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# Evolution of Physical-Layer Communications Research in the Post-5G Era

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**ABSTRACT** The evolving fifth generation new radio cellular standardization efforts at the third generation partnership project brings into focus a number of questions on relevant research problems in physical-layer communications for study by both academia and industry. To address this question, we show that the peak download data rates for both WiFi and cellular systems have been scaling *exponentially* with time over the last 25 years. While keeping up with the historic cellular trends will be possible in the near-term with a modest bandwidth and hardware complexity expansion, even a reasonable stretching of this road-map into the far future would require significant bandwidth accretion, perhaps possible at the millimeter wave, sub-millimeter wave, or terahertz regimes. The consequent increase in focus on systems at higher carrier frequencies necessitates a paradigm shift from the reuse of over-simplified (yet mathematically elegant) models, often inherited from sub-6 GHz systems to a more holistic view, where real measurements guide, motivate, and refine the building of relevant but possibly complicated models, solution space(s), and good solutions. To motivate the need for this shift, we illustrate how the traditional abstraction fails to correctly estimate the delay spread of millimeter wave wireless channels and hand blockage losses at higher carrier frequencies. We conclude this paper with a broad set of implications for future research prospects at the physical-layer, including key use-cases, possible research policy initiatives, and structural changes needed in telecommunications departments at universities.

**INDEX TERMS** 5G, 5G new radio (5G-NR), 5G-evolution, post-5G, 6G, communications theory, physical-layer research, science and technology policy.

## I. INTRODUCTION

With growing demands on data rates, reduced end-to-end latencies, and connectivity across a diversity of new applications such as the industrial Internet of Things (IIoT), automotive, massive machine-type communications (mMTC), etc., the Fifth Generation New Radio (5G-NR) standard specifications for wireless systems build on prior standard releases and try to address these complex design objectives seamlessly. The Release 15 specifications for non-standalone and standalone deployments have been completed and approved in December 2017 and June 2018, respectively, with continued evolution expected over the next few months and years. Given this state of wireless evolution, the scope for follow-up work in terms of future releases and enhancements, and more specifically, broader questions on relevant physical-layer research problems for study by both academia and industry become pertinent. Such questions are important and existential, and have been repeatedly asked in the coding theory [1], information theory [2], digital signal processing [3] and communications theory [4] communities over many decades.

To address this question in the context of 5G-NR, we first study the historical evolution of WiFi and cellular modems' capabilities in terms of peak download data rates and spectral efficiencies. We show that the peak data rates have been consistently growing *exponentially* over the last twenty five years for both systems, with cellular on the brink of catching up with WiFi very soon. More importantly, the projection of these growth rates into the near-term (next five years) can be met with a modest increase in bandwidth acquisition and signal processing complexity of the modem. On the other hand, a meaningful stretching of this road-map into the far future (next ten years) would require significant bandwidth accretion at higher carrier frequencies (than currently commercially available), commensurate signal processing complexity scaling, and further network densification allowing the use of higher-order modulation and coding schemes. While the business use-cases for such increased peak data rates in future modems are unclear as of now, applications such as pervasive health monitoring, advanced driver assistance systems (ADAS), cellular-WiFi coexistence, etc., appear to

be reasonable drivers for sustained rate increases and latency reductions.

From a physical-layer research perspective, the evolution of 5G-NR and WiFi systems into the millimeter wave regime signal a key transition point into the increased focus of communications systems at higher carrier frequencies. We show by the way of two simple examples (on delay spreads and hand blockage losses) that the traditional abstraction of using simplified modeling techniques, sometimes inherited from sub-6 GHz<sup>1</sup> systems, for *systems* studies at higher carrier frequencies is not sufficient. This is because simplified models often have no capability to emulate unknowns that remain unknown till a deeper systemic understanding of the impact of different components of the system on the concerned figures-of-merit.

Thus, these illustrative examples hint at a paradigm shift in the evolution of systems research with time. In particular, systems research has to incorporate far more of circuits and device level abstractions and capabilities in generating relevant models, the space of possible solutions, and in closing the feedback loop on the efficacy of the generated solutions for the intended original problem. Both science and technology policy as well as telecommunications departments need to evolve with these emerging trends in terms of the scope and shape of systems research.

## II. CELLULAR AND WIFI SYSTEM ROAD-MAPS

### A. HISTORIC TRENDS

We start with a brief glimpse into the WiFi and cellular systems' road-maps in terms of the  $\log^2$  of the peak download data rates and spectral efficiencies<sup>3</sup> over the past (approximate) twenty five years. In particular, the time-period of interest is from January 1997 through December 2020 (including future forecasts) over a period of 288 months.

For WiFi, we use open-source data from [5, Table 1] on peak data rates, maximum occupied bandwidths, and release dates (approximated to the month level) of different standard specifications. This data is also presented in the Appendix for the sake of self-containment of this work. For cellular systems, we use open-source data from Qualcomm (see Appendix) on the approximate commercial sampling dates at the month level of 23 different (in both stand-alone and integrated forms) cellular modems as well as their corresponding capabilities such as supported bandwidth, peak modulation scheme, number of antennas, and signal processing complexity [6]. For the signal processing complexity, we consider the number of spreading codes in a code-division multiple access (CDMA) system, or the number of anten-

<sup>1</sup>Recent 3GPP standardization work has extended the upper point of the frequency regime of interest in traditional systems from 6 GHz to 7.125 GHz. Thus, the above usage should be seen with the technical caveat of sub-7.125 GHz systems.

<sup>2</sup>All logarithms are to base  $e$  in this work.

