INVITED PAPER

Millimeter-Wave Cellular Wireless Networks: Potentials and Challenges

Over 90% of the allocated radio spectrum falls in the millimeter-wave band (30–300 GHz). Can we make better use of this band to alleviate spectrum crowding at lower frequencies?

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ABSTRACT | Millimeter-wave (mmW) frequencies between 30 and 300 GHz are a new frontier for cellular communication that offers the promise of orders of magnitude greater bandwidths combined with further gains via beamforming and spatial multiplexing from multielement antenna arrays. This paper surveys measurements and capacity studies to assess this technology with a focus on small cell deployments in urban environments. The conclusions are extremely encouraging; measurements in New York City at 28 and 73 GHz demonstrate that, even in an urban canyon environment, significant non-line-of-sight (NLOS) outdoor, street-level coverage is possible up to approximately 200 m from a potential low-power microcell or picocell base station. In addition, based on statistical channel models from these measurements, it is shown that mmW systems can offer more than an order of magnitude increase in capacity over current state-of-the-art 4G cellular networks at current cell densities. Cellular systems, however, will need to be significantly redesigned to fully achieve these gains. Specifically, the requirement of highly directional and adaptive transmissions, directional isolation between links, and significant possibilities of outage have strong implications on multiple access, channel structure, synchronization, and receiver design. To address these challenges, the paper discusses how various technologies including adaptive beamforming, multihop relaying, heterogeneous network architectures, and carrier aggregation can be leveraged in the mmW context.

KEYWORDS | Cellular systems; channel models; millimeter-wave radio; urban deployments; wireless propagation; 28 GHz; 3GPP LTE; 73 GHz

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I. INTRODUCTION

Demand for cellular data has been growing at a staggering pace, with conservative estimates ranging from 40% to 70% year upon year increase in traffic [1]–[3]. This incredible growth implies that within the next decades, cellular networks may need to deliver as much as 1000 times the capacity relative to current levels. At the same time, as the benefits of wireless connectivity move beyond smartphones and tablets, many new devices will require wireless service—perhaps as many as 50 billion devices will be connected by 2020 in one estimate [4]. Meeting this demand will be a formidable task. Many of the requirements envisioned for what are now being called beyond fourth-generation (4G) and fifth-generation (5G) cellular systems, such as multi-gigabits per second (Gb/s) peak throughputs and tens of megabits per second (Mb/s) cell edge rates [5], are already daunting.

To address this challenge, there has been growing interest in cellular systems for the so-called millimeter-wave (mmW) bands, between 30 and 300 GHz,[1] where the available bandwidths are much wider than today's cellular networks [6]–[9]. The available spectrum at these higher

[1]While the mmW spectrum is defined as the band between 30 and 300 GHz, industry has loosely considered mmW to be any frequency above 10 GHz

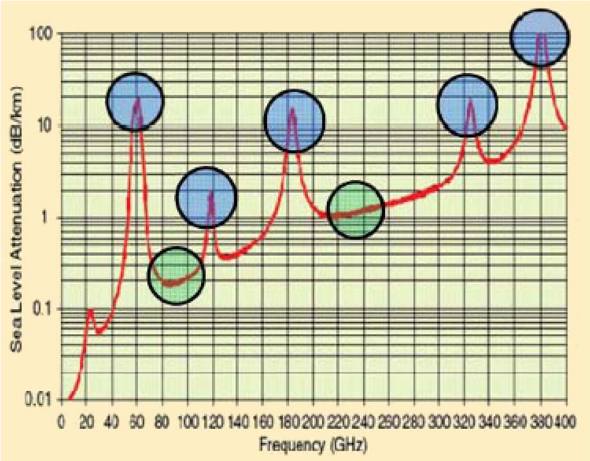


Fig. 1. ***Millimeter-wave (mmW) bands between 30 and 300 GHz offer more than 200 times the spectrum than current cellular allocations, with ample regions with sufficiently low attenuation for small outdoor cells. In bands with the green bubbles, the oxygen attenuation is only a fraction of a decibel greater than free space over distances of several hundred meters. Figure from [6].***

