mmWave for Future Public Safety Communications

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ABSTRACT

The technologies developed for the next generation of cellular networks (i.e., 5G) are potential enablers for future Public Safety Communication (PSC) systems. These will indeed need advanced communication techniques, capable of providing real-time, low-latency and reliable interactions in different scenarios (vehicular, aerial, unmanned) and different network architectures. There is great interest in the millimeter wave (mmWave) band and in general in the spectrum above 6 GHz, since the bandwidth that can be allocated at these frequencies is much higher compared to the traditional (and congested) sub-6 GHz bands. This would enable orders of magnitude greater throughput and low latency, which could be used for example to stream high definition video or virtual/augmented reality data to first responders or for the remote control of autonomous robots. In this paper we illustrate both the potential of mmWave communications for PSC (also with a typical use case) and the issues that must be solved before this technology can be reliably adopted and mmWave PSC networks become a reality.

CCS CONCEPTS

• **Networks → Network performance evaluation**; **Mobile networks**;

KEYWORDS

Public safety communications; emergency networks; mmWave

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1 INTRODUCTION

Fast and reliable communications are a key ingredient in a rapid and coordinated response to emergencies in public safety scenarios. Recently, in the US there has been a growing interest in providing a broadband, nationwide network to emergency responders, and this led in 2012 to the creation of the First Responder Network Authority (FirstNet)[1]. The end goal is to realize a PSC system able to support high-definition real-time video streaming (e.g., for remote monitoring of an incident site, or the cooperation of on-site and far-off operators), ultra-low latency information exchange (e.g., for remote control of unmanned vehicles) and high-quality voice communication, with and without using the civil communication infrastructure, which might not be available.

In order to limit the costs, FirstNet is currently leveraging the technologies which were developed for the 4th Generation (4G) commercial cellular networks, standardized by the 3rd Generation Partnership Project (3GPP)[2] in the Long Term Evolution (LTE) specifications. The 3GPP is currently developing the next generation of cellular networks (5G) in the New Radio (NR) standard, and PSCs are among the services that 5G could provide [1, 24].

Among the different innovations proposed for 5G, the adoption of frequency bands in the spectrum above 6 GHz (including mmWave) is at the same time one of the most promising and challenging items [28, 29]. This is a new frontier for mobile wireless networks, and the massive amount of untapped spectrum in the mmWave bands is a potential enabler of multi-Gbps data rates and communications with ultra-low latency, thus providing tremendous opportunities for next-generation PSC networks [31]. For example, this technology would allow a rapid distribution of high-definition video or virtual reality data to a large number of nodes (first responders on the ground, command stations, unmanned vehicles), without using a fixed network infrastructure.

However, in order to make the mmWave technology reliable and ready to be adopted for public safety communications, several challenges need to be solved. They are mainly related to the harsh propagation environment that characterizes such high frequencies, with a very high pathloss [4] and sensitivity to blockage by a wide range of materials [12]. In order to solve these problems some solutions have been developed in the cellular domain (e.g., the usage of beamforming to increase the antenna gain [28], multi-connectivity solutions to provide fall back to other networks in case of outage [25]), but the conditions that a communication system will have to endure in a PSC context are much more extreme, and the applicability of mmWave networks in this domain has not yet been studied. In this paper we provide an overview of the main issues related both to the propagation in the frequency bands above 6 GHz, and to the application of mmWave communications to disaster response networks, illustrating a typical use case for a wildfire scenario.

The remainder of the paper is organized as follows. A basic overview of requirements and existing wireless technologies for PSC is provided in Sec. 2. Then, the main issues related to mmWave adoption for PSC are described in Sec. 3. The use case is introduced

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[1] https://www.firstnet.gov
[2] http://www.3gpp.org