<sup>3</sup>Spectral efficiency in bps/Hz is simplistically computed as the ratio of peak data rate and the maximum occupied bandwidth necessary to achieve this rate.

nas in a digital beamforming system such as Long Term Evolution (LTE), or the number of radio frequency (RF) chains in a hybrid beamforming system such as in 5G-NR. The modems studied in this work encompass Mobile Station Modem (MSM) 3000/3100 addressing the IS-95 (2G) specifications through the X50 modem addressing 5G-NR with intermediate stopping points in the CDMA2000 (2.5G), WCDMA (3G) and LTE (4G) families.

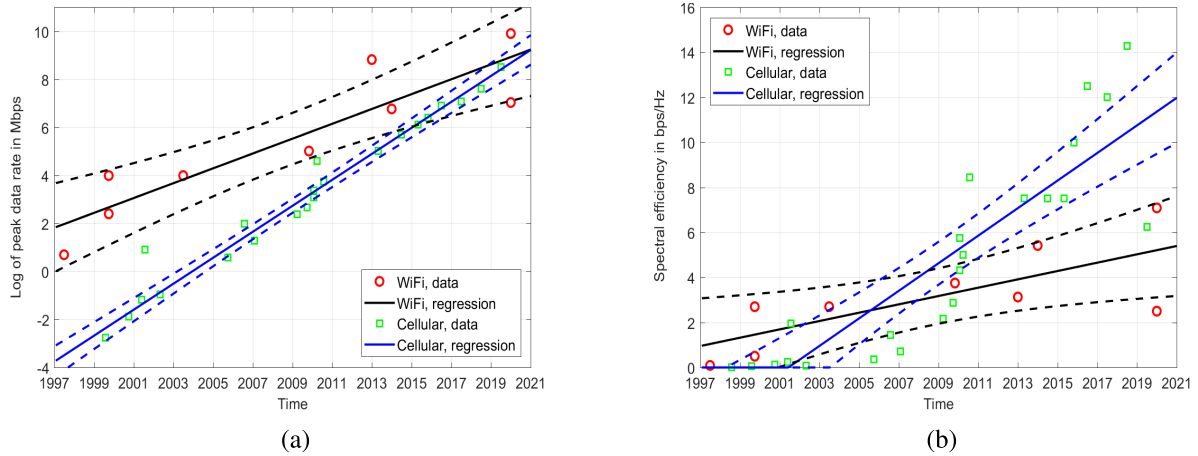
The raw data for WiFi and cellular systems lead to scatter plots of  $\log$  (Peak data rate in Mbps) or spectral efficiency, as illustrated in Fig. 1. For this data, linear regression models of the form

$$Y = \alpha_0 + \alpha_1 t + \varepsilon, \quad (1)$$

and a confidence interval around the regression fit are generated. The methodology behind the linear regression modeling (including confidence interval estimation) is described in [7, Ch. 2.4.2]. In (1),  $Y$  denotes the metric of interest,  $t$  denotes the month index, and  $\varepsilon$  denotes the random error term. The best linear regression fits are obtained for WiFi data (peak rates) with  $\alpha_0 = 1.816$  and  $\alpha_1 = 0.026$  corresponding to a standard deviation of error term of 3.60. Similarly, for cellular, we have  $\alpha_0 = -3.764$ ,  $\alpha_1 = 0.045$  with the standard deviation of error term being 3.09. Further, most of the data points (especially for cellular in the recent past) fall within the two-sided 95% confidence interval around the regression fits, as seen in Fig. 1. These observations suggest a reasonable fit with the regression model in (1) for the two sets of data.

From this study, we observe that the peak data rates have grown almost *exponentially* (with time) for both WiFi and cellular systems. In particular, the peak rates with WiFi and cellular systems have doubled over a time-period of  $\approx 26.9$  and  $\approx 15.4$  months, respectively. These observations suggest that both the WiFi and cellular industries have been successful in developing progressive road-maps with increasing capabilities for their respective modems over time. This relentless growth has been possible due to a number of enhancements over multiple generations of wireless standardization efforts such as:

- Increase in bandwidth of signaling transmissions corresponding to higher levels of carrier aggregation [6], as well as increasing bandwidth accretion by mobile network operators over time.
- Increase in the number of antennas and the number of RF chains/layers, corresponding to a commensurate increase in cost, complexity, power consumption and real-estate at the user equipment (UE) end [6].
- Densified network with smaller cell sizes and a higher frequency reuse factor [8], [9].
- Increase in total and effective isotropically radiated powers (TRPs and EIRPs).
- Better coding schemes that can achieve higher reliabilities with lower overheads [10] (or higher rates).
- More efficient coordinated transmissions and multiple access strategies that manage and mitigate interference, etc. [11].



**FIGURE 1.** Evolution of (a) the log of peak data rates and (b) the spectral efficiencies with WiFi and cellular systems, along with linear regression fits (solid lines) and 95% confidence intervals (dashed lines).

- Reduction in operational expenses via energy-efficient or green transmission schemes [12]–[16].

While such observations have been made in the past [17], this work presents evidence over a significantly longer time-frame and evolution across multiple generations of standardization efforts. From Table 2, a more careful compartmentalization of some of the specific factors leading to this exponential growth (with time) in cellular systems is provided in Fig. 2(a). From this plot, we note that a simple linear regression fits the evolution of the peak modulation scheme (with bits/symbol as the metric), log of the peak bandwidth (in MHz) and number of antennas (as a proxy for complexity) with time. Thus, the peak bandwidth appears to be the only exponentially scaling factor with time from the three factors studied here.