frequencies can be easily 200 times greater than all cellular allocations today that are largely constrained to the prime RF real estate under 3 GHz [6], [8] (see Fig. 1). Moreover, the very small wavelengths of mmW signals combined with advances in low-power complementary metal–oxide–semiconductor (CMOS) radio-frequency (RF) circuits enable large numbers ($\geq$ 32 elements) of miniaturized antennas to be placed in small dimensions. These multiple antenna systems can be used to form very high gain, electrically steerable arrays, fabricated at the base station (BS), in the skin of a cellphone, or even within a chip [6], [10]–[17]. As described in Section II-A, these advances will accelerate with the recent commercialization of 60-GHz Wi-Fi products. This tremendous potential has led to considerable recent interest in mmW cellular both in industry [7]–[9], [18], [19] and academia [20]–[26], with a growing belief that mmW bands will play a significant role in beyond 4G and 5G cellular systems [27].

Despite this activity, this interest in mmW is still very recent and the use of mmW bands remains a largely unexplored frontier for cellular communication. While every other aspect of cellular mobile technology—including processing power, memory, digital communications methods, and networking—have seen tremendous progress since digital cellular systems began some 25 years ago, the carrier frequencies of those systems remain largely the same. With today's severe shortage of spectrum, the time is thus ripe to consider unleashing the capacity in these new bands.

However, the development of cellular networks in the mmW bands faces significant technical obstacles, and the feasibility of mmW cellular communication requires careful assessment. As we will see below, while the increase in omnidirectional path loss due to the higher frequencies of mmW transmissions can be completely compensated through suitable beamforming and directional transmissions, mmW signals can be severely vulnerable to shadowing, resulting in outages and intermittent channel quality. Device power consumption to support large numbers of antennas with very wide bandwidths is also a key challenge.

The broad purpose of this paper is to survey recent results to understand how significant these challenges are, provide a realistic assessment of how mmW systems can be viable, and quantify the potential gain they can provide. We also use the insights from this evaluation to offer guidance on the research directions needed for the realization of next-generation cellular systems in the mmW space.

Since the most significant obstacle to mmW cellular is signal range for non-line-of-sight (NLOS), longer distance links, a large focus on this paper is on outdoor channel measurement studies. In particular, we survey our own measurements [26], [28]–[33] made in New York City (NYC) in both 28- and 73-GHz bands and the statistical models for the channels developed in [34]. NYC provides an excellent test case for mmW propagation studies, since it is representative of a dense, urban outdoor environment where mmW system will likely be initially targeted due to the high user density, small cell radii (typically 100–200 m) and lower mobility. At the same time, NYC is a particularly challenging setting for mmW propagation since the urban canyon topology results in a frequent lack of line-of-sight (LOS) connectivity, severe shadowing, as well as limitations on the height and placement of cells.

As we describe below, our survey of these channel propagation studies shows that, even in a dense, urban NLOS environment, significant signal strength can be detected 100–200 m from a BS with less than 1 W of transmit power. Such distances are comparable to the cell radii in current urban ultrahigh-frequency (UHF)/microwave cells and thus we conclude that mmW systems would not necessarily require greater density for such use cases. In fact, using a recent capacity analysis of ours in [34] that was based on the NYC experimental data, we show that mmW cellular systems can offer at least an order of magnitude increase in capacity relative to current state-of-the-art 4G networks with comparable cell density. For example, it is shown that a hypothetical 1-GHz bandwidth time-division duplex (TDD) mmW system could easily provide a 20-fold increase in average cell throughput in comparison to a 20 + 20-MHz long-term evolution (LTE) system. In cellular systems, where even small increases in capacity can be significant, these gains are truly remarkable.