Technological component	**Motivation**	**Open challenges above 6 GHz**
Aerial communications	- UAV-mounted base stations can provide coverage in scenarios with failures of the civil cellular infrastructure [13, 21]. - Scalable, self-forming and mobile communication networks with UAVs.	- Lack of air-ground measurements for mmWave. Preliminary results – based on ray-tracing – are provided in [14]. - Very directional beams to support high data rate at long distances require sophisticated beam tracking procedures.
Vehicular communications (*V2X*)	- Enable coordination of vehicles (e.g., ambulances) in emergency scenarios, by decreasing interference thanks to highly directional links. - Support unmanned vehicles in dangerous areas, while enabling very high data rate data and video streaming.	- Highly dynamic beam tracking for alignment between transmitter and receiver. Preliminary results are provided in [11]. - Lack of measurements for mmWave V2X channels.
Machine-type communications (*MTC*)	- PSC can enable remotely-controlled devices and MTCs, which however need low latency. - Ultra-low latency is one of the goals of 5G, and mmWave communications can potentially enable low latency given their very high data rates.	- Low latency frame structures have been designed for mmWave cellular networks [8, 16], but PSC are characterized by much more dynamic channels and network topologies, which may introduce additional unreliability.
Ad hoc deployments	- Ad hoc multi-hop structures are needed when the fixed cellular infrastructure is not available. - mmWave multi-hop networks can improve coverage and overcome outdoor-indoor penetration.	- Ad hoc and multi-hop scenarios are relatively unexplored in the mmWave band. There may be a need for frequent link adaptation and handovers [25, 27]. - The end-to-end performance may be sub-optimal, because of the interaction between the transport and application layers and the mmWave channel [26, 33, 34].

Table 1: Open challenges above 6 GHz.

in Sec. 4. Finally, in Sec. 5 we draw our conclusions. A more extensive discussion on this topic is provided in [22], with additional details on the research platform which we plan to develop to address the challenges related to the adoption of mmWave in public safety scenarios.

2 PUBLIC SAFETY COMMUNICATIONS

As shown in [5, 9, 15], wireless communications are already used in public safety communications. There are two main categories of wireless PSC technologies [15]: (i) legacy *Land Mobile Radio Systems* (LMRS), which are dedicated terrestrial wireless networks, used only for mission critical communications, with a good and reliable support for voice but with high cost and limited data rates; (ii) *broadband-based* technologies, like LTE, which have been considered for PSC after the creation of FirstNet in the US. This use case for LTE obtained the full support of 3GPP from Release 12 in 2015, with the integration of public safety-related features such as proximity services for device-to-device communications, and group call enablers for dynamic group call among responders. LTE and, broadly speaking, commercial cellular infrastructures, are considered the future of PSC [5].

The technologies adopted in public safety networks must provide a reliable service to first responders [5, 9]. Several organizations, such as for example 3GPP, or the Next Generation Mobile Network Alliance (NGMNA), have defined requirements that PSC must satisfy. SAFECOM [30], a program of the US Department of Homeland Security, has highlighted a number of operational and functional performance indicators for public safety communication networks. Examples are requirements on:

- QoS, in terms of packet loss, latency and jitter (i.e., the variability of latency in different packets);
- the performance of speech and video transmission;
- radio coverage and resilience/availability of the network.

Additional requirements are specified by the European Telecommunications Standard Institute (ETSI) to target the interoperability of different systems in emergency scenarios [6].

3 OPEN CHALLENGES ABOVE 6 GHZ

MmWave communication is a promising technology that could meet the requirements of PSC [15], due to the large swaths of available spectrum that can support high data rates and reduced network congestion. However, as we will explain in this section, the use of mmWaves for PSC faces significant challenges. While there have been extensive studies on mmWave for cellular networks, research on the use of the mmWave bands for PSC applications is still in its infancy. We provide an overview of the challenges related to PSC above 6 GHz in Table 1, for different technological components which could be part of PSC networks: aerial, vehicular and machine-type communications, and ad hoc deployments.

The propagation at mmWave frequencies suffers from a very high isotropic pathloss [28] and low penetration of obstacles and of the human body (with losses from 20 to 80 dB [19, 36]). Thus, the fundamental problems of using the mmWave bands in any mobile scenario are related to *directionality* and *blockage*. The first is needed to provide a high Signal to Noise Ratio (SNR), which translates into higher data rates, and is enabled by narrow beams, which can be created using very high-dimensional arrays. Thanks to the small wavelength of mmWave signals, it is possible to pack a large number of antennas in arrays of limited size. For example, at 28 GHz the wavelength λ is approximately 1.07 cm, thus a rectangular array with 16 antennas (4 by 4) spaced by $\lambda/2$ each would be smaller than 5 cm by 5 cm, making it practical for the deployment on an Unmanned Aerial Vehicle (UAV). However, the transmitter and receiver have to discover and track the beam direction while moving, trying to maintain communication despite possible blocking obstacles which may disrupt the link or change the optimal beamforming vectors at the transmitter and the receiver.