More interestingly, we also observe that while WiFi has dominated in peak rates for almost all the time, cellular systems have been catching up rather quickly. This trend is further clear from the spectral efficiency behavior in Fig. 1(b), where cellular has dominated WiFi for a long time. A number of explanations can be offered for these observations. As carrier aggregation efforts have speeded up in cellular systems along with coexistence in unlicensed bands, the main differentiator in performance has been in terms of the number of RF chains/layers and power levels. Since WiFi primarily targets indoor scenarios, the TRP/EIRP is limited to ensure regulatory compliance, which is compensated with wider bandwidths for higher rates, but resulting in poorer spectral efficiencies. Further, the lower cost factor associated with the WiFi modem (relative to the cellular modem) limits the hardware features/capabilities and peak rates, leading to the observed trends.

### B. FUTURE PROSPECTS FOR CELLULAR

We now consider the implications of these trends in terms of the future trajectory of cellular evolution. Projecting the historic trends over the next ten years, the peak data rates

should evolve as presented in the second column of Table 1 (see more details later) for certain key milestone points in time. Due to the exponential growth rate in the past, it is not surprising to see projections for peak data rates on the order of a few Tbps in 2030.

We assume a similar subframe structure for the air-link specifications as used in 5G-NR [18, Sec. 5.3] (namely, a  $15 \cdot 2^L$  kHz subcarrier spacing with  $L = 0, \dots, 5$  that is possibly expanded/extended to higher carrier frequencies), as illustrated in Fig. 2(b). With a modest 90% bandwidth occupancy, a simplistic calculation shows that the number of modulated symbols per second (denoted as  $N$ ) that is theoretically feasible with a bandwidth allocation of  $W$  Hz is given as

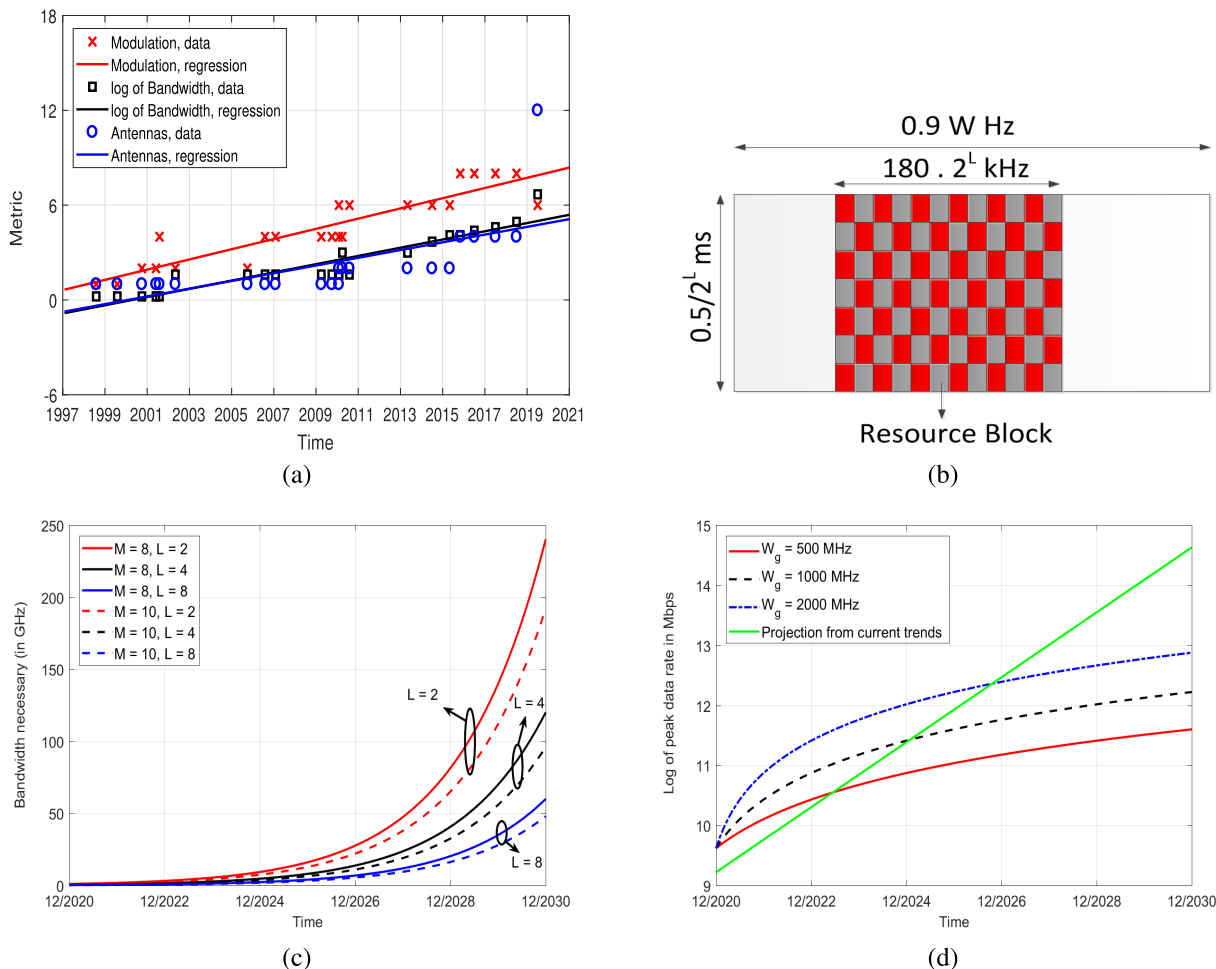
$$N = \frac{W \times 90\%}{\underbrace{12 \text{ subcarriers} \times 15 \cdot 2^L \cdot 10^3}_{\text{Number of resource blocks}}} \times \frac{12 \text{ subcarriers} \cdot 7 \text{ OFDM symbols}}{\underbrace{500 \text{ us}/2^L}_{\text{Resource elements per second}}} = 0.84 W. \tag{2}$$