We also show that the design of a cellular system based in the mmW range will need significant changes, more than just simply scaling the carrier frequency to reach their full potential. Most significantly, communication will

depend extensively on adaptive beamforming at a scale that far exceeds current cellular systems. We show that this reliance on highly directional transmissions has significant implications for cell search, broadcast signaling, random access, and intermittent communication. In addition, due to the particular front–end requirements in the mmW range, support of highly directional communications also has implications for multiple access and support of small packet communications.

A related consequence of highly directional transmissions is that the links become directionally isolated, with interference playing a much smaller role than in current small cell networks. One result is that many of the technologies introduced in the last decade for interference mitigation, such as coordinated multipoint, intercellular interference coordination, and interference alignment, may have limited gains in mmW systems. On the other hand, despite rich multipath and scattering, signal outage may be a larger bottleneck in delivering uniform capacity, and we discuss various alternate technologies, including multihop relaying, carrier aggregation, and heterogeneous networking, to address these issues.

II. MILLIMETER-WAVE CELLULAR NETWORKS

A. The Path to Millimeter-Wave Cellular

For this paper, mmW signals will refer to wavelengths from 1 to 10 mm, corresponding to frequencies approximately in the range of 30–300 GHz. Wireless communications in these mmW bands are not new. Indeed, the first millimeter communications were demonstrated by Bose more than 100 years ago [35]. Currently, mmW bands are widely used for satellite communications [36] and cellular backhaul [37]–[39]. More recently, mmW transmissions have been used for very high throughput wireless local area network (LANs) and personal area network (PAN) systems [6], [40]–[43] in the newly unlicensed 60-GHz bands. While these systems offer rates in excess of 1 Gb/s, the links are typically for short-range or point-to-point LOS settings.

The application of mmW bands for longer range, NLOS cellular scenarios is a new frontier, and the feasibility of such systems has been the subject of considerable debate. While mmW spectrum offers vastly greater bandwidths than current cellular allocations, there is a fear that the propagation of mmW signals is much less favorable. As we will see below, mmW signals suffer from severe shadowing, intermittent connectivity, and will have higher Doppler spreads. Given these limitations, there has been considerable skepticism that mmW bands would be viable for cellular systems that require reliable communication across longer range and NLOS paths [26], [42].

Two recent trends have encouraged a reconsideration of the viability of mmWave cellular. First, advances in CMOS RF and digital processing have enabled low-cost mmW chips suitable for commercial mobiles devices [6], [10], [33]. Significant progress has been made, in particular, in power amplifiers and free space adaptive array combining, and these technologies are likely to advance further with the growth of 60-GHz wireless LAN and PAN systems [6], [40]–[43]. In addition, due to the very small wavelengths, large arrays can now be fabricated in a small area of less than 1 or 2 cm^2. To provide path diversity from blockage by human obstructions (such as a hand holding a part of the device, or the body blocking the path to the cell), several arrays may be located throughout a mobile device.

Second, cellular networks have been evolving toward smaller radii, particularly with support for picocell and femtocell heterogeneous networks in the latest cellular standards [44]–[48]. In many dense urban areas, cell sizes are now often less than 100–200 m in radius, possibly within the range of mmW signals based on our measurements (see Section III).

In the absence of new spectrum, increasing capacity of current networks will require even greater "densification" of cells. While greater densification is likely to play a central role for cellular evolution [47]–[49], building networks beyond current densities may not be cost effective in many settings due to expenses in site acquisition, rollout, and delivering quality backhaul. Indeed, backhaul already represents 30%–50% of the operating costs by some estimates [50], [51], and that share will only grow as other parts of the network infrastructure decrease in price [50], [52], [53]. In contrast, in very high density deployments, the wide bandwidths of mmW signals may provide an alternative to cell splitting by significantly increasing the capacity of individual small cells. Backhaul may also be provided in the mmW spectrum, further reducing costs.

B. Challenges

Despite the potential of mmW cellular systems, there are a number of key challenges to realizing the vision of cellular networks in these bands.

