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Public Safety Communications above 6 GHz: Challenges and Opportunities

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ABSTRACT Advanced public safety communication (PSC) services call for fast, reliable and low-latency communication technologies, capable of supporting diverse communication modes (aerial, unmanned, vehicular, and peer-to-peer), fast channel dynamics, and ad hoc or mesh structures. For this reason, PSC has been identified as one of the key potential uses cases for the next generation of communication systems, the so-called 5G. In this scenario, the millimeter wave (mmWave) bands and other frequencies above 6 GHz are particularly interesting, since they are largely untapped and offer vastly more spectrum than current cellular allocations in the highly congested bands below 6 GHz, thus enabling orders of magnitude greater data rates and reduced latency. For example, new PSC networks in the mmWave bands could support high-definition video, virtual reality, and other broadband data to large numbers of first responders. Surveillance drones or ambulances could also be provided high-speed connectivity along with machine-type communication for remotely controlled robotic devices entering dangerous areas. However, the way towards this ambitious goal is hindered by a number of open research challenges. In this paper, after a brief introduction to PSC services and requirements, we illustrate the potential of the frequencies above 6 GHz for PSC and discuss the open problems that need to be solved in order to pave this way. Finally, we describe the main components of a test platform for mmWave systems that is functional to the study of such complex scenarios and that we plan to develop as an invaluable tool for realizing mmWave PSC networks.

INDEX TERMS Public safety and emergency communications, channel sounding, mmWave.

I. INTRODUCTION

Public safety and emergency services are of primary importance in modern society. The National Telecommunications and Information Administration (NTIA), a US consulting agency for telecommunications and information policy, has recently branched off the First Responder Network Authority (FirstNet) as an independent entity to provide emergency responders with the first nationwide, high-speed, broadband network dedicated to public safety communications (PSC). The ultimate goal is to realize a communication system capable of supporting high-quality real-time video streaming (e.g., for remote and collaborative medical examination of injured persons in the ambulances, or for the aerial reconnaissance of a disaster site), clear voice communication among operators (for the coordination of the rescue team), ultra-low delay data exchange (e.g., for continuous monitoring of rescuers' vital parameters), and dependability in all the possible emergency situations, including those where civil communication infrastructures may be compromised.

To contain costs, FirstNet is tasked with leveraging the existing telecommunications infrastructure including 4th Generation (4G) Long Term Evolution (LTE) commercial cellular networks, standardized through the 3rd Generation Partnership Project (3GPP) [2]. However, 5G standards are now being developed [3] and future versions of FirstNet may be able to incorporate these more advanced systems as well. One of the most promising 5G technologies is the use of the high-frequency bands above 6 GHz, including the so-called millimeter wave (mmWave) frequencies [4]–[8]. The mmWave bands are a relatively new frontier for

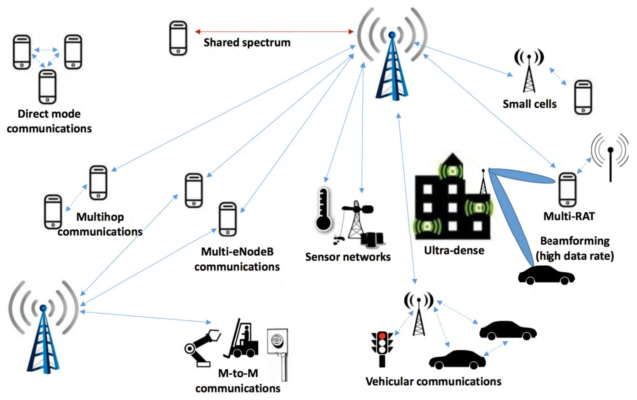


FIGURE 1. 5G network architecture as illustrated in Public Safety Perspective: A 5G Worldview by National Institute for Standards and Technology. Taken from [1] with permission granted from the authors.

wireless systems, offering orders of magnitude greater spectrum than currently available in the highly congested bands below 6 GHz. Given the enormous potential of these bands, the latest FCC Notice of Proposed Rule Making (NPRM) is already considering opening up to 18 GHz of mmWave spectrum [9] – vastly more than all cellular spectrum today.

The massive bandwidths at the mmWave frequencies can enable multi-Gbps throughputs and ultra-low latency communications, thereby providing tremendous opportunities for next-generation PSC networks [1] – see Fig. 1. The Next Generation Mobile Networks alliance (NGMN) has already identified PSC as one of the key use cases of 5G mmWave networks [10]: The broadband data rates can support real time video, high quality pictures, and even virtual or augmented reality streams to first responders. Data can be sent to large numbers of nodes including crews on the grounds as well as support drones and backhaul to fixed infrastructure. The low latency can also be used for machine-type communication including robotically-controlled devices that may be necessary to enter scenes too dangerous for humans.

The remainder of this paper is structured as follows:

- **Overview of PSC:** In Section II, we provide a brief overview of existing wireless technologies and requirements for public safety communications;
- **Open challenges above 6 GHz:** In Section III, we describe some of the fundamental challenges related to propagation in the spectrum above 6 GHz, and illustrate the additional set of challenges related to using mmWave communications for disaster response networks;
- **A use case for mmWave PSC:** In Section IV, we explore a potential use case of mmWave applied to PSC, i.e., a wildfire. This section leverages the collaboration with the Austin Fire Department (AFD) for the scenario definition, and the mmWave simulator developed at NYU and University of Padova for the performance evaluation.
- **A research platform for mmWave PSC:** Finally, in Section V, we describe the key components of the research platform which is under development at NYU and that will be used, in our future works, to address the challenges of mmWave PSC, as listed in Section III.

II. PUBLIC SAFETY COMMUNICATIONS

Wireless technologies represent an essential component of public safety services. The PSC ecosystem exhibits a number of solutions tailored for different emergency applications, as comprehensively captured in [11]–[13]. In this section, we provide a brief overview of the existing emergency response *technologies* along with its fundamental operational/technical *requirements*.

Key Technologies: As done in [13], we broadly classify PSC technologies into two main categories.

Land Mobile Radio System (LMRS): LMRS is a terrestrial wireless communication system that has been used for many years in military, commercial, and emergency applications. The main goal is to provide mission critical communications and provide integrated voice and data communications for emergency response. APCO-25 and European Terrestrial Trunked Radio (TETRA) are the main digital technologies used for LMRS based radio communications.

Broadband: Due to high cost and limited data communication rates of LMRSs, broadband technologies such as LTE have recently gained traction in the PSC ecosystem. As reported in [11], in January 2011 the FCC in US adopted a Third Report and Order and Fourth Further Notice of Proposed Rulemaking (FNPRM) to support the build-out of a nationwide broadband network based on LTE Release 8 [14]. As a consequence, 3GPP has started since Release 12 [15] to accommodate PS-related discussions within the standardization activities. This effort has resulted in a formal definition and integration of key emergency-related components such as *proximity services* [16], to identify mobiles in physical proximity and enable optimized communications between them, also known as device-to-device communications, and *group call enablers* [17], for efficient and dynamic group communications operations. LTE and, broadly speaking, commercial cellular infrastructures, are considered the future of PSC.

Key Requirements: A number of organizations have outlined a common set of requirements. In particular, the US Department of Homeland Security (DHS) Program, SAFECOM, has highlighted necessary communication services and their operational/functional requirements for the emergency domain [11], [12], [18]:

- Support to Command and Control hierarchy
- Support to interactive and non-interactive voice and data communications
- Inter-agency interoperability
- Security
- Support to new data applications
- Speech transmission performance
- Video transmission performance
- QoS (packet loss, jitter, latency)
- Timeliness in delivering messages
- Radio coverage

- Call prioritization
- Robustness of PS equipment
- Energy consumption
- Security
- Resilience/Availability of the networks

Additionally, the European Telecommunications Standard Institute (ETSI) has worked on programs for Emergency Telecommunications (EMTEL) targeting interoperability of services and systems in emergency situations.

Finally, both 3GPP and NGMN have also recently started to work towards defining a set of technical requirements for emergency communications [10], [42]. For example, as explained in [43], mission-critical data services controlling unmanned aerial vehicles, or drones, have an end-to-end delay budget of 50 ms, whereas mission-critical push-to-talk (MCPTT) access time needs to come under 300 ms 95% of the time. On the other hand, Table 1 of NGMN's white paper on 5G [10] captures in detail the targeted user experience key performance indicators (KPIs) of different use case categories, including lifeline communications.

III. OPEN CHALLENGES ABOVE 6 GHz

As mentioned in [13], the mmWave technology represents a promising emerging PSC solution due to its vast untapped spectrum that results in reduced network congestion and high data rates. Mobile communication at such frequencies, however, is still very much in its infancy. As explained in this section, their use for PSC faces enormous challenges. While there has been extensive research in mmWave for cellular networks, the use of the mmWave bands for PSC applications is relatively less understood. We refer to Table 1 for an overview of the challenges related to PSC above 6 GHz.

