type of connections should be done. Moreover, even though towers were properly designed and could withstand strong ground motions, cables and other electrical components are likely to be damaged when subjected to large displacements and rotations.

In this preliminary analysis, the vulnerability of the network was related directly to the vulnerability of the built environment. This means that a tower and the corresponding BTS installed in a building would fail if that building collapsed.

3.3 Seismic scenario and damage assessment

Details about the methodology developed to estimate the damage to the *Ideal City*'s built environment can be found in [4]. The seismic scenario to evaluate the structural response of the building portfolio is simply defined by epicenter location, moment magnitude, and acceleration time history recorded at the site of the epicenter. At each building location, two horizontal seismic inputs were applied along the principal directions using Ambraseys ground motion model [19]. The damage state of each structure was determined in terms of the maximum inter-story drift thresholds proposed by Ghobarah [20].

3.4 Vulnerability metrics

The first metric that is introduced is R_{TOW} which is defined as the ratio between the number of functional towers (n) and the total number of towers (N_T).

$$R_{TOW} = \frac{n}{N_T} \tag{2}$$

A value close to 1 indicates that the network is robust. Typically, the more redundant the network the higher the probability to obtain a large R_{TOW} value. However, in large-scale networks, if many towers collapse the economic loss might still be substantial and should be considered.

The second proposed metric is R_{THR} which is defined as the ratio between the post- and pre-event mean throughput ($\overline{THR}$).

$$R_{THR} = \frac{\overline{THR}_{post}}{\overline{THR}_{pre}} \tag{3}$$

$\overline{THR}$ is the throughput weighted by the number of users in each cluster as shown in Equation 4:

$$\overline{THR} = \frac{\sum_{i=1}^{k} N_{U,i} \cdot THR_i}{N_U} \tag{4}$$

where: $N_{U,i}$ is the number of users in each cluster, k is the number of clusters, THR_i is the highest throughput for the *i-th* cluster, N_U is the total users. Low values of R_{THR} mean a significant loss in performance, which translates to slow data transfer.

4 APPLICATION TO IDEAL CITY

4.1 Signal to interference plus noise ratio (SINR)

The proposed procedure was tested on Ideal City under the El Centro (Imperial Valley Irrigation District substation, California, USA) earthquake (Table 2).

	El Centro
Date	5/18/1940
Region	Imperial Valley
M_w	6.9
Depth [km]	16.00
PGA [g]	0.35

Table 2: Characteristics of the seismic scenario.

BTSs and BSCs were determined from the building damage assessment and the vulnerability model adopted. Figure 5 shows the damage map after the earthquake. The map allows for a preliminary and straightforward understanding of the impact of the event. The number of failed components is reported in Table 3. The collapse of BSCs seemed to be a key factor. Under the applied scenario, the actually collapsed towers were only 31, but since 8 out of 18 BSCs collapsed, the total number of failed towers increased to 141.

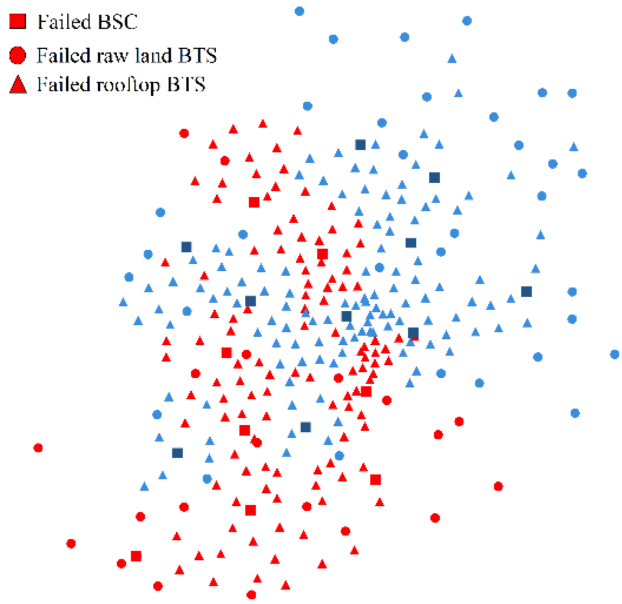


Figure 5: Network damage after the seismic scenario.