The PSC scenario makes the need to support directionality and overcome blockage even more challenging, mainly because of the high mobility. In disaster and emergency scenarios, the presence of obstacles can lead to much more sudden variations in the received signal quality. In environments with manned or unmanned vehicles (e.g., UAVs) or with emergency responders operating within buildings, the channel dynamics are likely to be even faster [32]. Therefore, a key aspect of PSC at mmWave frequencies is the need to quickly identify the available nodes of the network (which may be even intermittently available) and the suitable beams for communication in highly dynamic scenarios. Even though beam tracking and beam alignment protocols for mmWave communication have been recently studied in a cellular context [10, 17], how to bring such techniques into the PSC scenarios is still to be investigated. Moreover, the scenarios in which PSCs are needed generally cover wider areas than the typical cell size in cellular networks, thus another challenge is related to the design of flexible and ad hoc network deployments that can cover kilometers-wide spaces with mmWaves.

4 WILDFIRE - A USE CASE OF MMWAVE PSC

Despite the challenges described in Sec. 3 and in Table 1, mmWave frequencies hold great potential for PSC scenarios. To show both the issues and the promises of mmWave PSC networks, we present in this section a possible use case with a real emergency situation inspired by the experience of the Robotic Emergency Deployment department at the Austin Fire Department.

In particular, we focus on the needs of a communication system that coordinates and monitors the remote operations and enables strategic decisions in a wildfire scenario. In this situation, the main use is to safely monitor the wildfire in order to (i) understand its shape and extension and (ii) check if there are people that may be affected by the fire. Currently, a firefighter in proximity of the emergency area operates the UAV and records the scene on a secure digital (SD) card. Ideally, this video should be available to the remote IC station, but without a fixed network infrastructure the SD should be physically transferred to the command post. Therefore the information is usually accessed in the area close to the wildfire.

This limitation explains why public safety communications would benefit from more advanced wireless technologies, which can enable real-time ultra-low latency exchange of monitoring information among remote UAVs and the IC. This data can include 360° videos for an immersive point of view of the scenario, which can be watched with VR headsets at the IC station, and video or images from multiple high-resolution lenses that can provide a better view of critical details, like humans in danger in the wildfire.

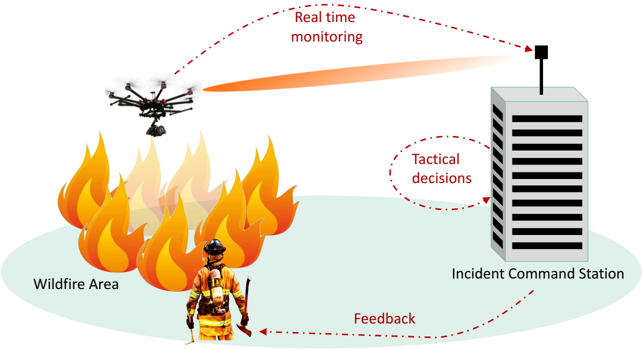


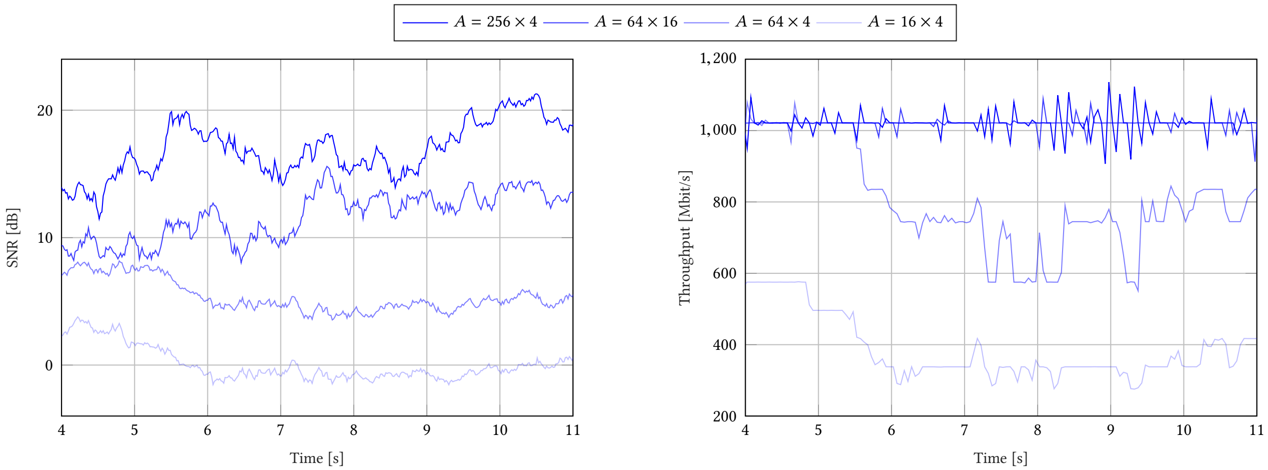
Figure 1: Wildfire scenario. The UAV monitors the wildfire and sends data to the IC station. It may stream a 360° video, or the flows of multiple cameras and lenses, as well as information from a plethora of sensors. The IC station makes strategic decisions using the data transmitted by the UAV, and provides feedback to the first responders which operate close to the wildfire [22].