The fundamental challenges of using the mmWave bands in any mobile scenario are *directionality* and *blockage*. To overcome the high isotropic path loss of mmWave propagation, mmWave signals must be transmitted and received in narrow directional beams. While the small wavelengths of mmWave signals enable very high-dimensional arrays to form narrow beams, these must be discovered and tracked in any mobile situation. In addition, mmWave signals are extremely susceptible to blocking. For example, materials such as brick can attenuate signals by as much as 40 to 80 dB [4], [47]–[50] and the human body itself can result in a 20 to 35 dB loss [51].

The need to support directionality and overcome blockage is particularly challenging in a PSC scenario, primarily due to the high mobility. Due to blockage, the appearance of obstacles can lead to much more dramatic swings in the channel quality. In highly mobile environments with vehicles or Unmanned Aerial Vehicles (UAVs) or with first responders moving within buildings, these channel dynamics are likely to be even more rapid [52]. Therefore, a critical aspect of PSC is the need to rapidly identify network elements and directions for communication in highly dynamic scenarios. Although beam tracking and beam alignment protocols for mmWave communication have been recently studied in a cellular context [44]–[46], [53]–[56] (see Fig. 2(a)), how to bring such techniques into the PSC scenarios is still to be investigated.

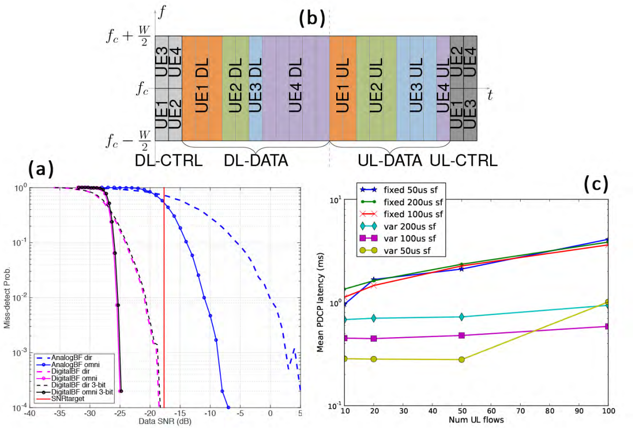


FIGURE 2. The SDR platform will be able to support key areas for PSC prototyping: (a) Fast initial access and directional synchronization techniques developed in [44]–[46]; (b) Flexible frame structures [31], [32] that obtain (c) very low latency, esp. for short control messaging [32]. ©[2015, 2017] IEEE. Reprinted, with permission, from [31], [32], [44].

Another important topic that needs to be studied is how mmWave signals affect the human body. While frequencies in the mmWave bands of 30-300 GHz are one to two orders of magnitude greater than today's cellular and public safety carrier frequencies of 1-3 GHz, they are still 5 to 6 orders of magnitude smaller than the frequencies at which radiation is ionizing, i.e., where wave energy is sufficiently large to break electrons from the valence shell of atoms within human DNA or air. Ionizing radiation is known to cause unstable atoms (free radicals) that may potentially cause unstable cell growth which can lead to cancer, but mmWave radiation is not believed to pose such threats [57]. Any potential health effects of mmWave radiation are believed to stem from tissue heating, which could cause RF burns and unstable atoms in human tissue after prolonged exposure. It has become apparent that steerable, adaptive antennas will be useful in assuring that transmitted energy is radiated away from sensitive parts of the body, such as the eyes and skull, where there is little blood flow and hence little ability to dissipate heat due to RF radiation [57], [58], and these same steerable antennas will be able to bounce energy off of structures and people in the far field to improve instantaneous radio coverage.

IV. WILDFIRE - A USE CASE OF mmWAVE COMMUNICATIONS APPLIED TO PUBLIC SAFETY

To illustrate both the potentials and the challenges of mmWave PSC systems, we consider a real disaster scenario based on the experiences of the Robotic Emergency Deployment department at the Austin Fire Department [59]. Specifically, we describe some of the major pain-points related to communications technology for strategic operations and tactical assessment during a *wildfire*.

In wildfire communication, the main goal is to monitor the affected area in order to (i) infer its size and shape and

TABLE 1. Open challenges above 6 GHz.

Technological component	Motivation	Open challenges above 6 GHz
Aerial communications	The authors in [19] explore the issues, challenges, and future research challenges associated with the integration of unmanned aerial vehicles and cognitive radio technology for solving the challenges caused by scarce spectrum. On the other hand, recent works [20], [21] have proposed to mount Base Stations (BSs) on UAVs for PSC in case of failures due to natural disasters or malevolent attacks, and are currently studying the feasibility of aerial communications operating in the mmWave bands in a National Science Foundation (NSF) grant [22]. Similarly, the Defense Advanced Research Projects Agency (DARPA) Mobile Hotspots Program seeks to provide high-bandwidth communications for troops in remote forward-operating locations through mmWave connected UAVs, aiming at demonstrating a scalable, mobile, self-forming and managing network of mmWave air-to-air and air-to-ground gigabit class data links [23].	There is a rich literature related to understanding the air-ground propagation at traditional frequencies [24], [25], [26], [27]. Up to now, however, the "aerial" mmWave channel has not yet been characterized, and the establishment and maintenance of aerial links are still open problems. The authors in [28] conduct a preliminary study of the behavior of air-ground mmWave signals at two different frequencies: 28 GHz and 60 GHz. However, the channel characterization is based on ray tracing simulations, which still need to be validated through real measurements. Additionally, if compared to mmWave for commercial cellular applications, there will be additional challenges related to much more directional links, which will probably be in the order of fractions of degrees to support massive data rate at long distances. This would indeed require more sophisticated beam tracking and beamforming procedures.
Vehicular communications	In disaster response, vehicular communication (generally denoted by *V2X*) may be required for ambulances, as well as vehicles for exploration of dangerous and hazardous areas, or during a leakage of radioactive material [10]. The supporting technology hence should make it possible to quickly establish links between mobile vehicles or mobile vehicles and fixed infrastructure nodes and to maintain connectivity by performing fast handover to other vehicles/infrastructure nodes when needed. The directionality of mmWave connections will allow for massive spatial reuse of the frequency bands, thus enabling a large number of simultaneously active links with minimal cross interference.	Sophisticated beam forming and beam tracking techniques are required to maintain alignment between transmitter and receiver. While these challenges have already received some attention in the context of cellular networks, their investigation in vehicular communication has just started [29]. Again, the lack of appropriate mmWave channel models for inter-vehicle communication is a first fundamental roadblock that needs to be attacked in order to open the way to practical mmWave-based V2X services.
Machine-type communications	PSC systems may also benefit from the support of robotically-controlled devices and machine-type communication within a response area. A key challenge here is that remote controlled vehicles and other robotic devices may need to directly communicate with centralized servers requiring much higher data rates and lower latency than what can be offered by today's cellular technologies. Ultra-reliable and low-latency communication (URLLC) is one of the basic goals of the IMT 2020 vision for 5G [30]. Due to the wide bandwidths and very high data rates, mmWave systems can offer potentially much lower latencies than systems below 6 GHz.	The authors in [31], [32], [33] explore low-latency at mmWave bands, thanks to utilizing shorter and more flexible frame structures, as illustrated in Fig. 2(b) and (c). However, these works have considered primarily cellular links, and the challenge in PSC scenarios is to support these low latency / high bandwidth links in situations where the channels and network topologies are more dynamic.
Ad hoc deployments	In disaster scenarios, a fixed cellular infrastructure may be unavailable and communication may need to be performed via *ad hoc* and multi-hop structures [34], [35]. Since range and blockage are key challenges for mmWave communication [8], multi-hop networks may also be necessary for coverage, particularly to overcome outdoor-indoor penetration. Despite the massive literature on ad hoc networks, these aspects have not yet been addressed in the (relatively new) literature on mmWave communication, and hence represent a still unexplored field of investigation.	The high-rate and variable nature of the mmWave channel is a big challenge also at the network and transport layers. At the transport layer, the wide swings in available rate become a key challenge for end-to-end congestion control. Studies in cellular systems [36], [37], [38], [39] have shown that conventional TCP mechanisms can result in bufferbloat and link underutilization in transitions of link quality. Also, at the network layer, maintaining end-to-end reliable service requires much more frequent handovers and path switching in mmWave scenarios since the quality on any one link is so variable [40], [41]. Given the ad hoc nature of deployments along with the increased mobility and blocking, we expect that these challenges will be even more pronounced in a mmWave PSC setting.