The peak data rate (in Gbps) assuming an  $L$  layer transmission, a transmission efficiency<sup>4</sup> of  $\eta$ , and a  $2^M$ -ary modulation scheme is given as

$$\begin{aligned} \text{Peak rate (in Gbps)} \\ = N \cdot \eta \cdot L \cdot M \cdot 10^{-9} = 0.84 W \cdot \eta \cdot L \cdot M \cdot 10^{-9}. \end{aligned} \tag{3}$$

In particular, with a practical choice such as  $\eta = 70\%$  and different values for  $L$  (from 2 to 8) and  $M$  (from 8 for 256-QAM to 10 for 1024-QAM), the bandwidth  $W$  necessary

<sup>4</sup>Transmission efficiency is a simplistic metric to account for overheads such as control signaling, reference and synchronization signals, and coding. While more involved calculations as in LTE and/or 5G-NR can be performed, the simplistic calculations done here shall suffice to extract the main trends on cellular evolution.



**FIGURE 2.** (a) Evolution of key factors in the exponential data growth (along with linear regression fits) for the cellular modems in Table 2. (b) Typical subframe structure assumed for a mini-slot of 7 symbols in the post-5G air-link specifications, building on legacy models. (c) Bandwidth necessary to meet peak data rate demands in line with the current trends of cellular data rate evolution. (d) Log of the peak data rate growth with different amounts of average bandwidth accretion per year.

**TABLE 1.** Projected cellular data rate evolution according to current trends and bandwidth necessary to meet these rates.

Time	Peak data rates (in Gbps)	Bandwidth necessary ( $W$ in GHz)					
		256-QAM ( $M = 8$ )			1024-QAM ( $M = 10$ )		
		$L = 2$	$L = 4$	$L = 8$	$L = 2$	$L = 4$	$L = 8$
Dec. 2020	10.1	1.07	0.54	0.27	0.86	0.43	0.22
Dec. 2022	29.8	3.17	1.59	0.79	2.54	1.27	0.63
Dec. 2025	151.1	16.06	8.03	4.02	12.85	6.43	3.21
Dec. 2030	2259.9	240.22	120.11	60.05	192.17	96.09	48.04

to meet the projected peak data rates (at different points in time over the 2020-30 period) are presented in Fig. 2(c). This information is also presented in Table 1 for certain milestone points in time over this period. From this data, we observe that the near-term projections and demands (*ca.* 2023) can be met with a spectral efficiency improvement of the cellular modem. In particular, a small bandwidth expansion (from 800 MHz to 2 GHz), a hardware complexity expansion (from  $L = 2$  to  $L = 4$  RF chains), and a commensurate signal processing overhead increase are sufficient to meet these demands.

However, as we stretch out the road-map far into the future (*ca.* 2030), a substantial portion of the bandwidth necessary to meet these peak data rates (at least 45 GHz) is not realizable except at the millimeter wave, sub-millimeter wave and THz regimes. Further, such a rate scaling depends on licensing-related complexities across multiple disparate geographies to be resolved before the commercialization of these future modems. In a more realistic setting of an average year-on-year bandwidth accretion (denoted as  $W_g$ ) of 500 MHz, 1 GHz, or 2 GHz, Fig. 2(d) plots the achievable peak data rates relative to the current trends projected into the future.

This plot also reinforces the ability to meet near-term trends, but not the trends far into the future.

### C. POTENTIAL USE-CASES FOR FUTURE CELLULAR

The above studies showed that even partially meeting the historic trends on cellular data rate growth could only be possible with increased bandwidths of signaling transmissions. Such an increase would take us into higher carrier frequencies than those currently envisioned or used today (e.g., 15, 28, 39, 42, 57-71, or 73 GHz, etc.). Meeting these high data rate and low latency requirements can be extremely challenging, if not impossible, beyond certain key milestones at price points of commercial interest. Nevertheless, even reaching these milestones would require the design of robust, low-cost and energy-efficient hardware (antennas, RF front-ends, etc.) that work across multiple wide frequency bands and at higher carrier frequencies than possible commercially today.

While the necessity/use-cases for the sustained high peak data rates as projected above are unclear as yet, three possible applications are listed below.

- Applications on the cellular phone can coordinate with other devices/sensors and monitor human health near-constantly and non-invasively producing large amounts of data. Transmitting such data from the phone to other inferencing nodes in an *edge computing* framework could necessitate high data rate bursts as well as addressing security-related concerns [19], [20].
- Advanced driver assistance systems (ADAS) that help with cognitive distraction detection, collision avoidance and accident prevention, semi-autonomous driving, etc., are expected to be a cornerstone of post-5G systems as the cellular industry attempts to address the needs and demands of other horizontal industry segments. Such systems are expected to consist of a number of devices/sensors performing real-time monitoring tasks in highly dynamic environments. Coordinating such systems with other vehicles, processing/inferencing nodes on busy streets or downtown settings, or even other pedestrians via either the Cellular Vehicle-to-Everything (CV2X) or the Dedicated Short Range Communications (DSRC) protocols requires high data rate links with ultra-low latencies.
- Coexistence of Bluetooth, WiFi and cellular systems to offer a single *universal* ecosystem providing universal mobile coverage in an *always on, always connected* framework has been long overdue and a possible solution could require higher rates and lower latencies than possible today. In this context, from Fig. 1(a), we observe that while WiFi has dominated in peak rates for almost all the time, cellular systems have been catching up rather quickly. This trend is further clear from the spectral efficiency behavior in Fig. 1(b), where cellular has dominated WiFi for a long time. Such a crossover is bound to have significant impact on viable coexistence solutions.