Parameter	Value
mmWave carrier frequency f_c	28 GHz
mmWave bandwidth	1 GHz
mmWave max PHY rate	3.2 Gbit/s
Beamforming vector update period	5 ms
Antenna combinations $A = N_{\text{eNB}} \times N_{\text{UE}}$	$\{16 \times 4, 64 \times 4,$ $64 \times 16, 256 \times 16\}$
Video source rate R	$\{1, 100, 1000\}$ Mbit/s
Transport protocol	UDP
Max UAV speed v	30 m/s
Wildfire - IC distance	$\{1.6, 2.4\}$ km
UAV height	30 m

Table 2: Simulation parameters

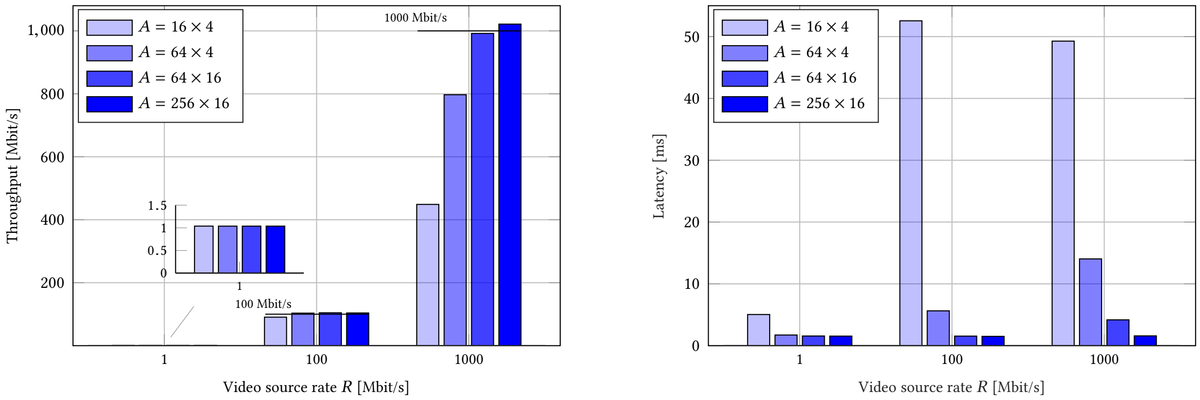
The performance of mmWave PSC for aerial communications in this use case is assessed using the simulation framework described in [7, 23]. The reference scenario is shown in Fig. 1. The system performance will be evaluated as a function of a number of parameters, such as the number of antennas both at the IC station and on the UAV, beamforming techniques, data rates, and other parameters, as shown in Table 2. The simulation results are obtained with a Monte Carlo approach, averaging the metrics of interest over multiple independent realizations of the simulations. This is a preliminary evaluation of the feasibility of a mmWave solution for PSC, in a particular scenario, given different beamforming and antenna configurations, and additional evaluations in a wider range of scenarios with additional optimizations will be part of our future work.

The wildfire is located in an area which is from 1.6 to 2.4 km away from the IC station. As shown in [20] it is possible to reach high distances (up to several kilometers) in LOS even with mmWave. In this paper we consider a single link solution, while in future works



(a) SNR **(b) Throughput**

Figure 2: SNR and throughput of the UAV flying over the wildfire for different configurations of antennas A at the base station and at the UAV. The legend is the same in both plots [22].