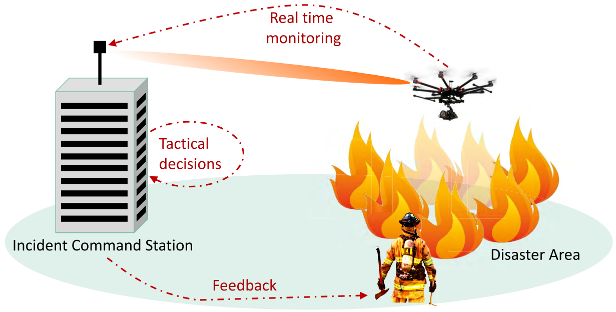


FIGURE 3. **Wildfire scenario. The UAV flies over the wildfire area and transmits data to the IC station. For example, it may use a 360° camera, or multiple cameras, and a wide variety of sensors. The IC station defines tactical strategies according to the information provided by the UAV, and sends feedback to the firefighters in the proximity of the wildfire.**

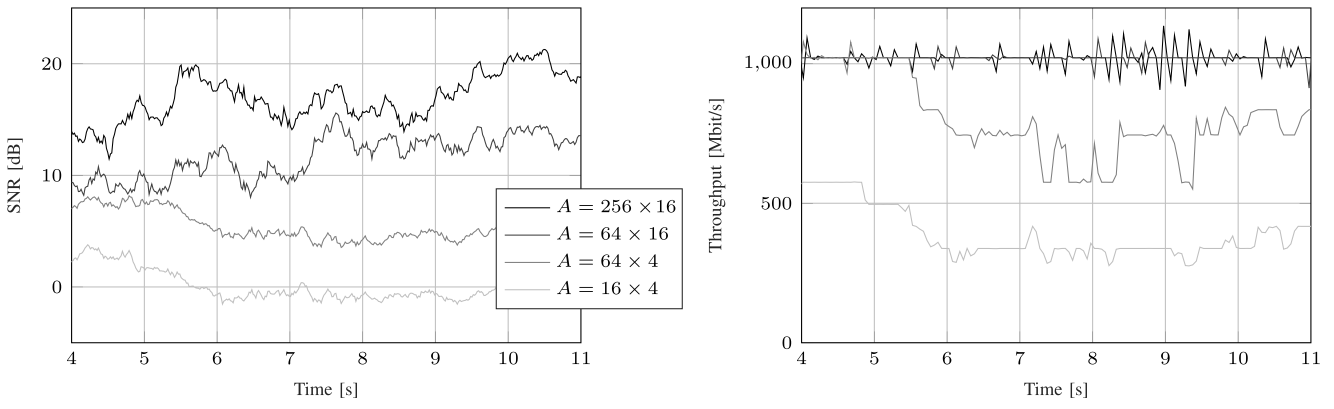
(ii) determine whether there are people in danger within the disaster area. In current operations, the firefighter remotely operates a drone equipped with a camera to record the scene on a secure digital (SD) card. The video content is either processed in the field with laptops/monitors or, preferably — but rarely a possibility given the distance to the incident command (IC) station — shared with the IC center by physically transferring the memory card. This scenario motivates better wireless connectivity that can enable real-time exchange of high quality monitoring systems directly with the incident command center. These systems may include 360° cameras for immersive wide-scale capture of the environment, which can be projected onto VR headsets at the IC station, and multiple high-end lenses that can zoom and steer around to detect critical details, like humans in the wildfire.

Using the simulation framework described in [37], [60], and [61], we can assess the feasibility of high data rate aerial communications based on mmWaves. The scenario is shown in Fig. 3. We will evaluate the impact on the network performance of a different number of antennas both at the IC station and on the UAV, beamforming techniques, data rates, and other parameters, as shown in Table 2.

TABLE 2. **Simulation parameters.**

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
Max UAV speed v	30 m/s
Wildfire - IC distance	$\{1.6, 2.4\}$ km
UAV height	30 m

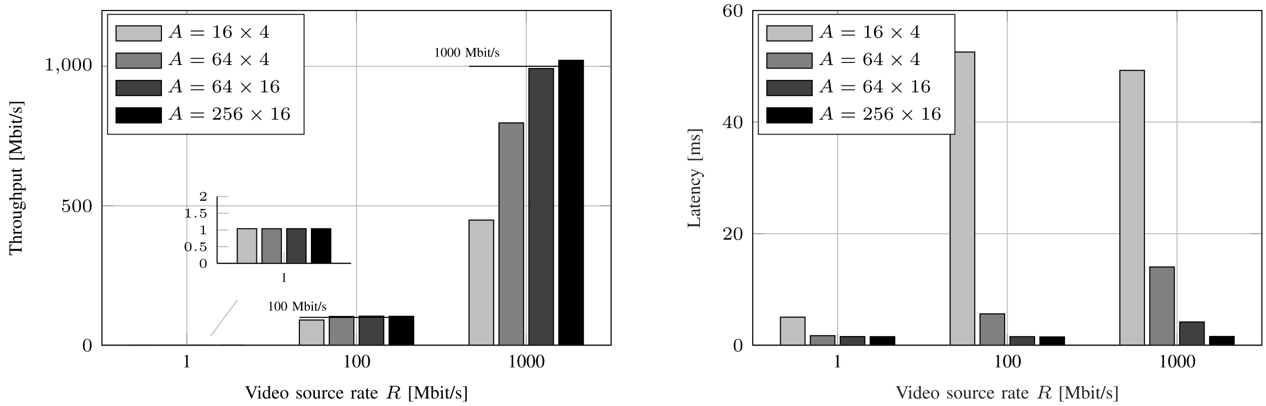
The UAV flies above the wildfire, and moves following random trajectories and velocities according to a Gauss-Markov mobility model [62] in an area which is from 1.6 to 2.4 km away from the IC station. For the channel model, we consider free space propagation with a single LOS ray, shadowing, and the Doppler effect due to the movement of the UAV. The carrier frequency is $f_c = 28$ GHz, which is part of the spectrum allocated to cellular communications, but results can be generated for any carrier frequency in the 6-100 GHz spectrum thanks to the channel model described in [63]. Moreover, we update the beamforming vectors at the IC station and the UAV side with periodicity $T = 5$ ms, following the specifications under discussion at 3GPP [64]. The beamforming vectors are computed with the methods described in [63], assuming the knowledge of the long term components of the covariance matrix (Long-term Covariance Matrix method [65]) or with a brute-force search for the best matching pair (Beam Search method [66]). Fig. 4a shows an extreme example of the variability of the SNR of the IC-UAV link, given by very rapid movements of the UAV and the impact of the Doppler effect. The UAV may also loiter at a specific location for an extended time interval, and in that case there would be smaller variations of the SNR, but in this article a worst case scenario is considered.



(a) SNR

(b) Throughput

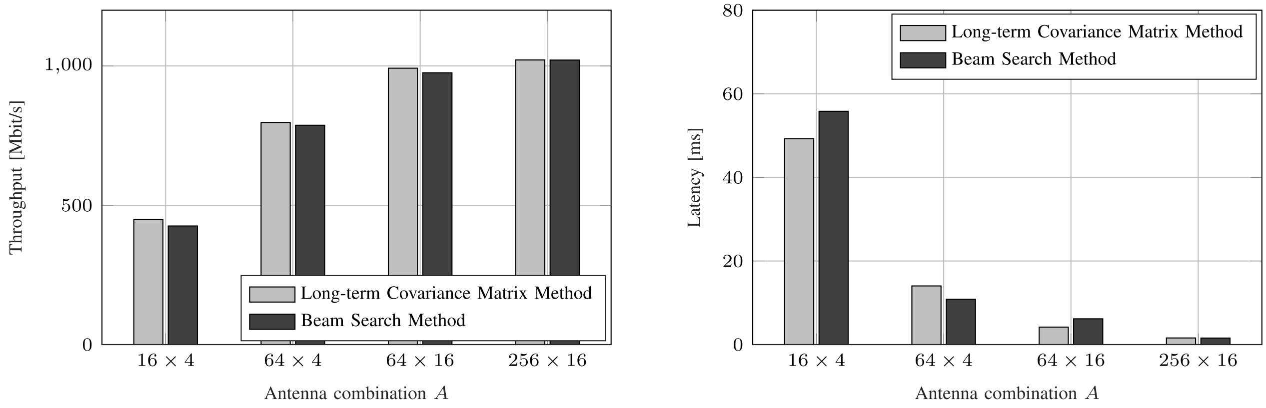
FIGURE 4. **SNR and throughput of the UAV moving randomly over the wildfire area for different combinations of antennas *A* at the base station and at the UAV. The legend is the same in both plots. (a) SNR. (b) Throughput.**



(a) Throughput

(b) Latency

FIGURE 5. Average throughput and latency for different combinations of antennas *A* and video source rate *R*. The throughput is measured at the PDCP layer of the IC station, therefore it includes also the overhead introduced by the headers of the transport and network protocols. (a) Throughput. (b) Latency.



(a) Throughput

(b) Latency

FIGURE 6. Average throughput and latency for different combinations of antennas *A* and beamforming strategies. (a) Throughput. (b) Latency.

As it can be seen in Fig. 4, the gain provided by beamforming is a key factor in reaching a high SNR at the large distance of the scenario considered. This makes it possible to balance the increase in propagation loss that is present at mmWave frequencies. Moreover, at such high frequencies, the size of the antenna arrays is smaller with respect to lower frequencies, and therefore it is feasible to pack a large number of antennas also on a small UAV. The cost is an increase in the power consumption, and the trade-off between range and autonomy of the UAV will be an important element of our future work. In particular, in the simulation instance shown in Fig. 4, both the combinations with 256 or 64 elements at the IC station and 16 at the UAV side manage to sustain the source rate of 1 Gbit/s.