### III. CHALLENGES AT HIGHER CARRIER FREQUENCIES: ILLUSTRATIVE EXAMPLES

At this point, it is important to take a segue and to note that the key progresses in communications and information theories [2], [4] (as well as much of technology and engineering) have been built on simple models that reflect real systems, that are mathematically elegant, and lead to a deep intuition on system design and practice, aptly summarized by the famous maxim of George Box [21]:

“Since all models are wrong the scientist cannot obtain a ‘correct’ one by excessive elaboration. On the contrary following William of Occam he should seek an economical description of natural phenomena. Just as the ability to devise simple but evocative models is the signature of the great scientist so over-elaboration and over-parameterization is often the mark of mediocrity.”

As we march into the post-5G era of higher carrier frequencies, more care is necessary especially since much of system design intuition relies on simplistic models, primarily inherited from our understanding of sub-6 GHz systems. We illustrate how such legacy-driven understanding can fail with two studies on 28 GHz systems.

#### A. DISCREPANCIES IN DELAY SPREAD

The delay spread is an important metric characterizing a wireless channel and is used to understand its frequency coherence properties. The first step in estimating the delay spread is to estimate the gains and delays of all the propagation paths from the transmitter to the receiver. The excess and root-mean squared (RMS) delay spreads of the channel are then computed as given in [22, eqs. (4) and (5), p. 6526]:

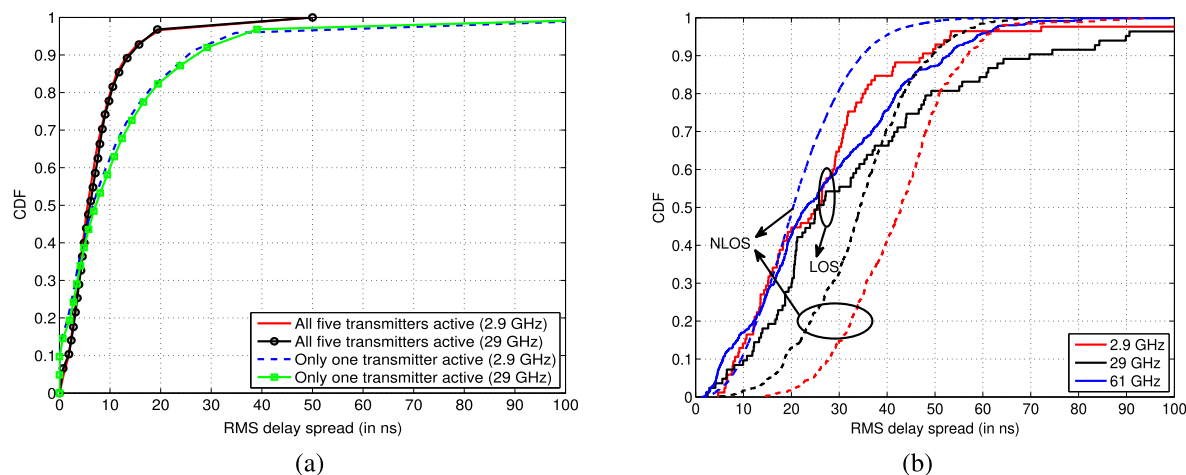
$$\tau_{\text{excess}} = \frac{\sum_i \tau_i p_i}{\sum_i p_i} \quad (4)$$

$$\tau_{\text{rms}} = \sqrt{\frac{\sum_i \tau_i^2 p_i}{\sum_i p_i} - \left(\frac{\sum_i \tau_i p_i}{\sum_i p_i}\right)^2} \quad (5)$$

where  $\tau_i$  and  $p_i$  denote the delay and power corresponding to the  $i$ -th path in an omni-directional antenna scan.

In the first study, an indoor office environment (the third floor of the Qualcomm building, Bridgewater, NJ) described in [22] and [23] is studied at 2.9 and 29 GHz with five transmitter locations offering coverage for the whole area. A number of receiver locations in the building are considered and two scenarios are studied: the transmitter that provides the best link margin is chosen for each receiver location, and only one *a priori* chosen transmitter is made active for all the receiver locations. All the transmitter and receiver locations are deployed with omni-directional antennas at either 2.9 or 29 GHz. In either scenario, the gains and delays from the transmitter to the receiver are estimated using an electromagnetic ray-tracing software suite such as WinProp.<sup>5</sup>

<sup>5</sup>See more details at <https://altairhyperworks.com/product/FEKO/WinProp-Propagation-Modeling>.



**FIGURE 3.** CDF of RMS delay spreads with omnidirectional antennas in a typical indoor office deployment based on (a) ray-tracing studies and (b) measurements.

More details on the experiments conducted are described in [24]. Fig. 3(a) illustrates the cumulative distribution function (CDF) of the RMS delay spread for either scenario at the two frequencies. From this study, we observe that transmitter diversity reduces the delay spread as expected. More importantly, these studies show that the RMS delay spreads are comparable across 2.9 and 29 GHz, and the medians are less than 10 ns in both cases.

In the second study, a channel sounder (described in detail in [22]) that allows omnidirectional antenna scans at 2.9, 29 and 61 GHz is used to study the RMS delay spreads at the same indoor office location. The transmit-receive location pairs used for CDF generation here are similar to those used in the ray-tracing study described previously. Fig. 3(b) illustrates the CDF of the RMS delay spreads for line-of-sight (LOS) and non-line-of-sight (NLOS) links at these three frequencies. Unlike the earlier study, we observe that the RMS delay spreads of NLOS links generally decrease with carrier frequency, whereas the LOS behavior is inconsistent with frequency. Further, the ray-tracing study appears to significantly *underestimate* the true delay spreads estimated from measurements.