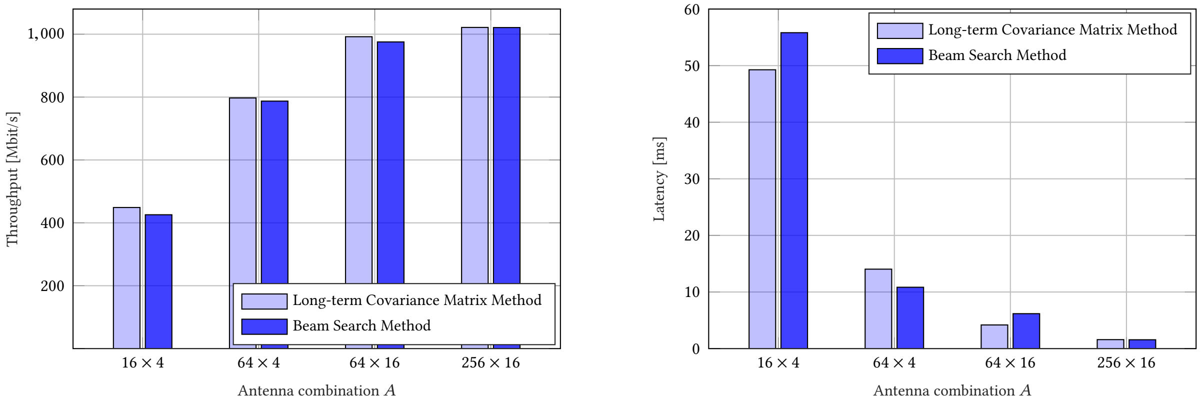
(a) Throughput **(b) Latency**

Figure 3: Average throughput and latency for different values of the video source rate R and of the antennas configurations A. The metrics are measured at the PDCP layer of the IC station, and therefore include also the overhead given by the headers of the network and transport protocols [22].

we will consider multi-hop configurations to cover larger distances. The drone flies over the wildfire following a Gauss-Markov mobility model for random speed and trajectories, which accounts for random variations in the UAV movement, for example introduced by the wind.

The channel model accounts for free space propagation with one LOS ray, shadowing and the Doppler effect, which is introduced by the moving UAV. The beamforming vectors at the base station of the IC station and at the drone side are updated every $T = 5$ ms, which is one of the candidates for beamforming update periodicity in 3GPP [2]. We consider two possible procedures for the computation of the vectors [35]: (i) the Long-term Covariance Matrix method assumes the knowledge of the long-term components of the covariance matrix and (ii) the Beam Search technique performs a brute-force search for the best matching pair. An extreme example of the SNR variability in the link between the UAV and the IC is shown in Fig. 2a. The fluctuations are given by very fast movements of the UAV and by the Doppler effect. Instead, if the UAV loiters over a certain spot for a prolonged period of time, the variations would be smaller. However, in this article we consider a worst case scenario.

The beamforming gain is a fundamental elements for reaching a high SNR, and therefore a high data rate, as shown in Figs. 2 and 3a. Thanks to the adaptive antenna arrays, indeed, it is possible to balance the high propagation loss of mmWave frequencies. At these frequencies, antenna arrays with a large number of antennas can be easily mounted also on small UAVs, given the smaller wavelength. At the distance of the reference scenario, only two combinations of antenna elements among those considered (i.e., 256 or 64 antennas at the IC station and 16 at the UAV side) provide a steady data rate of 1 Gbit/s. Notice that even with 16 antennas at the UAV side the power consumption related to the data transmission [3] is at least



(a) Throughput **(b) Latency**

Figure 4: Average throughput and latency for different beamforming strategies and antenna configurations A [22].

one order of magnitude smaller than that required to hover the UAV over the wildfire (which is in the order of 160 W for a small multi-rotor drone [18]), thus the communication impact on the total energy consumption is limited. Nonetheless, the increase in the energy consumption of the UAV given by both the communication and the payload is an important element to be considered in future studies on the trade-off between communication capabilities and UAV operational autonomy.