In Figs. 5a and 5b different source rates are considered, in order to account for different use cases: a low quality video, or simple sensor information ($R = 1$ Mbit/s), a 360° camera ($R = 100$ Mbit/s) or a combination of multiple video streams from a 360° camera, multiple lenses and other sensors ($R = 1$ Gbit/s). The throughput and the latency are measured at the PDCP layer at the IC station, and obtained as the average over multiple independent simulations. As shown in Fig. 5a, all the combinations considered manage to reach the 1 Mbit/s throughput, but as R increases, a larger number of antennas is needed. In particular, for $R = 1$ Gbit/s, only the 64×16 and 256×16 configurations reach a throughput comparable to the source rate R. Moreover, a larger number of antennas results in lower latency, because the higher the SNR the smaller the probability of having a transmission error which triggers retransmissions.

Finally, Figs. 6a and 6b compare the average throughput and latency for the two different beamforming strategies previously introduced, i.e., the Long-term Covariance Matrix method and the Beam Search method [63], with different antenna configurations and $R = 1$ Gbit/s. It can be seen that the throughput and latency that can be achieved with both strategies are comparable, with a gain of the Long-Term Covariance Matrix method only for the 16×4 configuration. The method based on the long-term covariance matrix is in general able to reach a slightly higher SNR, but this gain has an impact only on the 16×4 configuration, which yields the smallest beamforming gain, and thus the smallest SNR, and benefits the most from this small SNR gain.

TABLE 3. **The four research components of our end-to-end research platform.**

Research component	Motivation & Challenges	Contribution
Dynamic channel sounding	PSC systems will experience peer-to-peer, as well as aerial and vehicular links not seen in cellular / WiFi systems. High dynamics due to blockage and mobility are not fully understood.	Phased-array spatial, dynamic channel sounder; configurable, motorized blocking environment testbed; orientation and reflection channel sounding for UAVs.
Software-defined radio	PSC systems require ultra-reliable communications and ultra-low latency not achievable in current mmWave prototyping platforms. New synchronization algorithms are required for fast peer-to-peer networks and relaying.	Modifications of the mmWave SDR for ultra-fast MAC-PHY interface; design and implementation of fast synchronization algorithms.
Channel emulation	Complex scenarios and channels in PSC are difficult to reproduce in conventional over-the-air testing. Current channel emulation tools do not scale to the bandwidths and number of antennas expected at mmWave.	FPGA-based baseband channel emulation where complex, dynamic channels and high-dimensional antenna systems can be emulated at low-cost with high flexibility.
End-to-end network simulation	Current mmWave network simulation does not scale to the large, highly mobile PSC networks. PSC scenarios are not fully developed and integrated in conventional simulators.	Ultra-fast low-rank channel simulation. Migration of the ns3 system to cluster computers. Development and integration of PSC specific scenarios in collaboration with Austin Fire Department.

Overall, we can conclude that mmWave can offer a strong potential for remote communication in a key real-life use case. However, our study illustrates two key challenges: the need for accurate beamforming to an aerial vehicle, and the effect of transport control mechanisms and rate adaptation to properly adjust to the variability in rate.

V. RESEARCH PLATFORM FOR mmWAVE PSC

Due to the lack of accurate channel models, we made some simplifying assumptions in the above performance assessment, relatively to the mmWave propagation in aerial links, the mobility of the UAV, and the beam tracking mechanisms. However, to better assess the feasibility of mmWave for PSC, and to ultimately develop such technologies, the community will require new R&D tools.

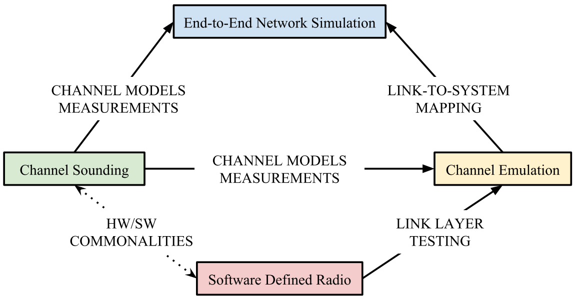


FIGURE 7. **Research platform components and their interdependencies.**

To fill this gap we advocate the need for an open-source research platform that, combining prototyping and simulation tools, can effectively accelerate the design, evaluation and adoption of PSC in the mmWave bands. According to our vision, such a platform can be realized by pursuing four main components, as described in Table 3 and depicted in Fig. 7. The *first* is a channel sounding platform to be used to perform dynamic channel measurements for each public safety scenarios. The results of this effort will make it possible to build realistic propagation models that can then be used to develop accurate simulation modules. The *second* is a new SDR platform to test low-latency and multi-hop services required for PSC, and will provide link-layer measurements that, together with the channel measurements, can drive the design of the channel emulator, which is the *third* component. Both the channel models and link-layer performance can then be integrated into the end-to-end network simulator, which represents the *fourth* component of our research platform.

In the following, we describe in greater detail which instruments are already available in our labs and how we plan to improve, extend and combine such tools to substantiate these research components.

A. DYNAMIC CHANNEL SOUNDING

Understanding channel dynamics is essential for mmWave mobile design [6], [67]. Initial studies in this area [67]–[69] have captured and analyzed real-time traces of the mmWave channel in blocking situations. The article [70] describes a more advanced channel sounder that has the ability to measure wide band mmWave channels for both transient deep fades as well as longer paths (several hundred meters) for spatial and angular data. However, these measurements are made in a single direction with a fixed horn antenna. Critical to understanding dynamics in mmWave channels, particularly for high-mobility PSC scenarios, is to measure the channel in multiple directions simultaneously.

To address this need, one possibility is to use a steerable phased array system. A prototype system under development is shown in Fig. 8(a). The tool in the figure was developed in collaboration with National Instruments and SiBeam [71] and includes a 60 GHz phased array with 12 steerable elements over a 45 degree steerable beam-width. The system is mounted on a mechanically rotatable steerable gimbal for additional orientation control and is connected to a powerful LabVIEW-based baseband processing system, as shown in Fig. 8(b). The tool makes it possible to rapidly scan the channel over multiple TX-RX direction pairs, completing a 12 × 12 directional scan in under 1 ms. Data analysis, shown in Fig. 8(c), extracts directions along multiple distinct spatial clusters. Collecting data over ensembles of such measurements can then yield the first channel models that examine the dynamics of these mmWave links.

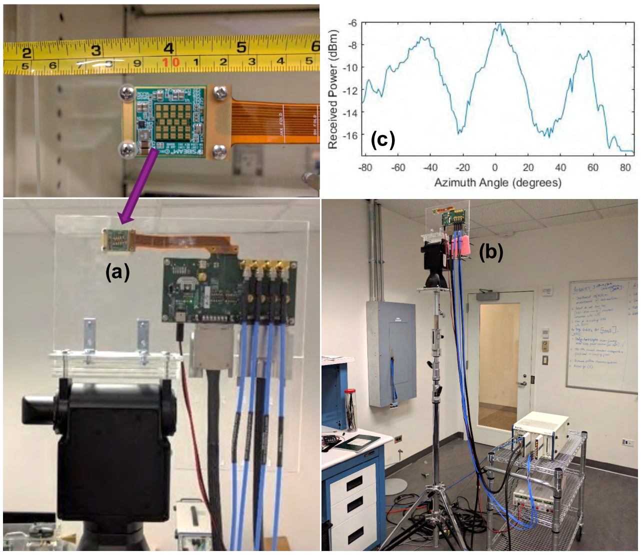


FIGURE 8. **(a) 60 GHz SiBeam Phased Array with 12 steerable antenna elements and 45 degree steerable range. (b) The phased array is mounted on steerable gimbal to simulate orientation motion and is connected to a high-performance baseband processing system for channel sounding and SDR; (c) Transmit radiation pattern of a vector.**

This tool makes it possible to carry out repeated scans during a simple human blocking events. Furthermore, to simulate complex blocking environments in PSC scenarios, we plan to add motorized tracks that move objects within the environment in a repeatable manner. The transmitter and receiver are also mounted on motorized gimbals to simulate orientation motion. Such a tool will then allow a complete characterization of blocking events, thus providing insight on the link behavior in a dynamic environment and on the blockage effects of different materials.

In principle, this equipment may also be used to collect measurements for UAV connections. A challenge in developing these models is that the channel sounding equipment may exceed the payload limits to mount in drones. A possible solution is to conduct terrestrial measurements for blocking and diffraction, to account for the ground effects, and then combine such measurements with well-understood free space transmission models [8]. To improve the accuracy of the model, it is possible to obtain gyroscopic measurements from the drones and then simulate the UAV rotations with the steerable gimbal system described above.