- Range and directional communication: Friis' transmission law [54] states that the free space omnidirectional path loss grows with the square of the frequency. However, the smaller wavelength of mmW signals also enables proportionally greater antenna gain for the same physical antenna size. Consequently, the higher frequencies of mmW signals do not in themselves result in any increased free space propagation loss, provided the antenna area remains fixed and suitable directional transmissions are used. We will confirm this property from our measurements below; see, also, [55]. However, the reliance on highly directional transmissions will necessitate certain design

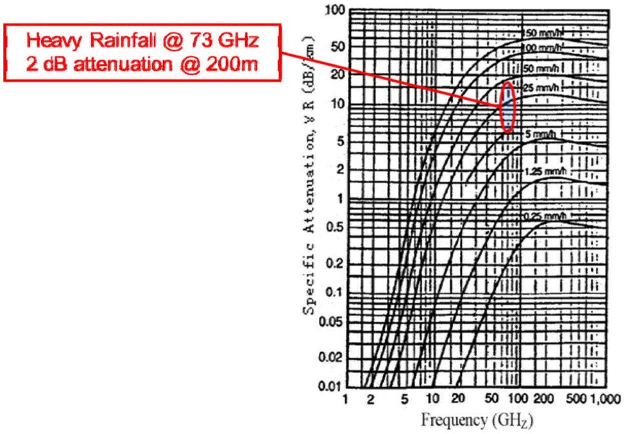


Fig. 2. ***Rain fades: Even in very heavy rainfall, rain fades are typically less than 1 dB per 100 m, meaning they will have minimal impact in cellular systems with cell radii less than 200 m. Figure from [32].***

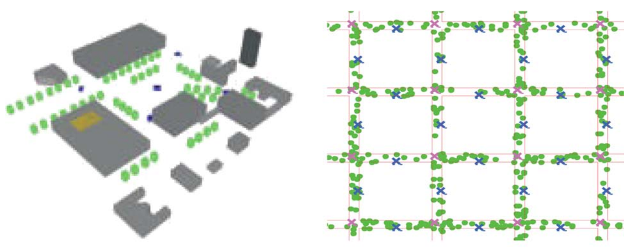
changes to current cellular systems that we discuss in Section V.

- Shadowing: A more significant concern for range is that mmW signals are extremely susceptible to shadowing. For example, materials such as brick can attenuate signals by as much as 40–80 dB [8], [30], [56]–[58] and the human body itself can result in a 20–35-dB loss [59]. On the other hand, humidity and rain fades—common problems for long-range mmW backhaul links—are not an issue in cellular systems; see Fig. 2 and [6] and [26]. Also, the human body and many outdoor materials being very reflective allow them to be important scatterers for mmW propagation [28], [30].
- Rapid channel fluctuations and intermittent connectivity: For a given mobile velocity, channel coherence time is linear in the carrier frequency [54], meaning that it will be very small in the mmW range. For example, the Doppler spread at 60 km/h at 60 GHz is over 3 kHz, hence the channel will change in the order of hundreds of microseconds, much faster than today's cellular systems. In addition, high levels of shadowing imply that the appearance of obstacles will lead to much more dramatic swings in path loss, although beamsteering may overcome this [26]. Also, mmW systems will be inherently built of small cells, meaning that relative path losses and cell association also change rapidly. From a systems perspective, this implies that connectivity will be highly intermittent and communication will need to be rapidly adaptable.
- Multiuser coordination: Current applications for mmW transmissions are generally for point-to-point links (such as cellular backhaul [60]), or LAN and PAN systems [40]–[43] with a limited number of users or MAC-layer protocols that prohibit multiple simultaneous transmissions. However, for high spatial reuse and spectral efficiency, cellular systems require simultaneous transmissions on multiple interfering links, and new mechanisms will be needed to coordinate these transmissions in mmW networks.
- Processing power consumption: A significant challenge in leveraging the gains of multiantenna, wide-bandwidth mmW systems is the power consumption in the analog-to-digital (A/D) conversion. Power consumption generally scales linearly in the sampling rate and exponentially in the number of bits per samples [6], [61], [62], making high-resolution quantization at wide bandwidths and large numbers of antennas prohibitive for low-power, low-cost devices. For example, scaling power consumption levels of even a state-of-the-art CMOS A/D converter designs such as [63] and [64] suggests that A/D converters at rates of 100 Ms/s at 12 b and 16 antennas would require more than 250 mW, a significant drain for current mobile devices. Also, efficient RF power amplification and combining will be needed for phased array antennas.