Figs. 3a and 3b account for different use cases of the data streaming from the UAV, represented by the different source rates. R = 1 Mbit/s is typically a low quality video, or a combination of sensor information, while R = 100 Mbit/s and R = 1 Gbit/s are respectively a 360° camera without or with additional flows from high definition cameras and other sensors. The values of latency and throughput of Fig. 3 are the average of those measured at the PDCP layer over multiple independent simulations. The combinations with a larger number of antennas are beneficial for both the throughput and the latency. The latter decreases with an increasing number of antennas because as the SNR increases the probability of needing link-layer retransmissions (and thus additional delay) decreases. This is also beneficial on the latency variability and on the jitter. Moreover, while all the considered antenna arrays are able to sustain the source rate of 1 Mbit/s, only the 64×16 and 256×16 configurations can reach a throughput comparable to the source rate R = 1 Gbit/s.

Another parameter we consider in this evaluation is the beamforming strategy. In Figs. 4a and 4b the two beamforming techniques previously introduced, i.e., the Long-term Covariance Matrix method and the Beam Search method [35], are compared in terms of throughput and latency, for different antenna configurations and a fixed source rate R = 1 Gbit/s. The two solutions are equivalent in this scenario, with the Long-Term Covariance Matrix showing a gain for the 16×4 combination. The optimal method, which is based on the knowledge of the long-term covariance matrix, generally provides a slightly higher SNR, but this gain is relevant in terms of throughput and latency only in the 16×4 configuration, which is the one with the smallest coding gain and SNR at the receiver.

This simple real-life case study revealed the strong potential of mmWave in PSC systems. Nonetheless, as mentioned in Sec. 3, there are a lot of open research issues that will need to be solved in order to make this technology suitable for practical deployment in emergency scenarios. Among these, there is a need for a more precise characterization of the aerial mmWave channel, also in terms of channel dynamics, as well as the development of architectures and protocols that enhance coverage and reliability in more complex scenarios. This is what motivated us to promote the development of an end-to-end research platform for mmWave PSC, which will conduct dynamic channel sounding campaigns, develop a software defined radio platform and an advanced channel emulator, and extend the ns–3-based simulator used in this paper. More details are given in [22].

5 CONCLUSIONS

Reliable and efficient communications are a vital ingredient for the protection of emergency responders – police, firefighters, medics – which operate on a daily basis in dangerous scenarios. The mmWave spectrum potentially increases the capabilities of public safety communication systems, in order to provide a better assistance to public safety personnel in their duty.

In order to reap these benefits, several challenges need to be solved, which arise from two peculiarities of mmWave communications, i.e., the impact of blockage and the need for directional transmissions. These issues are being faced also in cellular systems, but are expected to have a greater impact in PSC systems, because of the high mobility of vehicles, the different classes of traffic and the more demanding performance requirements in an ad hoc and distributed architecture.

In this paper we provided an overview of these challenges, as well as of the potential of mmWave networks for future PSC describing a real-life scenario with UAV communications and a wildfire. As part of our future work, we will develop a research platform to better understand the needs of PSC scenarios and develop a communication technology that could be life-saving in emergency situations.

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REFERENCES

[1] 3GPP. 2016. Study on Scenarios and Requirements for Next Generation Access Technologies. TR 38.913, Rel. 14. (October 2016).

[2] 3GPP. 2017. LS on set of configuration values for SS burst set periodicity. Intel - Tdoc R1-1706708. (April 2017).

[3] W. B. Abbas and M. Zorzi. 2016. Towards an Appropriate Receiver Beamforming Scheme for Millimeter Wave Communication: A Power Consumption Based Comparison. In *22th European Wireless Conference.*

[4] M.R. Akdeniz, Y. Liu, M.K. Samimi, S. Sun, S. Rangan, T.S. Rappaport, and E. Erkip. 2014. Millimeter Wave Channel Modeling and Cellular Capacity Evaluation. *IEEE J. Sel. Areas Comm.* 32, 6 (June 2014), 1164–1179.

[5] G. Baldini, S. Karanasios, D. Allen, and F. Vergari. 2014. Survey of Wireless Communication Technologies for Public Safety. *IEEE Communications Surveys & Tutorials* 16, 2 (September 2014), 619–641. DOI: http://dx.doi.org/10.1109/SURV.2013.082713.00034

[6] ETSI. 2015. Satellite Earth Stations and Systems (SES); Reference scenario for the deployment of emergency communications. TS 103 260. (May 2015).