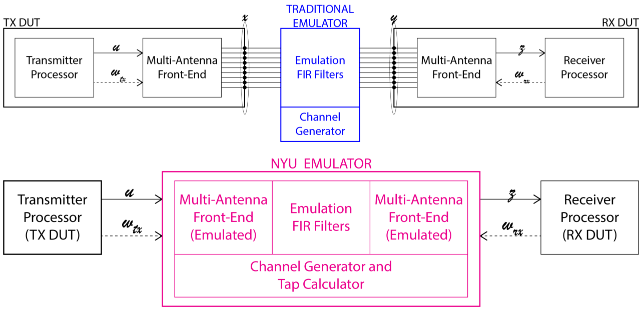


FIGURE 9. **Top: Traditional emulation paradigm where the DUTs interface with the emulator over RF. This emulation paradigm is unsuitable for systems with a large number of antennas. Bottom: Proposed emulation paradigm where the DUTs interface with the emulator at baseband, enabling support of large numbers of elements.**

B. SOFTWARE DEFINED RADIO

Developing SDR platforms for mmWave is daunting due to the need to support advanced phased array front-ends and very high data rate, low latency links. The hardware used in the phased-array channel sounding system can also provide a powerful software-defined radio (SDR) system for prototyping and experimentation of mmWave PSC systems. The phased arrays interface with a powerful baseband system based on the National Instruments PXI platform. In its current configuration this system has 3 Xilinx Kintex-7 FPGA modules at both the transmitter and receiver, as well as I/O modules to send control signals and I/Q baseband signals to the arrays. The transmitter and receiver respectively have a DAC and ADC operating at 1.25 GS/s. Altogether, the system provides enormous computational power.

The phased array platform can be used to implement directional search algorithms for mmWave PSC scenarios and study the initial access and directional synchronization problems, which will be further complicated in PSC systems due to the rapid dynamics and the need to discover peer-to-peer links in mesh topologies. Effort has to be dedicated to the design of an FPGA-based MAC (and RLC) layer with hardware accelerators (soft-cores like ARM, Microblaze, etc.) stitched into the FPGA fabric, in order to speed up the communication between physical and application layers in PSC devices.

C. CHANNEL EMULATION

One method of designing and testing protocols at various layers of the stack involves over-the-air (OTA) experimentation under different wireless scenarios. Unfortunately, OTA testing is extremely time-consuming, expensive, and difficult to reproduce in a controlled manner. Thus, almost all lab development today uses *channel emulation* as illustrated in the top panel of Fig. 9. The transmitter (TX) and receiver (RX) devices under test (DUTs) are physically connected to a channel emulator which is a box that simulates a configurable wireless channel between the two devices. The wireless channel is generally described via a multipath fading profile which

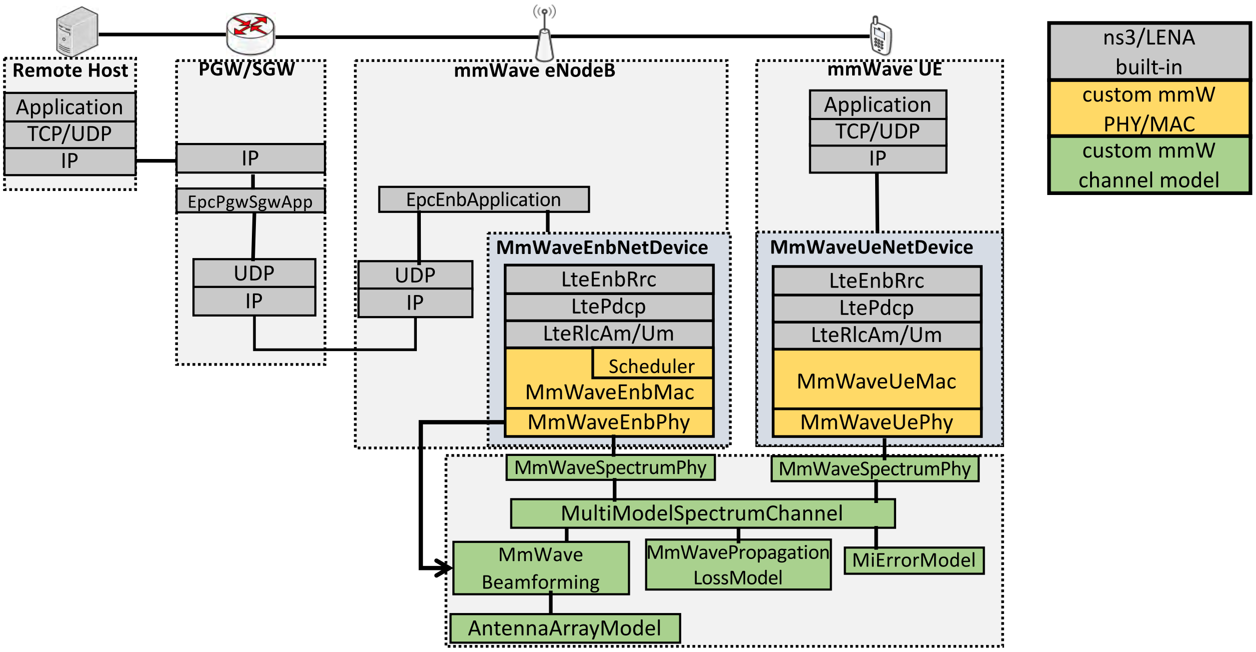


FIGURE 10. **Class diagram for the end-to-end mmWave module. Taken from [61] with permission granted from the authors.**

can be configured to reproduce measured traces or standard profiles such as in the 3GPP models [72]. Channel emulators such as [73] are widely used for LTE development, and are indeed a staple in any Radio Frequency (RF) lab.

A key challenge with traditional emulation for mmWave scenarios is the need to support high-dimensional phased arrays. As described in the Introduction, mmWave devices will likely have large numbers of elements to achieve high-gain directional beams. For example, the Qualcomm 28 GHz array in [74] has 128 elements, while traditional cellular systems today typically have only 1-2 antennas at the UE side and 8 or less at the BS side. Moreover, PSC scenarios may use even higher dimensional arrays for large antenna systems at the command center, and can experience much more complex channels.

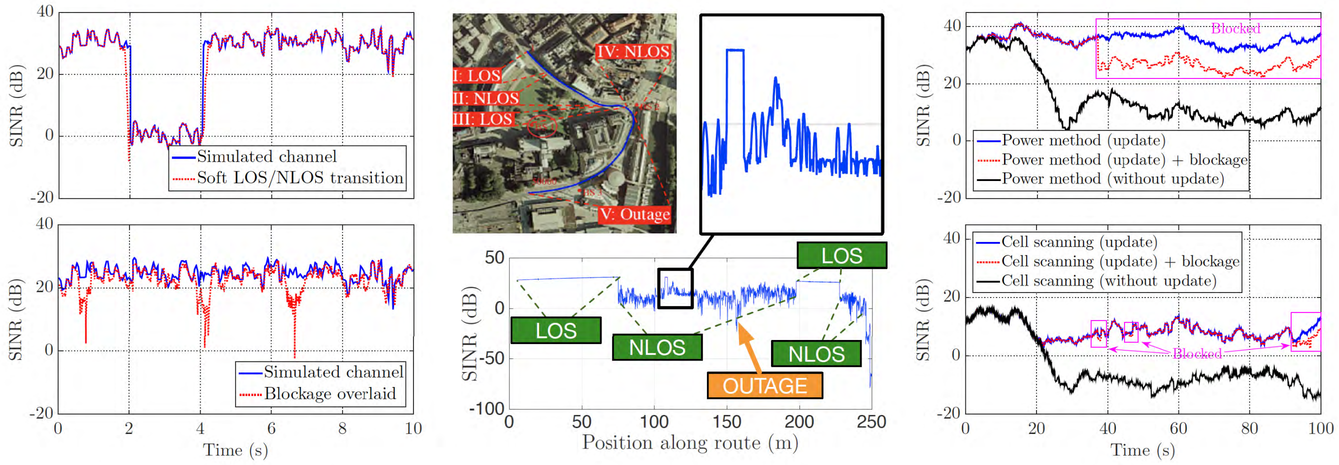
The problem with supporting such high-dimensional arrays can be seen in Fig. 9. Both the TX and RX DUTs will have two main parts: a) the baseband processor, and b) the RF front-end. The TX baseband processor generates the signal u_k, where k is time. This baseband signal is up-converted to RF and a beamforming vector w_{tx} is applied, leading to the signal x_k that is sent from its N_{tx} antenna ports. Symmetrically, the RX device receives the signal y_k from its N_{rx} antenna ports and applies the beamforming vector w_{rx} to it to generate the received baseband signal z_k. The channel emulator is responsible for transforming the signal from x_k to y_k, which represents the wireless channel. The main problems with supporting large N_{rx} and N_{tx} in the conventional design are: a) the computational requirements become prohibitive, given that the complexity of the emulator is $O(N_{tx}N_{rx})$; b) the hardware cost also becomes prohibitive, given that the emulator will need an order of magnitude more DACs, ADCs, up/down-converters, as well as two orders of magnitude more multipliers; and c) physically connecting the DUTs to the emulator itself becomes very challenging. Already, emulators with 8 ports are prohibitively expensive and supporting devices in the mmWave range would be impossible.