C. Deployment Models

Due to the limited range of mmW signals, most of the cellular applications for mmW systems have focused on small-cell, outdoor deployments. For example, a capacity study by Pietraski *et al.* [9], [65] considered deployments in campus- and stadium-like settings where the users could obtain relatively unobstructed connections to the mmW cells; see Fig. 3(a).

The focus in this paper will be in urban microcellular and picocellular deployments with cell radii in the range of 100–200 m, similar to current cell sizes for such deployments. Coverage in urban environments will



(a) Campus setting (b) Urban picocell

Fig. 3. ***Millimeter-wave cellular use cases. (a) Outdoor coverage in a campus-like environment, as illustrated in [65]. (b) Urban microcells or picocells as illustrated in a figure detail from [66] showing mmW access points (blue and pink crosses) placed on every block on an urban grid to serve mobiles (green circles) on the streets.***

encounter NLOS propagation much more frequently than outdoor campus or stadium settings, and is thus significantly more challenging. To provide dense coverage in such scenarios, the mmW cells could be deployed, for example, in a picocellular manner on street furniture such as lampposts or sides of buildings to enable direct coverage onto the streets with minimal shadowing. Fig. 3(b) shows such a picocellular layout for an urban environment considered in [66] where one to three mmW access points were placed in each block in a city grid. Other deployments are also possible. For example, cells could be placed similar to current urban microcells on top of buildings for larger area coverage.

D. Heterogeneous Networking Aspects

Due to the inherent limitations of mmW propagation, mmW cellular systems cannot alone provide uniform, robust high capacity across a range of deployments. Millimeter-wave networks will be inherently *heterogeneous*; see Fig. 4. In fact, it is quite likely that cellular and local area networks will blur over time.

Heterogeneous networks, or HetNets, have been one of the most active research areas in cellular standards bodies in the last five years [45], [48], [67], [68], with the main focus being intercell interference coordination and load balancing. However, the introduction of mmW cells into current cellular networks will create heterogeneity in the network in many more aspects than cell size.

- Millimeter-wave and microwave/UHF: Most importantly, since mmW cells will be inherently limited in range (due to the physical limitations of antenna structures and the corresponding gain in a portable device), they will have to coexist with a conventional UHF/microwave cellular overlay for universal coverage.
- Relay versus wired access points: With large numbers of small cells, it may be impractical or expensive to run fiber connectivity to every cell. As we will discuss in Section V-C, relays (or, in a simpler from, repeaters) provide an attractive cost-effective alternative that can build on existing mmW backhaul technology and exploit the full degrees of freedom in the mmW bands.
- Short-range LOS picocells versus NLOS wide-area microcells: As described above, there may be significant differences in coverage between microcells and picocells. Microcells may offer larger range, but more diffuse NLOS coverage. In practice, both cell types will likely need to coexist [30].
- Ownership: A key challenge of mmW is indoor penetration. Reasonable coverage will require that mmW cells be placed indoors [30], [32]. Analogous to the femtocell concept [44]–[48], and neighborhood small cells [69], [70], third parties may be better suited to provide these cells, thereby creating a network with multiple operators and third-party ownership.

Such heterogeneous networks present several design issues, particularly in cell selection and networking. We discuss some of these issues in Section V-F.