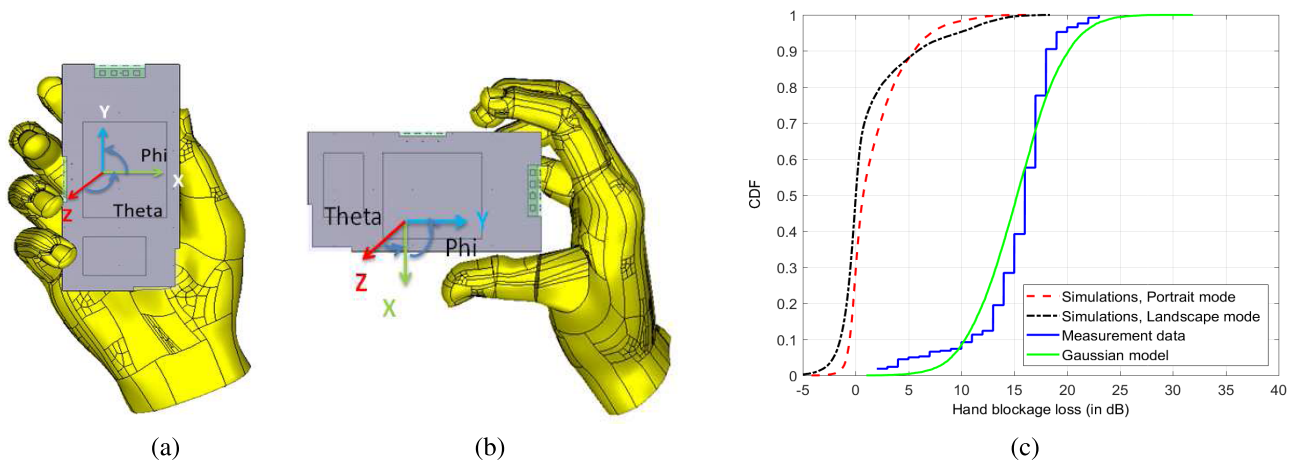
Two plausible explanations are put forward in [22] to explain the discrepancies seen with ray-tracing: i) *Waveguide effect* where long enclosures such as walkways/corridors, dropped/false ceilings, etc., tend to capture more electromagnetic energy than a simplistic LOS scenario in ray-tracing and also increase observed delay spreads with frequency, and ii) *Radar cross-section effect* where small objects of sizes commensurate with the roughness of surfaces such as walls, light poles, metallic objects, etc., take part in propagation at higher frequencies (by increasing the number of channel taps) and distort the delay spreads. In general, a ray-tracing software primarily captures scattering due to buildings and large objects/macroscale features in the environment, and only those features that are explicitly modeled. Thus, ray-tracing misses out on many potential (small) reflectors and scatterers

and cannot be relied on to accurately capture the delay spread in a wireless channel at higher carrier frequencies.

### B. DISCREPANCIES IN HAND BLOCKAGE LOSS

Another important feature of transmissions at millimeter wave, sub-millimeter wave and THz carrier frequencies is blockage of the transmitted signal by obstructions in the environment. In particular, electrically small objects at microwave carrier frequencies become electrically large at higher frequencies affecting the antenna's radiation performance. Specifically, the blockage loss associated with the hand holding a form-factor UE has become an important metric to understand at these carrier frequencies.

To understand the effect of the human hand, in the first study, a simplified model of the UE corresponding to a typical size of 60 mm × 130 mm and designed for transmissions at 28 GHz is studied. As is common with sub-6 GHz frequencies, a simplified model of the UE is studied in an electromagnetic simulation framework (see details in [25] and [26]). In particular, several layers of materials emulating a realistic form-factor design such as glass with a thickness of 1 mm, LCD shielding beneath the glass, FR-4 board, etc., are incorporated in the simulation framework. In addition, a battery and few shielding boxes of random sizes are placed over the printed circuit board (PCB) and are modeled. All the metallic objects are connected to the ground plane of the PCB which covers its bottom plane. For the antennas, multiple subarrays are placed on the long-left and top-short edges of the UE as illustrated in Figs. 4(a)-(b) for the Portrait and Landscape modes, respectively. The antenna modules are designed on a relatively low loss dielectric substrate (Rogers 4003) and are placed on the FR-4 substrate. The antenna elements are either dipole elements or dual-polarized patch elements with the size of each subarray being 4 × 1. The antennas are designed to radiate at 28 GHz and are simulated in Freespace (with no hand) and with a hand phantom model, as also illustrated in Fig. 4.



**FIGURE 4.** A typical UE design with multiple subarrays and a hand phantom model in (a) Portrait mode and in (b) Landscape mode. (c) CDF of hand blockage loss with electromagnetic simulations and measurements using a 28 GHz experimental prototype.

In terms of electromagnetic properties, the hand is modeled as a homogeneous dielectric with the dielectric properties of skin tissue. These dielectric properties determine the penetration depth of signals into the hand and the reflection of electromagnetic waves from the hand. At 28 GHz, a relative dielectric constant  $\epsilon_r = 16.5$  and conductivity  $\sigma = 25.8$  S/m are used in the studies [27]. The UE is then simulated with and without hand using a commercial electromagnetics simulation software suite such as CST Microwave Studio.<sup>6</sup> Fig. 4(c) illustrates the CDF of hand blockage loss using simulated data captured as the differential in beamforming array gains between Freespace and Portrait/Landscape modes over a sphere around the UE.