The core idea is to build a low-cost emulation tool by taking the input from the *baseband* as illustrated in the bottom panel of Fig. 9. The emulator emulates not only the wireless channel, but the RF front-ends at the two end-points as well. Given that the emulator knows the wireless channel as well as the instantaneous beamforming vectors, it calculates the effective baseband SISO channel that can be used to transform the input baseband signal u_k directly to the output baseband signal z_k. The advantages of this approach are: a) it de-couples the design of the baseband algorithms from the design of the RF front-end, leading to faster iterations of system design and testing; b) significantly lower computational complexity to O(1), irrespective of the number of antennas in the emulated front-ends; c) lower hardware costs; d) suitable for implementation over generic SDR components (such as FPGAs) that we already have in our labs.

D. END-TO-END NETWORK SIMULATION

The tools in the previous subsections have focused on the link-layer characteristics of mmWave PSC systems, notably channel dynamics, propagation and PHY-MAC design. However, in order to fully test a PSC scenario, it is necessary to develop a tool that makes it possible to study the effect of the mmWave links on the higher layer protocols, and to evaluate the quality of experience perceived at the application layer.

Discrete-event network simulators have, for long, been one of the most powerful tools available to researchers for developing new protocols and simulating complex networks.



(a) (b) (c)

FIGURE 11. **(a) Statistical channel model overlaid with real blockage measurements; (b) Real measurements overlaid with ray-tracing [36]; (c) 3GPP channel model and performance of different beamforming strategies [61]. ©[2016] IEEE. Reprinted, with permission, from [36].**

The ns–3 network simulator [75] currently implements a wide range of protocols in C++, making it particularly useful for cross-layer design and analysis. The first open-source ns–3 millimeter wave module, that can be used to evaluate the cross-layer and end-to-end performance of 5G mmWave networks, has been recently developed in [37] and [60]. This ns–3 module, whose simplified class diagram is shown in Fig. 10, already has many powerful features for simulating complex networks. For example, the PHY and MAC classes are parameterized and highly customizable in order to be flexible enough for testing different designs, like the OFDM numerology and the beamforming architecture, without major modifications to the source code, as detailed in [37] and [60]. Devices can simultaneously connect to both 4G LTE and 5G mmWave cells [76], [77], allowing the test of protocol harmonization across different Radio Access Technologies, at multiple layers, and to compare different smart handover strategies, as reported in [40]. Given the modular nature of the simulator, new channel models can be easily integrated. In [61], as illustrated in Fig. 11, we describe both the statistical (based on NYUSIM [78]) and trace-driven models that are currently available. In particular, in a recent paper [63] we provide a detailed explanation of the 3GPP channel models for frequency spectrum above 6 GHz using the most recent 3GPP specification [79]. The full stack end-to-end implementation allowed us to conduct the first Transport Layer Protocol (TCP) performance evaluation over mmWave bands [36], [39], and to integrate some novel networking strategies to better utilize the available spectrum [38].

Nonetheless, the module does not capture some of the critical aspects of interest in the PSC context. It is therefore necessary to extend the simulation platform, in order to address the needs of mmWave PSC networks. Our future research, hence, aims at improving the ns–3 platform on the following aspects.

1) SCALABILITY

The most significant challenge when using the ns–3 simulator for PSC networks is *scalability*. PSC networks will likely comprise a large number of nodes with high mobility, and thus channel states must be updated frequently. In addition, the use of low-latency applications in PSC systems requires that packet timelines must be scheduled at very fast interaction times. One approach to address this challenge can consist in a novel low-rank statistical channel modeling. In current 3GPP channel models such as [72] and [79], each channel is modeled via spatial clusters, which involves simulating the dynamics over a large number of paths, e.g., 20 clusters of 20 subpaths each for NLOS urban macro topologies, which is impractical in high-mobility scenarios. Instead, we propose a fast low-rank simulation method to greatly simplify the channel evolution. Suppose the TX and RX scan over N_{rx} and N_{tx} discrete directions. Thus, we can directly model $N_{rx}N_{tx}$ channel states. In general, this will have a low-rank structure over time due to the spatial sparsity of the channel. Indeed, our preliminary experiments in the phased array system have shown that even complex channel scenarios may only have 2 or 3 dominant paths. Therefore, the statistical modeling of the channel data collected with the studies described in Subsection V-A can be used to develop computationally simple low-rank models that approximate the end-to-end phased array system well. This approximation will offer high accuracy even in high mobility public safety use cases, while simplifying the channel state processing by at least an order of magnitude.

2) DISTRIBUTED COMPUTATION

Current multi-core ns–3 models have focused on custom Message Passing Interface (MPI) clusters which require extensive building and maintenance [80], [81]. This characteristic may limit the size of the scenarios that can be simulated by a single ns–3 instance. Further scaling, however, can be achieved by empowering the simulation platform with a distributed computation feature, in order to enable its deployment onto open-source large cluster platforms, such as Amazon Web Services (AWS) [82], which make it possible to increase the number of running instances of the simulator based on the size of the scenario to be studied. This objective should be achieved by maintaining as much as possible the backward compatibility, in order to guarantee the possibility of reusing the existing modules. While there is a rich literature on parallel and distributed simulations [83], [84], the performance gain of a parallel approach in the wireless domain largely depends on the specific network simulated, in terms of architecture, interconnections between nodes and protocols deployed. Indeed, the main factor that allows parallelization of wireless simulations in a conservative way is the lookahead time, i.e., the interval in which a processor can ignore the computations and the events of the other processors in a safe way before synchronizing again. For example, if the simulation domain is split into multiple loosely interacting clusters, then the lookahead time would be the propagation time of the links connecting the different clusters. The logic to define the clusters and interconnect them automatically so that there is an actual gain given by the parallelization is an open research issue. Another option is the optimistic parallel simulation approach, in which the different processors are allowed to proceed independently, and, if there is an inconsistency in time between the processors, the simulation events can be rolled back until the consistency is restored. While this approach is more general than those based on lookahead, its applicability to ns–3 is still limited and in its infancy [85].

3) PUBLIC SAFETY CHANNELS AND MESH NETWORKS INTEGRATION

To run realistic network performance evaluations of PSC over mmWave bands, the simulator should be able to use real channel traces (e.g., obtained with the channel sounder presented in Subsection V-A). Further, using the link-layer SDR and emulator developed in Subsections V-B and V-C, it may be possible to obtain realistic simulations based on a lightweight link abstraction model for key physical layer procedures such as beam tracking, synchronization, control signaling and code performance. Finally, a multi-hop/relaying feature can be introduced in our simulator to enable a feasibility study related to mmWave aerial mesh networks. In this case, the goal is to study the optimal way to provide robust connectivity to areas affected by fire or any other natural disaster.

VI. CONCLUSIONS

Every day, countless numbers of public safety personnel – firefighters, police, and medics – enter the most dangerous scenarios for the protection of the public. Communication technology is vital to their service. The mmWave bands offer the potential to provide a powerful communication system to assist these first responders in the trying and often dangerous settings they enter.

However, developing reliable PSC systems in the mmWave bands faces significant technical challenges. At root, the difficulties arise due to the fundamental nature of mmWave communication: the need to transmit directionally and to overcome blockages. While these issues are present in cellular systems under development today, they are likely to be much more pronounced in PSC scenarios due to the high mobility of vehicles, heterogenous nature of traffic, the need to support very low latency communication and the ad hoc and distributed network topology.

Nonetheless, the potential gains, for first responders and the public they serve, are significant. We have described one real-life example scenario in wildfire remote drone communication. Other use cases can exploit similar capabilities. To better understand these situations and to develop the communication technology, we have presented some possible methods that we can use to build a key research platform using tools available today. Building this research platform can ultimately bring mmWave PSC scenarios into study for the broader mmWave research community and in turn develop life-saving technology for emergency scenarios.