[7] Russell Ford, Menglei Zhang, Sourjya Dutta, Marco Mezzavilla, Sundeep Rangan, and Michele Zorzi. 2016. A framework for end-to-end evaluation of 5G mmWave cellular networks in ns-3. In *Proceedings of the Workshop on ns-3.* ACM, 85–92.

[8] R. Ford, M. Zhang, M. Mezzavilla, S. Dutta, S. Rangan, and M. Zorzi. 2017. Achieving Ultra-Low Latency in 5G Millimeter Wave Cellular Networks. *IEEE Communications Magazine* 55, 3 (March 2017), 196–203. DOI: http://dx.doi.org/10.1109/MCOM.2017.1600407CM

[9] S. Ghafoor, P. D. Sutton, C. J. Sreenan, and K. N. Brown. 2014. Cognitive radio for disaster response networks: survey, potential, and challenges. *IEEE Wireless Communications* 21, 5 (October 2014), 70–80. DOI: http://dx.doi.org/10.1109/MWC.2014.6940435

[10] M. Giordani, M. Mezzavilla, C. N. Barati, S. Rangan, and M. Zorzi. 2016. Comparative analysis of initial access techniques in 5G mmWave cellular networks. In *Annual Conference on Information Science and Systems (CISS).* 268–273.

[11] M. Giordani, A. Zanella, and M. Zorzi. 2017. Millimeter wave communication in vehicular networks: Challenges and opportunities. In *2017 6th International Conference on Modern Circuits and Systems Technologies (MOCAST).* DOI: http://dx.doi.org/10.1109/MOCAST.2017.7937682

[12] Farooq Khan and Zhouyue Pi. 2011. An introduction to millimeter-wave mobile broadband systems. *IEEE Comm. Mag.* 49, 6 (June 2011), 101–107.

[13] W. Khawaja, I. Guvenc, and D. Matolak. 2016. UWB Channel Sounding and Modeling for UAV Air-to-Ground Propagation Channels. In *IEEE Global Communications Conference (GLOBECOM).* DOI: http://dx.doi.org/10.1109/GLOCOM.2016.7842372

[14] W. Khawaja, O. Ozdemir, and I. Guvenc. 2017. UAV Air-to-Ground Channel Characterization for mmWave Systems. *ArXiv e-prints* (July 2017). arXiv:cs.IT/1707.04621

[15] A. Kumbhar, F. Koohifar, I. Guvenc, and B. Mueller. 2017. A Survey on Legacy and Emerging Technologies for Public Safety Communications. *IEEE Communications Surveys & Tutorials* 19, 1 (September 2017), 97–124. DOI: http://dx.doi.org/10.1109/COMST.2016.2612223

[16] Toni Levanen, Juho Pirskanen, and Mikko Valkama. 2014. Radio interface design for ultra-low latency millimeter-wave communications in 5G era. In *Proc. IEEE Globecom Workshops (GC Wkshps).* 1420–1426.

[17] Yingzhe Li, Jeffrey G Andrews, François Baccelli, Thomas D Novlan, and Charlie Zhang. 2016. Design and Analysis of Initial Access in Millimeter Wave Cellular Networks. *arXiv preprint arXiv:1609.05582* (2016).

[18] Z. Liu, R. Sengupta, and A. Kurzhanskiy. 2017. A power consumption model for multi-rotor small unmanned aircraft systems. In *2017 International Conference on Unmanned Aircraft Systems (ICUAS).* 310–315.

[19] Jonathan S. Lu, Daniel Steinbach, Patrick Cabrol, and Philip Pietraski. 2012. Modeling Human Blockers in Millimeter Wave Radio Links. *ZTE Communications* 10, 4 (December 2012), 23–28.

[20] George R. MacCartney, Jr., Shu Sun, Theodore S. Rappaport, Yunchou Xing, Hangsong Yan, Jeton Koka, Ruichen Wang, and Dian Yu. 2016. Millimeter Wave Wireless Communications: New Results for Rural Connectivity. In *Proceedings of the 5th Workshop on All Things Cellular: Operations, Applications and Challenges.* 31–36.