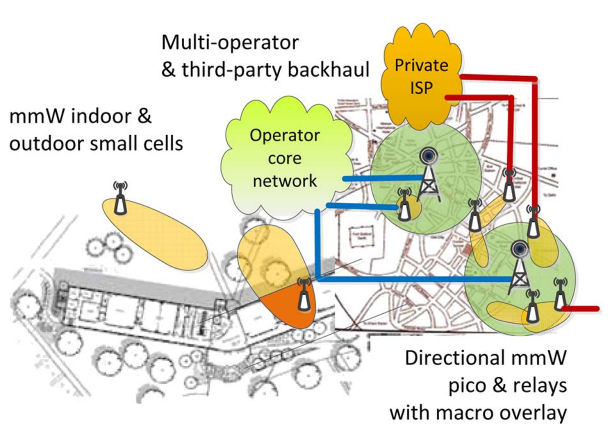


Fig. 4. ***Due to the inherent limitations of mmW propagation, mmW cellular systems will need to coexist and coordinate with conventional microwave cells. Also, to provide indoor coverage and efficiently use the spectrum, backhaul and spectrum may be shared between operators and third parties much more significantly than in current deployments.***

III. CELLULAR CHANNEL MEASUREMENTS

To assess the feasibility of mmW networks, we begin by surveying recent channel measurements of mmW signals in urban environments, particularly our wideband propagation studies in the 28- and 73-GHz bands in NYC.

A. Prior Measurements

Particularly with the development of 60-GHz LAN and PAN systems, mmW signals have been extensively characterized in indoor environments [6], [28], [42], [57], [71]–[75]. The propagation of mmW signals in outdoor settings for microcellular and picocellular networks is relatively less understood.

Due to the lack of actual measured channel data, many earlier studies [7], [9], [22], [23] have relied on either analytic models or commercial ray-tracing software with various reflection assumptions. These models generally assume that propagation will be dominated by either LOS links or links with a few strong specular reflections. As we will see below, these models may be inaccurate.

Also, measurements in local multipoint distribution systems (LMDSs) at 28 GHz—the prior system most close to mmW cellular—have been inconclusive: For example, a study [76] found 80% coverage at ranges up to 1–2 km, while Seidel [77] claimed that LOS connectivity would be required. Our own previous studies at 38 GHz [33], [78]–[81] found

that relatively long-range links (> 750 m) could be established. However, these measurements were performed in an outdoor campus setting with much lower building density and greater opportunities for LOS connectivity than would be found in a typical urban deployment.

B. Measurements in New York City

To provide a realistic assessment of mmW propagation in urban environments, our team conducted extensive measurements of 28- and 73-GHz channels in NYC. Details of the measurements can be found in [26], [28]–[33], [81].

The 28- and 73-GHz bands were selected since they are both likely to be initial frequencies where mmW cellular systems could operate. The 28-GHz bands were previously targeted for LMDSs and are now attractive for initial deployments of mmW cellular, given their relatively lower frequency within the mmW range. However, as mmW systems become more widely deployed, these lower frequency mmW bands will likely become depleted, particularly since they must compete with existing cellular backhaul systems. Expansion to the higher bands is thus inevitable. In contrast, the E-band frequencies (71–76 GHz and 81–86 GHz) [82] have abundant spectrum and are adaptable for dense deployment, providing a major option for carrier-class wireless indoor and outdoor transmission, should the lower frequency become congested. As shown in Fig. 1, the atmospheric absorption of E-band is only slightly worse (e.g., 1 dB/km) than today's widely used lower frequency (UHF/microwave) bands.

To measure the channel characteristics in these frequencies, we emulated microcellular-type deployments where transmitters were placed on rooftops two to five stories high and measurements were then made at a number of street level locations up to 500 m from the transmitters (see Fig. 5). To characterize both the bulk path loss and the spatial structure of the channels, measurements were performed with highly directional, rotatable horn antennas [30-dBm RF output, 10° beamwidths and 24.5-dBi gain at both transmitter (TX) and receiver (RX)]. In order to obtain high time resolution, we employed a 400-Mcps (megachip per second) channel sounder (see Fig. 6). At each TX–RX location pair, the angles of the TX and RX antennas were swept across a range of values to detect discrete clusters of paths [26], [28]–[33], [81].