In the second study, a 28 GHz experimental prototype described in [23] and capturing the attributes of a 5G base-station as well as a form-factor UE design is used to study hand blockage loss based on measurements. The UE design used in these studies corresponds to the same setup studied with simulations earlier. In these studies (see details in [25] and [26]), the UE is grabbed by the hand and the hand completely covers/envelops the active antenna arrays on the long-left edge. All the subarrays at the UE side except the enveloped subarray are disabled in terms of beam switching thus allowing us to capture the hand blockage loss in terms of received signal strength differentials between the pre- and post-hand blocked scenarios. Multiple experiments are performed with different hand grabbing styles, speeds, with different air gaps between fingers, and with different people. For each experiment, ten received signal strength indicator (RSSI) minimas spanning the entire event from signal degradation to recovery upon removing the hand are recorded. Link degradation is computed as the RSSI difference between the steady-state RSSI value and the ten minimas. The empirical CDF of hand blockage loss corresponding to 38 such experiments is plotted in Fig. 4(c) along with

a simple Gaussian fit (specifically, of the form  $\mathcal{N}(\mu = 15.26 \text{ dB}, \sigma = 3.80 \text{ dB})$ ) to the data.

This study illustrates the wide discrepancy between simulation-based studies and true measurements of blockage loss. Underestimating blockage losses can lead to a poorly designed UE with less antenna module diversity than necessary to effectuate its seamless functioning. A number of plausible explanations can be provided for these discrepancies. These include a poor understanding of the wide variations in material properties (such as the human hand) at higher carrier frequencies as well as the dynamics of hand blocking, impact of materials in the form-factor UE on signal distortion and deterioration [28], capability of simulation studies to only capture those features that can be deterministically modeled, etc. This example illustrates the need for great care in extrapolating established techniques for systems studies, often based on sub-6 GHz systems, to higher carrier frequencies.

#### IV. IMPLICATIONS ON BROADER RESEARCH ASPECTS

The arguments put forward in Sections II and III focus on the importance of higher carrier frequencies and the difficulty of simplistic simulation studies in capturing the true impact of these systems. These observations have a number of broad implications for future directions in physical-layer research.

- 1) In terms of the specific blockage study of Sec. III, overcoming blockage losses at higher frequencies requires mechanisms that endow path diversity at far higher levels than sub-6 GHz systems. One such mechanism is the use of modular UE designs with multiple antenna arrays. In contrast to sub-6 GHz systems (such as LTE), such modular designs would require a careful optimization of the antenna modules to tradeoff power consumption, diversity/spherical coverage, cost and implementation constraints such as real-estate issues. The divergence from sub-6 GHz systems in terms of UE design would require further careful studies of antenna module placement tradeoffs [28]. Another mechanism

<sup>6</sup>See <https://www.cst.com/products/cstmws> for details.

- could be the use of densified networks with multiple transmission points, which would also naturally allow the use of higher-order modulation and coding schemes.
- 2) At a general level, the studies described in Sec. III clearly demonstrate the gap between traditional simulation studies with simplistic models (often, but not always, inherited from legacy systems) from real observations in the field with measurements. Thus, in terms of philosophy, without closing the gap between theory and practice of higher carrier frequency systems, the results produced from simplified models can become meaningless in terms of the big picture in the post-5G era.
  - 3) This closing of the loop requires multiple steps:
    - A careful understanding of the different components of the system and how they interact with each other.
    - Accurate models that capture these interactions and the contours of the solution space along with the objective function(s) for optimization.
    - A proposed solution which can then be applied to the real scenario and studied in terms of its efficacy in solving the original problem of interest.
    - Refinement of the model, the solution space, the proposed solution(s), and its/their fit to the original problem.
  - 4) At an algorithmic level, the studies described in Sec. III suggest a possible role for non-parametric or even machine learning-inspired approaches [29]–[32] in supplanting traditional statistical signal processing and inferencing solutions in a number of applications in the cellular phone at the sensing, processing and communications levels. However, their success would rely on engineers' ability to extract intuition into the structure of these solutions.
  - 5) In terms of physical-layer transmissions, directional hybrid beamforming approaches over sparse channels are of importance at higher carrier frequencies than traditional digital beamforming approaches [28], [33]–[38]. The cost and complexity tradeoffs in implementing such approaches need further study as 5G standardization efforts mature and branch off to even higher carrier frequencies.
  - 6) While higher carrier frequency systems are important for post-5G evolution, advances of sub-6 GHz systems cannot be ignored (or de-emphasized) in future research and development efforts. In particular, advances in terms of form-factor UE designs with real-estate constraints targeting lower power consumption and acceptable thermal stability, advanced physical-layer capabilities and feature sets for different/emerging use-cases as well as highly-mobile applications, robust coverage with carrier aggregation over multiple contiguous/non-contiguous spectral bands, and meeting various regulatory compliance requirements (all at similar or lower cost and complexity in implementation [39]) are of importance at both sub-6 GHz and higher carrier frequencies. For example, while 4G systems primarily targeted the enhanced mobile broadband (eMBB) use-case, 5G (and beyond) systems already target other important use-cases such as ultra-reliable low latency communications (URLLC), IoT and mMTC with enhancements to non-terrestrial networks (e.g., drones), integrated access and backhaul, coexistence in unlicensed bands, positioning systems and vehicular coverage, etc., expected shortly. With such a diverse set of applications, both sub-6 GHz and higher carrier frequency systems are expected to play a prominent role in future efforts.
  - 7) While fulfilling all these objectives in a reasonable manner takes a significant amount of time and energy, such endeavors should be actively encouraged and rewarded in terms of research funding and policy initiatives. Some recent examples in this direction include the U.S. National Science Foundation's Platforms for Advanced Wireless Research (PAWR) program ([https://www.nsf.gov/funding/pgm\\_summ.jsp?pims\\_id=505316](https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505316)) and Millimeter Wave Research Coordination Network program (<http://mmwrcn.ece.wisc.edu>) for fostering academia-industry interactions in the post-5G era.
  - 8) All this said, the fundamental dilemmas confronting a theoretician in physical-layer research will continue to grow manifold as these systems will continue to breach the boundaries of circuit theory, electromagnetics, communications, optimization, statistics, signal processing, and economics. Thus, it is imperative that a modern telecommunications department develop a core curriculum that spans these hitherto distinct focus areas. Furthermore, it is important that such a department equip itself with at least one advanced wireless test-bed and offer hands-on exposure to the theory and practice of state-of-the-art telecommunications technologies to its students and researchers.