	El Centro
No. of collapsed BSCs	8
No. of collapsed towers	31
No. of failed towers	141
$\mathbf{R_{TOW}}$	0.54

Table 3: Number of failed components and RTOW.

Once failed towers were identified and removed from the network model, a post-event throughput was calculated for each cluster. Figure 6 shows part of the throughput map in normal conditions (Figure 6a) and after the El Centro scenario (Figure 6b). As expected, the throughput tends to decrease. However, it was observed that users closer to functional BTSs might experience a better connection because of the reduced interference. The mean weighted throughput in normal conditions was $\overline{THR}_{pre}$ = 19.98 Mbps, while the vulnerability index was R_{THR} = 0.65 indicating a significant performance reduction.

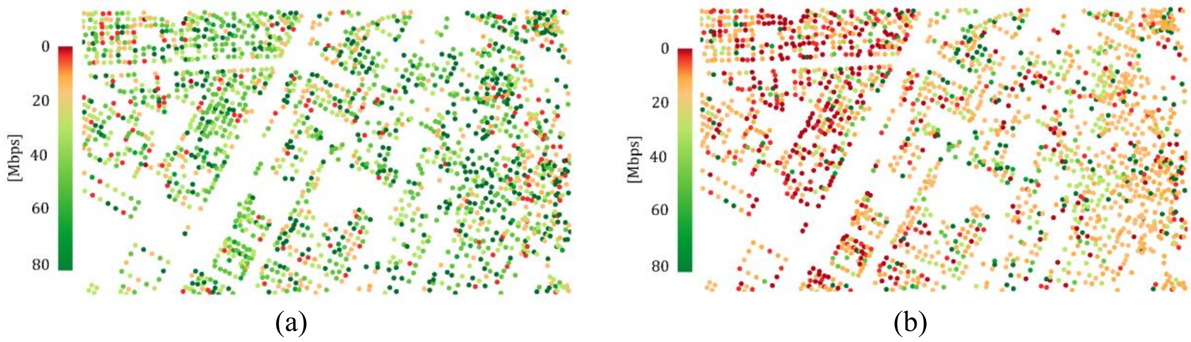


Figure 6: Throughput in (a) normal conditions and (b) after the seismic scenario.

5 CONCLUSIONS

This research focused on the evaluation of the seismic vulnerability of telecommunication networks. The physical infrastructures owned and managed by one of the MNOs was modelled through information collected from a crowdsourced website and satellite imagery. A hybrid topology scheme based on a three-layer hierarchy approach was adopted to define connectivity. Given the limited information available, the vulnerability of the network was related to the vulnerability of the buildings where BSCs and BTSs are located.

Two vulnerability metrics were proposed to evaluate the performance of the network under a simplified seismic scenario. The first metric is representative of the vulnerability of the towers, which could also be interpreted as an economic loss. The second metric is representative of the performance of the network and quality of the service in terms of throughput.

The procedure is intended to be used as a preliminary tool. The obtained results are dependent on the chosen topology and might vary under a different connection scheme. Given the large-scale nature of the problem and the lack of detailed information, simplifications had inevitably to be made, such as attributing the vulnerability of the telecommunication network only to the building vulnerability. However, because telecommunication networks are privately managed, many of the parameters required to perform a complete vulnerability assessment would have to be assumed. In addition, since no information on the actual data traffic was accessible, a hypothesis on the connection of the users to the network had to be made. In this research, it was considered that all the users connect at the same time to the network, which represents the most unfavorable case. Under these conditions, the presented procedure can generate valid results that can be used as a starting point to evaluate the seismic vulnerability of urban telecommunication networks.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Research Council under the Grant Agreement n° ERC_IDEal reSCUE_637842 of the project IDEAL RESCUE— Integrated DEsign and control of Sustainable CommUnities during Emergencies.