C. Large-Scale Path Loss Model

Using the data from [26] and [28]–[33], detailed statistical models for the channels were developed in our recent work [34], where we took the directional channel measurements and created narrowband isotropic (unity gain, omnidirectional) channel models by adding the powers received over all measurement angles, and subtracting the 49 dB of original antenna gains used in the measurements. Here, we summarize some of the main findings from [34] to help understand the potential capacity of mmW systems, and to identify the key design issues [33].

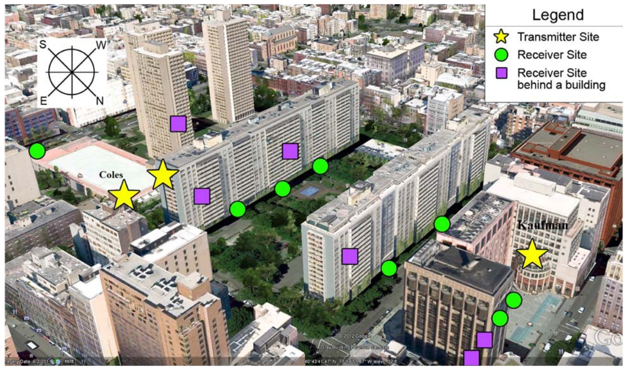


Fig. 5. *Image from [29] showing typical measurement locations in NYC at 28 GHz for which the isotropic path loss models in this paper are derived. Similar locations were used for the 73-GHz study.*

First, we summarize the path loss results. As mentioned above, range is one of the key issues facing mmW systems. Thus, critical to properly assessing mmW systems is to first determine how path loss varies with distance. Toward this end, Fig. 7 (taken from [34]) shows a scatter plot of the estimated omnidirectional path losses at different distances from the transmitter. In both 28- and 73-GHz measurements, each point was classified as either being in a NLOS or LOS situation, based on a manual classification made at the time of the measurements; see [26] and [28]–[33].

In standard urban cellular models such as [83], it is common to fit the LOS and NLOS path losses separately. Fig. 7 shows that the LOS path losses roughly follow the free space propagation based on Friis' law [54], at least for the points with distances < 100 m. For the NLOS points, Akdeniz *et al.* [34] applied a standard linear fit of the form

$$PL(d)\ [\mathrm{dB}] = \alpha + \beta 10\log_{10}(d) + \xi,\quad \xi \sim \mathcal{N}(0,\sigma^2) \tag{1}$$

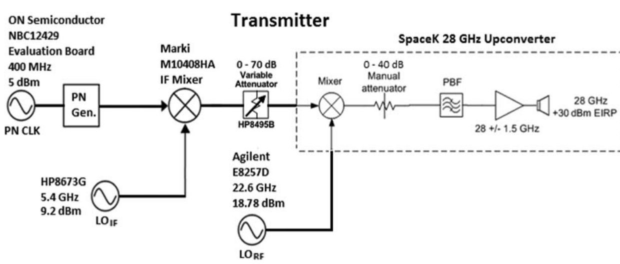


Fig. 6. *The 28-GHz channel sounder transmitter block diagram with 54.5-dBm effective isotropic radiated power (EIRP) and 800-MHz first null-to-null RF bandwidth for high temporal resolution. Figure from [29].*