## V. CONCLUDING REMARKS

The last twenty five years have been witness to a remarkable exponential scaling in cellular modem capabilities with time. A number of technological innovations such as carrier aggregation, higher-layer multi-antenna transmissions with more device and circuit complexities, higher-order modulation and reliable coding schemes, network densification, coordinated transmissions and interference management, etc., have played a key role in this relentless growth. Sustaining these growth rates at historic levels into the far future is both difficult as well as possibly needless due to lack of strong business use-cases (at least as of now). Nevertheless, there are enough opportunities in terms of both technological innovations and emergent use-cases to sustain slower growth rates in modem capabilities with time. A central component



**TABLE 2. WiFi data rate evolution and cellular data rate evolution with Qualcomm modems.**

	Standard	Specification release date	Peak downlink data rate (in Mbps)	Bandwidth (in MHz)
WiFi	802.11-1997	June 1997	2	22
	11a	Sept. 1999	54	20
	11b	Sept. 1999	11	22
	11g	June 2003	54	20
	11n	Oct. 2009	150	40
	11ac	Dec. 2013	866.7	160
	11ad	Dec. 2012	6757	2160
	11ax	Dec. 2019	1134	160
	11ay	Dec. 2019	20000	8000

	Modem identifier	Approx. commercial sampling date	Peak downlink data rate (in Mbps)	Bandwidth (in MHz)	Modulation	Antennas	Processing complexity
CDMA IS-95 2000	MSM 3000	July 1998	0.0144	1.25	BPSK	1	1 code
	MSM 3100	July 1999	0.064	1.25	BPSK	1	1 code
	MSM 5000	Sept. 2000	0.1536	1.25	QPSK	1	1 code
	MSM 5100	May 2001	0.3072	1.25	QPSK	1	1 code
	MSM 5500	July 2001	2.4576	1.25	16QAM	1	1 code
WCDMA	MSM 5200	Apr. 2002	0.384	5	QPSK	1	1 code
	MSM 6275	Sept. 2005	1.8	5	QPSK	1	5 codes
	MSM 6260	Jan. 2007	3.6	5	16QAM QPSK	1 1	5 codes 10 codes
	MSM 6280	July 2006	7.2	5	16QAM	1	10 codes
	QSC 7230	Mar. 2009	10.8	5	16QAM	1	15 codes
	MSM 7x30	Sept. 2009	14.4	5	16QAM	1	15 codes
	MDM 8200	Jan. 2010	21.6	5	64QAM	1	15 codes
	MDM 8200	Jan. 2010	28.8	5	16QAM	2	15 codes
	MDM 8220	July 2010	42.2	5	64QAM	2	15 codes
					10	64QAM	1
LTE	MDM 9x00	Mar. 2010	100	20	16QAM	2	2 layers
	MDM 9x25/X5	Apr. 2013	150	20	64QAM	2	2 layers
	MDM 9x35/X7	June 2014	300	40	64QAM	2	2 layers
	X10	Apr. 2015	450	60	64QAM	2	2 layers
	X12	Oct. 2015	600	60	256QAM	4	6 layers
	X16	June 2016	1000	80	256QAM	4	10 layers
	X20	June 2017	1200	100	256QAM	4	12 layers
	X24	June 2018	2000	140	256QAM	4	20 layers
5G	X50	June 2019	5000	800	64QAM	UE-specific	2 layers

in the evolutionary road-map of the cellular modem would be operation over a significantly wider bandwidth across a number of higher carrier frequencies (than currently possible today).

While such a reality is already visible today given that 5G-NR addresses millimeter wave systems (e.g., Qualcomm’s X50 modem), the focus of this work has been on the more dramatic implications of such trends for physical-layer research problems that would be of relevance in the next few years. This paper philosophically argues that *systems* research in its own cocoon and isolated from other areas such as circuits/device design, electromagnetics, economics, etc., would be futile, especially as we march inexorably to communications at higher carrier frequencies. Syncretic systems research needs to be both encouraged and advanced from a policy standpoint, and in the nature and scope of curriculum development and departmental structure across universities.

**APPENDIX  
EXPLANATION OF DATA USED IN OUR STUDY**

For the time evolution axis of WiFi and cellular data rates, we begin with Jan. 1997 as Month 1 and Dec. 2020 as Month 288 for the data. Table 2 provides the peak WiFi data rates and standard specification release dates. This table also

provides the peak cellular downlink data rates, release dates and modem capabilities used in our study.

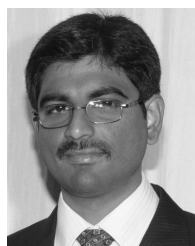
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