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Millimeter-Wave Testbed and Modeling in NeXt Generation URLLC Communications

Eurico Dias, Duarte Raposo, Homa Esfahanizadeh, Alejandro Cohen, Vipindev Adat Vasudevan, Tânia Ferreira, Miguel Luís, Susana Sargento, and Muriel Médard

***Abstract*—Modeling realistic millimeter-wave (mmWave) channels is crucial to the study of ultra-reliable communication in next-generation wireless networks. MmWave provides significant gains over sub-6GHz communication but has very stringent requirements on channel conditions, since slight variations in the channel may result in significant performance degradation of mmWave communication. In this work, we present an experimental mmWave testbed and the mathematical modeling of the channels using the measurements collected from an outdoor testbed that complies with IEEE 802.11ad. We show how the model fits the reality and demonstrate the impact of adaptive causal network coding in mmWave real and simulated networks.**

I. Introduction

Millimeter-wave (mmWave) technology is considered a key enabler for the development of 6G networks due to its ability to provide high bandwidth and low latency wireless communication, reducing costs of the densification on the Integrated and Access Backhaul (IAB), in smart living environments (e.g., smart cities and rural scenarios) [1]. However, mmWave technology also comes with its own set of challenges, such as limited range and a requirement for a clear Line-Of-Sight (LOS) between the transmitter and receiver. This LOS requirement can be challenging to achieve in urban environments, where buildings and other moving obstacles can block the signal. The significant degradation in the performance due to obstacles may require different solutions at different layers, like the advanced Forward Erasure Correction (FEC) schemes on the transport layer (i.e., using network coding [2], [3]); Artificial Intelligent (AI)-Assisted Software Defined Network (SDN) approaches (i.e., P4, In-Band monitoring) for self-organized network configuration; and more robust physical layer solutions, like faster Sector Level Sweep (SLS) searching algorithms. The theoretical modeling of the channel can support an easier validation of new algorithms, in all of these layers, however current studies only focus on indoor IEEE 802.11ad-compliant network that uses Commercial Off-the-Shelf (COTS) devices with limited coverage [4].

In this work, we present an outdoor testbed used within the Aveiro Tech City Living Lab (ATCLL) for studying and evaluating the performance of mmWave technology in the presence of obstacles, and how different modulation and coding schemes can compensate for the losses [5]. Setting up a testbed for mmWave studies can be challenging due to the high frequency and narrow beamwidth of mmWave signals. Furthermore, mmWave signals are more susceptible to interference from other sources, which can further complicate the testing process. We present a testbed set in a controlled environment and modeling of the mmWave communication at the transport layer using a cross-layer approach with Gilbert-Elliott (GE) model [6], [7]. In [8], we show the benefits of Sliding Window Network Coding for URLLC mmWave networks using the testbed and the GE model proposed herein.

E. Dias, T. Ferreira and S. Sargento are with the University of Aveiro and Instituto de Telecomunicações, Portugal (e-mail:eurico.omdias, tania.s.ferreira@av.it.pt, susana@ua.pt). D. Raposo is with Instituto de Telecomunicações, Aveiro, Portugal (e-mail:dmgraposo@av.it.pt). H. Esfahanizadeh, V. Adat Vasudevan and M. Médard are with EECS, MIT, Cambridge, MA 02139 USA (email: homaesf, vipindev, medard@mit.edu). A. Cohen is with ECE, Technion, Israel (e-mail: alecohen@technion.ac.il). M. Luís is with Instituto Superior de Engenharia de Lisboa and Instituto de Telecomunicações, Portugal (e-mail:nmal@av.it.pt).

II. Challenges of MmWave Technology

Radio links can be heavily impacted by changes in the wireless propagation channel over time, which can lead to a significant variation in the quality of the connection. This effect is especially noteworthy for technologies that operate within the mmWave spectrum, like IEEE 802.11ad, where higher frequencies make the connection more susceptible to blockage.

In order to lessen the adverse effects of obstacles, COTS devices using WiGig technology, such as the Cambridge Communication Systems (CCS) Metnet nodes, implement a dynamic selection of the parameters of modulation and error correction based on the instantaneous Signal-to-Noise Ratio (SNR) and error rate [9]. Specifically, these devices are capable of switching between four different modes of operation, each using specific modulation and FEC schemes. These modes are: a) Control PHY (Modulation and Coding Scheme - MCS 0); b) Single carrier (MCS 1-12) PHY; c) OFDM (MCS 13-24) PHY; and d) low-power SC (MCS 25-31) PHY. This range of options allows different performance requirements to be met, depending on the usage scenario, such as low-interference, low-complexity, or low-energy consumption. Moreover, the 802.11ad PHY standard uses Low-Density Parity-Check (LDPC) codes with four different rates (1/2, 5/8, 3/4, and 13/16), with a fixed codeword length of 672 bits [10]. Each modulation type combined with a specific code rate forms an MCS. For the rate identification, the manufacturers can adopt a maximum frame size of 2000 bytes, and the calculations are performed in the second layer. The experiments conducted in this work collect the blockage impact on the transport-layer with UDP, using the MCS that allows nodes to be connected (e.g., higher MCS like 9 could not maintain the link).