REFERENCES

[1] T. McElvaney. (2005). *5G: From a Public Safety Perspective*. [Online]. Available: http://www.atis.org/5g/presentations/5G_PublicSafety_TMcElvaney.pdf
[2] *3GPP Website*. Accessed: Nov. 7, 2017. [Online]. Available: http://www.3gpp.org/
[3] *Study on Scenarios and Requirements for Next Generation Access Technologies*, document TR 38.913, 3GPP, 2016.
[4] F. Khan and Z. Pi, “An introduction to millimeter-wave mobile broadband systems,” *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 101–107, Jun. 2011.
[5] T. S. Rappaport *et al.*, “Millimeter wave mobile communications for 5G cellular: It will work!” *IEEE Access*, vol. 1, pp. 335–349, May 2013.
[6] S. Rangan, T. S. Rappaport, and E. Erkip, “Millimeter-wave cellular wireless networks: Potentials and challenges,” *Proc. IEEE*, vol. 102, no. 3, pp. 366–385, Mar. 2014.
[7] F. Boccardi, R. W. Heath, Jr., A. Lozano, T. L. Marzetta, and P. Popovski, “Five disruptive technology directions for 5G,” *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 74–80, Feb. 2014.
[8] T. S. Rappaport, R. W. Heath Jr, R. C. Daniels, and J. N. Murdock, *Millimeter Wave Wireless Communications*. London, U.K.: Pearson Ed., 2014.
[9] FCC. *FCC Promotes Higher Frequency Spectrum for Future Wireless Technology*. [Online]. Available: https://www.fcc.gov/document/fcc-promotes-higher-frequency-spectrum-future-wireless-technology-0
[10] NGMN Alliance. (Feb. 2015). *NGMN 5G White Paper*. [Online]. Available: https://www.ngmn.org/uploads/media/NGMN_5G_White_Paper_V1_0.pdf
[11] G. Baldini, S. Karanasios, D. Allen, and F. Vergari, “Survey of wireless communication technologies for public safety,” *IEEE Commun. Surveys Tuts.*, vol. 16, no. 2, pp. 619–641, 2nd Quart., 2014.
[12] S. Ghafoor, P. D. Sutton, C. J. Sreenan, and K. N. Brown, “Cognitive radio for disaster response networks: Survey, potential, and challenges,” *IEEE Wireless Commun.*, vol. 21, no. 5, pp. 70–80, Oct. 2014.
[13] A. Kumbhar, F. Koohifar, I. Güvenç, and B. Mueller, “A survey on legacy and emerging technologies for public safety communications,” *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 97–124, 1st Quart., 2017.
[14] 3GPP. *LTE Release 8*. Accesses: Nov. 7, 2017. [Online]. Available: http://www.3gpp.org/specifications/releases/72-release-8
[15] 3GPP. *LTE Release 12*. Accesses: Nov. 7, 2017. [Online]. Available: http://www.3gpp.org/specifications/releases/68-release-12

[16] *Proximity-Based Services (ProSe)*, document TS 23.303, 3GPP, 2016. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=840

[17] *Group Communication System Enablers for LTE (GCSE_LTE)*, document TS 22.468, 3GPP, 2016. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=647

[18] "Public safety statements of requirements for communications and interoperability," Dept. Homeland Secur., SAFECOM Program, 2006, vols. I–II, accessed: Nov. 7, 2017. [Online]. Available: https://www.hsdl.org/?view&did=236086 and https://www.hsdl.org/?view&did=16166

[19] Y. Saleem, M. H. Rehmani, and S. Zeadally, "Integration of cognitive radio technology with unmanned aerial vehicles: Issues, opportunities, and future research challenges," *J. Netw. Comput. Appl.*, vol. 50, pp. 15–31, Apr. 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1084804514002811

[20] A. Merwaday, A. Tuncer, A. Kumbhar, and I. Guvenc, "Improved throughput coverage in natural disasters: Unmanned aerial base stations for public-safety communications," *IEEE Veh. Technol. Mag.*, vol. 11, no. 4, pp. 53–60, Dec. 2016.

[21] W. Khawaja, I. Guvenc, and D. Matolak, "UWB channel sounding and modeling for UAV air-to-ground propagation channels," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2016, pp. 1–7.

[22] A. Ibrahim and I. Guvenc, "NSF NeTS: Small: Collaborative research: Towards millimeter wave communications for unmanned aerial vehicles," Nat. Sci. Found., Alexandria, VA, USA, Award no. 1618692, Jul. 2016.

[23] J. Chandler and R. W. Steagall, "DARPA'S mobile hotspot program drives E-band performance benchmarks," *Microw. J.*, vol. 5, no. 17, Oct. 2014.

[24] R. Sun and D. W. Matolak, "Air-ground channel characterization for unmanned aircraft systems: The mountainous environment," in *Proc. IEEE/AIAA 34th Digit. Avionics Syst. Conf. (DASC)*, Sep. 2015, pp. 1–31.

[25] D. W. Matolak and R. Sun, "Air-ground channel characterization for unmanned aircraft systems: The suburban and near-urban environments," *IEEE Trans. Veh. Technol.*, vol. 66, no. 8, pp. 6607–6618, Aug. 2017.

[26] D. W. Matolak and R. Sun, "Air-ground channel characterization for unmanned aircraft systems: The hilly suburban environment," in *Proc. IEEE 80th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2014, pp. 1–5.

[27] D. W. Matolak and R. Sun, "Air-ground channel characterization for unmanned aircraft systems: The over-freshwater setting," in *Proc. Integr. Commun., Navigat. Surveill. Conf. (ICNS)*, Apr. 2014, pp. K1-1–K1-9.

[28] W. Khawaja, O. Ozdemir, and I. Guvenc. (Jul. 2017). "UAV air-to-ground channel characterization for mmWave systems." [Online]. Available: https://arxiv.org/abs/1707.04621

[29] M. Giordani, A. Zanella, and M. Zorzi, "Millimeter wave communication in vehicular networks: Challenges and opportunities," in *Proc. 6th Int. Conf. Modern Circuits Syst. Technol. (MOCAST)*, May 2017, pp. 1–6.

[30] A. Osseiran *et al.*, "Scenarios for 5G mobile and wireless communications: The vision of the METIS project," *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 26–35, May 2014.

[31] S. Dutta, M. Mezzavilla, R. Ford, M. Zhang, S. Rangan, and M. Zorzi, "Frame structure design and analysis for millimeter wave cellular systems," *IEEE Trans. Wireless Commun.*, vol. 16, no. 3, pp. 1508–1522, Mar. 2017.

[32] R. Ford, M. Zhang, M. Mezzavilla, S. Dutta, S. Rangan, and M. Zorzi, "Achieving ultra-low latency in 5G millimeter wave cellular networks," *IEEE Commun. Mag.*, vol. 55, no. 3, pp. 196–203, Mar. 2017.

[33] T. Levanen, J. Pirskanen, and M. Valkama, "Radio interface design for ultra-low latency millimeter-wave communications in 5G era," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2014, pp. 1420–1426.

[34] D. Malan, T. Fulford-Jones, M. Welsh, and S. Moulton, "Codeblue: An ad hoc sensor network infrastructure for emergency medical care," in *Proc. Int. Workshop Wearable Implant. Body Sensor Netw.*. Boston, MA, USA, 2004.

[35] D. G. Reina, M. Askalani, S. L. Toral, F. Barrero, E. Asimakopoulou, and N. Bessis, "A survey on multihop ad hoc networks for disaster response scenarios," *Int. J. Distrib. Sensor Netw.*, vol. 11, no. 10, Jan. 2015.

[36] M. Zhang *et al.*, "Transport layer performance in 5G mmWave cellular," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPS)*, Apr. 2016, pp. 730–735.

[37] R. Ford, M. Zhang, S. Dutta, M. Mezzavilla, S. Rangan, and M. Zorzi, "A framework for end-to-end evaluation of 5G mmWave cellular networks in ns-3," in *Proc. Workshop ns-3*, 2016, pp. 85–92.

[38] M. Zhang, M. Mezzavilla, J. Zhu, S. Rangan, and S. S. Panwar. "The bufferbloat problem over intermittent multi-gbps mmwave links." [Online]. Available: https://arxiv.org/abs/1611.02117

[39] M. Polese, R. Jana, and M. Zorzi, "TCP in 5G mmWave networks: Link level retransmissions and MP-TCP," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPS)*, May 2017, pp. 343–348.

[40] M. Polese, M. Giordani, M. Mezzavilla, S. Rangan, and M. Zorzi, "Improved handover through dual connectivity in 5G mmWave mobile networks," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 9, pp. 2069–2084, Sep. 2017.

[41] M. Polese, M. Mezzavilla, S. Rangan, and M. Zorzi, "Mobility management for TCP in mmWave networks," in *Proc. 1st ACM Workshop Millimeter-Wave Netw. Sensing Syst. (mmNets)*, Oct. 2017, pp. 11–16. [Online]. Available: https://dl.acm.org/citation.cfm?id=3130243

[42] *Mission Critical Data Services Over LTE*, document TS 22.282, 3GPP, 2016. [Online]. Available: http://www.3gpp.org/ftp/specs/archive/22_series/22.282/

[43] Nokia, "Mission-critical communications networks for public safety—White Paper," Jul. 2017, accessed: Nov. 7, 2017. [Online]. Available: https://resources.ext.nokia.com/asset/170422

[44] C. N. Barati *et al.*, "Directional cell discovery in millimeter wave cellular networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 12, pp. 6664–6678, Dec. 2015.

[45] C. N. Barati *et al.*, "Initial access in millimeter wave cellular systems," *IEEE Trans. Wireless Commun.*, vol. 15, no. 12, pp. 7926–7940, Dec. 2016.

[46] M. Giordani, M. Mezzavilla, C. N. Barati, S. Rangan, and M. Zorzi, "Comparative analysis of initial access techniques in 5G mmWave cellular networks," in *Proc. Annu. Conf. Inf. Sci. Syst. (CISS)*, Mar. 2016, pp. 268–273.