[21] A. Merwaday, A. Tuncer, A. Kumbhar, and I. Guvenc. 2016. Improved Throughput Coverage in Natural Disasters: Unmanned Aerial Base Stations for Public-Safety Communications. *IEEE Vehicular Technology Magazine* 11, 4 (December 2016), 53–60. DOI: http://dx.doi.org/10.1109/MVT.2016.2589970

[22] Marco Mezzavilla, Michele Polese, Andrea Zanella, Aditya Dhananjay, Sundeep Rangan, Coitt Kessler, Ted Rappaport, and Michele Zorzi. 2017. Public Safety Communications above 6 GHz: Challenges and Opportunities. *To appear on IEEE Access - Special Section on Mission Critical Public-Safety Communications: Architectures, Enabling Technologies, and Future Applications* (2017).

[23] Marco Mezzavilla, Menglei Zhang, Michele Polese, Russell Ford, Sourjya Dutta, Sundeep Rangan, and Michele Zorzi. 2017. End-to-End Simulation of 5G mmWave Networks. *Submitted to IEEE Communication Surveys & Tutorials* (2017). https://arxiv.org/abs/1705.02882

[24] NGMN Alliance. 2015. NGMN 5G WHITE PAPER. (Februray 2015). https://www.ngmn.org/uploads/media/NGMN_5G_White_Paper_V1_0.pdf

[25] M. Polese, M. Giordani, M. Mezzavilla, S. Rangan, and M. Zorzi. 2017. Improved Handover Through Dual Connectivity in 5G mmWave Mobile Networks. *IEEE JSAC Special Issue on Millimeter Wave Communications for Future Mobile Networks* 35, 9 (September 2017), 2069–2084.

[26] M. Polese, R. Jana, and M. Zorzi. 2017. TCP in 5G mmWave Networks: Link Level Retransmissions and MP-TCP. In *IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS).*

[27] Michele Polese, Marco Mezzavilla, Sundeep Rangan, and Michele Zorzi. 2017. Mobility Management for TCP in mmWave Networks. (2017), 11–16.

[28] S. Rangan, T. S. Rappaport, and E. Erkip. 2014. Millimeter-Wave Cellular Wireless Networks: Potentials and Challenges. *Proc. IEEE* 102, 3 (March 2014), 366–385.

[29] Theodore S Rappaport, Shu Sun, Rimma Mayzus, Hang Zhao, Yaniv Azar, Kevin Wang, George N Wong, Jocelyn K Schulz, Matthew Samimi, and Felix Gutierrez. 2013. Millimeter Wave Mobile Communications for 5G Cellular: It Will Work! *IEEE Access* 1 (May 2013), 335–349.

[30] SAFECOM, US communications program of the Department of Homeland Security. 2006. Public Safety Statements of Requirements for Communications and Interoperability Vols. I and II. (2006).

[31] Tracy McElvaney. 2015. 5G: From a Public Safety Perspective. (2015). http://www.atis.org/5g/presentations/5G_PublicSafety_TMcElvaney.pdf

[32] Vutha Va, Takayuki Shimizu, Gaurav Bansal, and Robert W. Heath Jr. 2016. Millimeter Wave Vehicular Communications: A Survey. *Found. Trends Netw.* 10, 1 (June 2016), 1–118. DOI: http://dx.doi.org/10.1561/1300000054

[33] Menglei Zhang, Marco Mezzavilla, Russell Ford, Sundeep Rangan, Shivendra Panwar, Evangelos Mellios, Di Kong, Andrew Nix, and Michele Zorzi. 2016. Transport layer performance in 5G mmWave cellular. In *IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS).* 730–735.

[34] Menglei Zhang, Marco Mezzavilla, Jing Zhu, Sundeep Rangan, and Shivendra S. Panwar. 2016. The Bufferbloat Problem over Intermittent Multi-Gbps mmWave Links. *CoRR* abs/1611.02117 (2016). http://arxiv.org/abs/1611.02117

[35] Menglei Zhang, Michele Polese, Marco Mezzavilla, Sundeep Rangan, and Michele Zorzi. 2017. ns-3 Implementation of the 3GPP MIMO Channel Model for Frequency Spectrum above 6 GHz. In *Proceedings of the Workshop on ns-3.* ACM, 71–78.

[36] H. Zhao, R. Mayzus, S. Sun, M. Samimi, J. K. Schulz, Y. Azar, K. Wang, G. N. Wong, F. Gutierrez, and T. S. Rappaport. 2013. 28 GHz millimeter wave cellular communication measurements for reflection and penetration loss in and around buildings in New York city. In *IEEE International Conference on Communications (ICC).* 5163–5167. DOI: http://dx.doi.org/10.1109/ICC.2013.6655403