III. Experimental Study

This section presents the mmWave testbed in the ATCLL, characterizing the mmWave communication in terms of packet loss and Round Trip Time (RTT), and how the channel profile is recorded.

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A. Experimental Outdoor mmWave Setup

The testbed for the mmWave network was deployed on the rooftop of Instituto de Telecomunicações, in Aveiro (Portugal) and consists of three CCS Metnet nodes [1]. The Personal basic service set Control Point (PCP) node is linked to the core network through ethernet while the two remote nodes are connected to the network through radio links via the PCP node. Each node is equipped with a single board unit (APU) that communicates via the mmWave network. To establish a wireless 5G meshed backhaul, each node in the ATCLL mmWave network testbed uses the standardized IEEE 802.11ad (WiGig) technology, which operates between the 57GHz to 66GHz unlicensed frequencies. Each device is equipped with four radio modules, each with a 19 dBi steerable antenna, capable of creating directional links. The WiGig standard supports beamforming training with a 5º horizontal beamwidth, which continuously searches for the most suitable transmit and receive antenna sectors between a given pair of stations.

During the experiment, a metallic obstacle was positioned between two Stations (STAs) to replicate the blockage scenario depicted in Fig.2. The obstacle remained in a fixed location for the entire 25-minute test duration, with each Modulation Coding Scheme (MCS) mode tested for 5 minutes. As soon as the obstruction was introduced, there was a significant drop in the instantaneous Received Signal Strength Indicator (RSSI) and SNR compared to the average values recorded during unobstructed operation (see [11] to check the instantaneous drop). Fig. 1 presents the SNR and packet loss under obstruction during 5 minutes.

B. Data Collection: Recording the mmWave Channel Profile

The dataset used to describe the behavior of the mmWave channel, *i.e.*, the RTT and the packet loss event at each time slot, was gathered using a mmWave setup shown in Fig. 2. The setup employed UDP traffic generation, with the RTT and packet status (erased or not) being collected simultaneously using the Two-Way Active Measurement Protocol (TWAMP) tool. This tool conforms to the standard defined in RFC 5357 [12], enabling two-way or round-trip measurements. In this particular case, one of the Linux APU nodes acted as the sender, while the other served as a reflector. The TWAMP tool was used as a server on the reflector APU throughout the data set creation process.

The raw dataset[2] includes a 5-minute execution of the TWAMP tool for each MCS mode, namely MCS 3, 6 and Auto. The time slot duration is 450 μs, which was determined through trial and error as the maximum duration that allows data to be transmitted without packet loss due to processing limitations. The system clocks on the APUs were synchronized using the Network Time Protocol (NTP) after each periodic measurement process. To collect the necessary metrics to evaluate channel behavior, we extracted a sequence of tuples from the raw dataset, represented as (RTT, packet loss) per time slot. We refer to this sequence as a "channel profile" or CP, which will be used in our proposed emulator described in the next subsection. In total, we obtained one channel profile for each MCS mode in the set $auto, 3, 4, 5, 6$.

IV. Modeling Transport mmWave Channel

In this section, we investigate the packet loss sequence for the transport-layer mmWave channel, and demonstrate that it can be well-modeled with a Gilbert-Elliott (GE) channel with erasures [6], [7]. Obtaining the mathematical model for the channel enables to derive upper bounds on the in-order delivery delay of the mmWave communication schemes, which is very helpful in defining delay guarantees.

We take a closer look at the nature of errors observed in the testbed experiments in Section III. The point-to-point packet loss pattern observed in the transport layer mmWave channel has a bursty behaviour, resulting in a contiguous sequence of packets to be erased in the case of failure. The top panel of Fig. 3 shows a binary sequence that indicates whether or not a packet is lost at a time slot, for the MCS 5, according to the field data. The same bursty behaviour was observed across all the MCS modes. Such behavior was already shown in [13] and can be explained by the LOS characteristics of the mmWave. When the link is blocked, the connection between the two

[1]https://www.adtran.com

[2]https://github.com/nap-it/SNOB5GModelingData

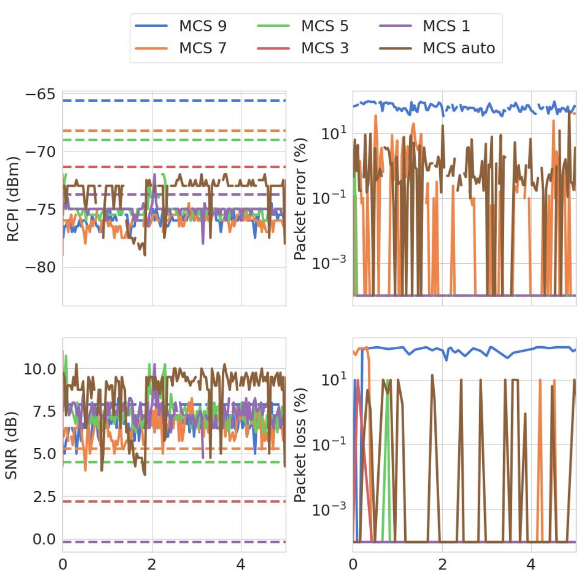

Fig. 1: Measurements for PHY and MAC layer under blockage, for a time interval of 5 minutes.