[47] K. Allen *et al.*, "Building penetration loss measurements at 900 MHz, 11.4 GHz, 28.8 MHz," U.S. Dept. Commerce, Nat. Telecommun. Inform. Admin., Boulder, CO, USA, Tech. Rep. 94-306, 1994.

[48] C. R. Anderson and T. S. Rappaport, "In-building wideband partition loss measurements at 2.5 and 60 GHz," *IEEE Trans. Wireless Commun.*, vol. 3, no. 3, pp. 922–928, May 2004.

[49] A. Alejos, M. Sanchez, and I. Cuinas, "Measurement and analysis of propagation mechanisms at 40 GHz: Viability of site shielding forced by obstacles," *IEEE Trans. Veh. Technol.*, vol. 57, no. 6, pp. 3369–3380, Mar. 2008.

[50] H. Zhao *et al.*, "28 GHz millimeter wave cellular communication measurements for reflection and penetration loss in and around buildings in New York city," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2013, pp. 5163–5167.

[51] J. S. Lu, D. Steinbach, P. Cabrol, and P. Pietraski "Modeling human blockers in millimeter wave radio links," *ZTE Commun.*, vol. 10, pp. 23–28, Dec. 2012.

[52] V. Va, T. Shimizu, G. Bansal, and R. W. Heath Jr, "Millimeter wave vehicular communications: A survey," *Found. Trends Netw.*, vol. 10, no. 1, pp. 1–118, Jun. 2016. [Online]. Available: https://doi.org/10.1561/1300000054

[53] V. Desai, L. Krzymien, P. Sartori, W. Xiao, A. Soong, and A. Alkhateeb, "Initial beamforming for mmWave communications," in *Proc. 48th Asilomar Conf. Signals, Syst. Comput.*, Nov. 2014, pp. 1926–1930.

[54] C. Jeong, J. Park, and H. Yu, "Random access in millimeter-wave beamforming cellular networks: Issues and approaches," *IEEE Commun. Mag.*, vol. 53, no. 1, pp. 180–185, Jan. 2015.

[55] S. Ferrante, T. Deng, R. Pragada, and D. Cohen, "mmWave Initial Cell Search Analysis under UE Rotational Motion," in *2015 IEEE Int. Conf. Ubiquitous Wireless Broadband (ICUWB)*, Oct. 2015, pp. 1–7.

[56] Y. Li, J. G. Andrews, F. Baccelli, T. D. Novlan, and C. Zhang. (2016). "Design and analysis of initial access in millimeter wave cellular networks." [Online]. Available: https://arxiv.org/abs/1609.05582

[57] T. Wu, T. S. Rappaport, and C. M. Collins, "Safe for generations to come: Considerations of safety for millimeter waves in wireless communications," *IEEE Microw. Mag.*, vol. 16, no. 2, pp. 65–84, Mar. 2015.

[58] T. Wu, T. S. Rappaport, and C. M. Collins, "The human body and millimeter-wave wireless communication systems: Interactions and implications," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2015, pp. 2423–2429.

[59] *Austin Fire Department Homepage*. Accessed: Nov. 7, 2017. [Online]. Available: http://www.austintexas.gov/department/fire

[60] M. Mezzavilla, S. Dutta, M. Zhang, M. R. Akdeniz, and S. Rangan, "5G mmWave module for the ns-3 network simulator," in *Proc. 18th ACM Int. Conf. Modeling, Anal. Simulation Wireless Mobile Syst.*, 2015, pp. 283–290.

[61] M. Mezzavilla *et al.*, "End-to-end simulation of 5G mmWave networks," *IEEE Commun. Surveys Tuts.*, submitted for publication. [Online]. Available: https://arxiv.org/abs/1705.02882

[62] T. Camp, J. Boleng, and V. Davies, "A survey of mobility models for ad hoc network research," *Wireless Commun. Mobile Comput.*, vol. 2, no. 5, pp. 483–502, Sep. 2002.

[63] M. Zhang, M. Polese, M. Mezzavilla, S. Rangan, and M. Zorzi, "ns-3 implementation of the 3GPP MIMO channel model for frequency spectrum above 6 GHz," in *Proc. Workshop ns-3*, 2017, pp. 71–78.

[64] Cohere Technologies. *SS Block Composition, SS Burst Set Composition and SS Time Index Indication—3GPP Tdoc R1-1705459*. Accessed: Nov. 7, 2017. [Online]. Available: https://www.cohere-technologies.com/wp-content/uploads/2017/06/R1-1708313-PRACH-Design.pdf

[65] D. J. Love and R. W. Heath, "Equal gain transmission in multiple-input multiple-output wireless systems," *IEEE Trans. Commun.*, vol. 51, no. 7, pp. 1102–1110, Jul. 2003.

[66] *Telecommunications and Information Exchange Between Systems—Local and Metropolitan Area Networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 3: Enhancements for Very High Throughput in the 60 GHz Band*, ISO/IEC/IEEE International Standard for Information Technology, 2014. [Online]. Available: http://ieeexplore.ieee.org/document/6774849/

[67] P. A. Eliasi and S. Rangan, "Stochastic dynamic channel models for millimeter cellular systems," in *Proc. IEEE Comput. Adv. Multi-Sensor Adapt. Process. (CAMSAP)*, Dec. 2015, pp. 209–212.

[68] G. R. MacCartney, S. Deng, S. Sun, and T. S. Rappaport, "Millimeter-wave human blockage at 73 GHz with a simple double knife-edge diffraction model and extension for directional antennas," in *Proc. IEEE 84th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2016, pp. 1–6.

[69] M. Giordani, M. Mezzavilla, A. Dhananjay, S. Rangan, and M. Zorzi, "Channel dynamics and SNR tracking in millimeter wave cellular systems," in *Proc. Eur. Wireless*, May 2016, pp. 1–8.

[70] G. R. MacCartney and T. S. Rappaport, "A flexible millimeter-wave channel sounder with absolute timing," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 6, pp. 1402–1418, Jun. 2017.

[71] S. Rangan and T. Rappaport, "NSF NeTS: EAGER: Development of a millimeter wave software defined radio," Nat. Sci. Found., Alexandria, VA, USA, Award no. 1602173, 2016.

[72] *Further Advancements for E-UTRA Physical Layer Aspects (Release 9)*, document TR 36.814, 3GPP, 2010.

[73] Spirent. *Spirent SR5000 Channel Emulator*. Accessed: Nov. 7, 2017. [Online]. Available: https://www.spirent.com/Products/SR5500-Channel-Emulator

[74] R. Merritt, "Qualcomm tips 28 GHz 5G chip: Pre-standard modem set for U.S. Korea trials," *EE Times*, Oct. 2016, accessed: Nov. 7, 2017. [Online]. Available: https://www.eetimes.com/document.asp?doc_id=1330637

[75] *ns-3 Network Simulator*. Accessed: Nov. 7, 2017. [Online]. Available: http://www.nsnam.org

[76] M. Polese, "Performance comparison of dual connectivity and hard handover for LTE-5G tight integration in mmWave cellular networks," M.S. thesis, Dept. Inf. Eng., Univ. Padova, Padua, Italy, Jul. 2016. [Online]. Available: http://arxiv.org/abs/1607.04330

[77] M. Polese, M. Mezzavilla, and M. Zorzi, "Performance comparison of dual connectivity and hard handover for LTE-5G tight integration," in *Proc. 9th EAI Int. Conf. Simulation Tools Techn.*, 2016, pp. 118–123. [Online]. Available: http://dl.acm.org/citation.cfm?id=3021426.3021445

[78] T. S. Rappaport, S. Sun, and M. Shafi, "Investigation and comparison of 3GPP and NYUSIM channel models for 5G wireless communications," presented at the 84th Veh. Technol. Conf. (VTC-Fall), 2017. [Online]. Available: https://arxiv.org/abs/1707.00291

[79] *Study on Channel Model for Frequency Spectrum Above 6 GHz, V14.2.0*, document TR 38.900, 3GPP, 2017.

[80] J. Pelkey and G. Riley, "Distributed simulation with MPI in ns-3," in *Proc. 4th Int. ICST Conf. Simulation Tools Techn.*, 2011, pp. 410–414.

[81] *MPI for Distributed Simulation*. Accessed: Nov. 7, 2017. [Online]. Available: https://goo.gl/ilyH1o

[82] *AWS Storage Services Overview*. Accessed: Nov. 7, 2017. [Online]. Available: https://goo.gl/h2yJje

[83] R. Fujimoto, "Parallel and distributed simulation," in *Proc. Winter Simul. Conf.*, 2015, pp. 45–59.

[84] P. Peschlow, A. Voss, and P. Martini, "Good news for parallel wireless network simulations," in *Proc. 12th ACM Int. Conf. Modeling, Anal. Simulation Wireless Mobile Syst.*, 2009, pp. 134–142.

[85] E. Kim and G. Riley, "Automatic state saving and rollback in ns-3," in *Proc. ACM SIGSIM Conf. Principles Adv. Discrete Simulation*, 2017, pp. 263–266.

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