REFERENCES

[1] FEMA, "Multi-hazard loss estimation methodology, earthquake model," *Washington, DC, USA: Federal Emergency Management Agency,* 2003.

[2] Y. Nemoto and K. Hamaguchi, "Resilient ICT research based on lessons learned from the Great East Japan Earthquake," *IEEE Communications Magazine,* vol. 52, pp. 38-43, 2014.

[3] T. Gomes, J. Tapolcai, C. Esposito, D. Hutchison, F. Kuipers, J. Rak*, et al.*, "A survey of strategies for communication networks to protect against large-scale natural disasters," in *2016 8th international workshop on resilient networks design and modeling (RNDM)*, 2016, pp. 11-22.

[4] S. Marasco, A. Cardoni, A. Z. Noori, O. Kammouh, M. Domaneschi, and G. P. Cimellaro, "Integrated platform to assess seismic resilience at the community level," *Sustainable Cities and Society,* p. 102506, 2020.

[5] CellMapper. (2021). *Cellular Coverage and Tower Map*. Available: https://www.cellmapper.net/

[6] Geoportale. (2021). *Geoportale e governo del territorio*. Available: https://geoportale.comune.torino.it/

[7] Google. (2021). *Google Maps*. Available: https://maps.google.com/

[8] S. Giovinazzi, A. Austin, R. Ruiter, C. Foster, M. Nayyerloo, N.-K. Nair*, et al.*, "Resilience and fragility of the telecommunication network to seismic events," *Bulletin of the New Zealand Society for Earthquake Engineering,* vol. 50, pp. 318-328, 2017.

[9] G. Miao, J. Zander, K. W. Sung, and S. B. Slimane, *Fundamentals of mobile data networks*: Cambridge University Press, 2016.

[10] J. Wannstrom, "LTE-advanced," *Third Generation Partnership Project (3GPP),* 2013.

[11] P. Series, "Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz," *tech. rep., ITU, Tech. Rep. ITU-R,* 2015.

[12] M. Series, "Guidelines for evaluation of radio interface technologies for IMT-Advanced," *Report ITU,* vol. 638, pp. 1-72, 2009.

[13] 3GPP, "Further advancements for E - UTRA physical layer aspects," *3GPP TR 36.814, Tech. Rep,* 2010.

[14] J. Fan, Q. Yin, G. Y. Li, B. Peng, and X. Zhu, "MCS selection for throughput improvement in downlink LTE systems," in *2011 Proceedings of 20th international conference on computer communications and networks (ICCCN)*, 2011, pp. 1-5.

[15] S. Rathi, N. Malik, N. Chahal, and S. Malik, "Throughput for TDD and FDD 4 G LTE Systems," *International Journal of Innovative Technology and Exploring Engineering (IJITEE), ISSN,* pp. 2278-3075, 2014.

[16] J. Lee, J.-K. Han, and J. Zhang, "MIMO technologies in 3GPP LTE and LTE-advanced," *EURASIP Journal on wireless communications and networking,* vol. 2009, pp. 1-10, 2009.

[17] J. Olmos, S. Ruiz, M. García-Lozano, and D. Martín-Sacristán, "Link abstraction models based on mutual information for LTE downlink," in *COST*, 2010, pp. 1-18.

[18] M. Mühleisen, D. Bültmann, R. Schoenen, and B. Walke, "Analytical evaluation of an IMT-advanced compliant LTE system level simulator," in *17th European Wireless 2011-Sustainable Wireless Technologies*, 2011, pp. 1-5.

[19] N. N. Ambraseys, K. u. Simpson, and J. J. Bommer, "Prediction of horizontal response spectra in Europe," *Earthquake Engineering & Structural Dynamics,* vol. 25, pp. 371-400, 1996.

[20] A. Ghobarah, "On drift limits associated with different damage levels," in *International workshop on performance-based seismic design*, 2004.