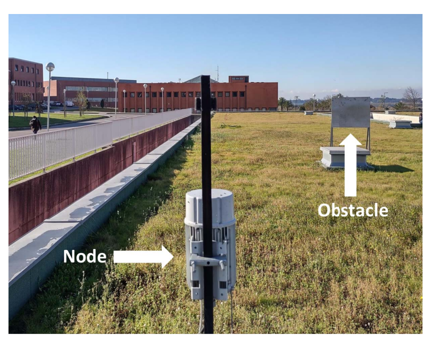

Fig. 2: Blockage scenario with the metal obstacle.

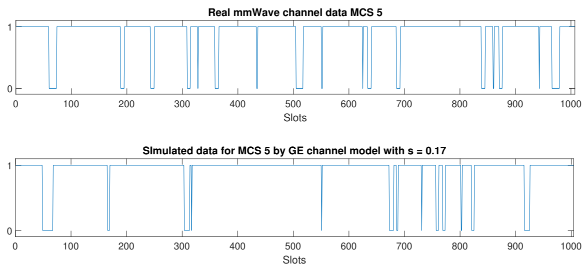

Fig. 3: The sequence of packet loss realizations for MCS mode 5: (top) recorded data from the testbed, (bottom) recorded data from the GE simulator and $s = 0.17$.

stations is lost, and the Sector Level Sweep (SLS) mechanism searches for a new pair of sectors capable to restore the link. The search time depends not only on the interference nature, but also on the size of the array of antennas, which could exceed the timeout.

Therefore, we model the point-to-point mmWave channel, observed from the transport layer, as a GE channel with erasures. The channel model is a Markov process with two states, i.e., good and bad. In the good state, the erasure probability is zero, and in the bad state, the erasure probability is one. We denote with s and q, the transition probabilities from good state to bad state, and from the bad state to good state, respectively. The stationary distribution of the GE channel is given by $\pi_G = s/(s+q)$ and $\pi_B = 1 - \pi_G$. The average erasure rate is $\epsilon_{\text{mean}} = \pi_B$, and $1/s$ is the average erasure burst. By computing the average erasure rate and the average erasure burst, from the data we collected in our experiments for MCS 5, we set $s = 0.17$ and $\epsilon = 0.1$. Hence, the transition probability from the bad state to good state is given by $q = s\pi_B/\pi_G = 0.019$. The bottom panel of Fig. 3 illustrates the packet loss sequence, for the MCS 5 mode, according to the GE channel model.

We then use the adaptive causal network coding solution given in [2] over real mmWave channel and simulated mmWave GE channel with the aforementioned parameters and RTT $= 16$. Fig. 4 shows the empirical CDF of the in-order delivery delay for the two sets of data. As we observe, there is a good agreement between the empirical distribution of delays, based on the simulator and the real-field mmWave data, which validates that the GE channel is the appropriate model to approximate the bursty mmWave channel we observed from the transport layer. The theoretical curve with dashed line shows the CDF for the type 1 extreme value distribution with location and scale parameters equivalent to the empirical mean and standard deviation of delays. It is used to model the distribution of the maximum of a number of samples.

V. Conclusion and Future Work

This paper showed how a Gilbert-Elliott channel with erasures is able to accurately emulate a real mmWave network with adaptive causal network coding. Future work will address the research of new algorithms to maximize the performance of mmWave networks towards URLLC communications.

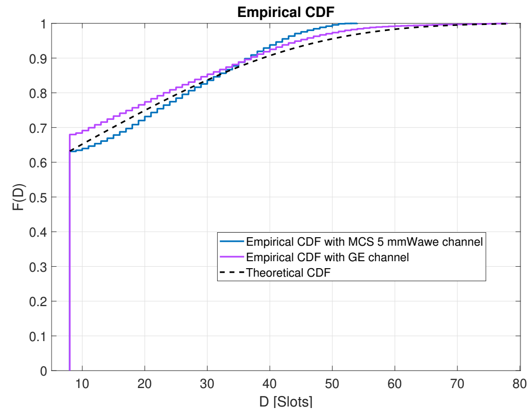

Fig. 4: Empirical CDF of the in-order delivery delay.

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