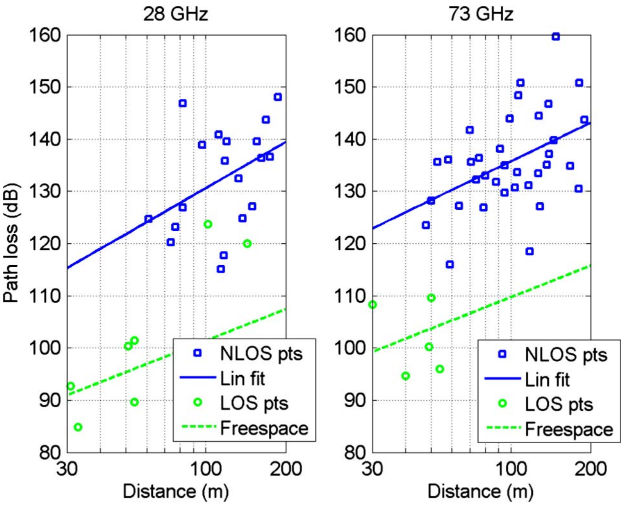


Fig. 7. *Scatter plot along with a linear fit of the estimated omnidirectional path losses as a function of the TX–RX separation for 28 and 73 GHz. Figure from [34] based on the NYC data in [26].*

where d is the distance in meters, α is the best [minimum mean square error (MMSE)] fit floating intercept point over the measured distances (30–200 m) [81], β is the slope of the best fit, and σ^2 is the lognormal shadowing variance. The parameter values for α, β, and σ are shown in Table 1 along with other parameters that are discussed below.

Note that a close-in free space reference path loss model with a fixed leverage point may also be used, which is equivalent to (1) with the constraint that $\alpha + \beta 10\log_{10}(d_0)$ has some fixed value $PL(d_0)$ for some close-in free space reference d_0. Work in [81] shows that this close-in free space model is less sensitive to perturbations in data and has valuable insights based on propagation physics for the slope parameter β (e.g., $\beta = 2$ is free space propagation and $\beta = 4$ is the asymptotic path loss exponent for a two-ray model). The close-in free space reference model has only a slightly greater (e.g., 0.5-dB larger standard deviation) fitting error. While the analysis below will not use this fixed leverage point, we point this out to caution against ascribing any physical meaning to the estimated values for α or β in (1) when a floating intercept is used.

We can compare the experimentally derived model (1) for the mmW frequencies with those used in conventional cellular systems. To this end, Fig. 8 plots the median omnidirectional path loss for the following models.

- Empirical NYC: These curves are based on the omnidirectional path loss predicted by our linear model (1) for the mmW channel with the parameters from Table 1, as derived from the directional measurements in [26].
- Free space: The theoretical free space path loss is given by Friis' law [54]. We see, for example, that at $d = 100$ m, the free space path loss is approximately 30 dB less than the omnidirectional propagation model we have developed here based on the directional measurements in [26]. Thus, many of the works such as [9], [22], and [23] that assume free space propagation may be somewhat optimistic in their capacity predictions. Also, it is interesting to point out that one of the models assumed in [7] (PLF1) is precisely free space propagation +20 dB—a correction factor that is 5–10 dB more optimistic than our experimental findings.
- 3GPP UMi: The standard 3GPP urban micro (UMi) path loss model with hexagonal deployments [83]

Table 1 Key Experimentally Derived Model Parameters Used Here and [34] Based on the NYC Data in [26]

Variable	Model	Model Parameter Values	
		28 GHz	73 GHz
Omnidirectional path loss, PL	$PL = \alpha + 10\beta\log_{10}(d) + \xi$, d in meters	$\alpha = 72.0$, $\beta = 2.92$	$\alpha = 86.6$, $\beta = 2.45$
Lognormal shadowing, ξ	$\xi \sim \mathcal{N}(0, \sigma^2)$	$\sigma = 8.7$ dB	$\sigma = 8.0$ dB
Number of clusters, K	$K \sim \max\{Poisson(\lambda), 1\}$	$\lambda = 1.8$	$\lambda = 1.9$
Cluster power fraction	See (3).	$r_\tau = 2.8$, $\zeta = 4.0$	$r_\tau = 3.0$, $\zeta = 4.0$
BS cluster rms angular spread	σ is exponentially distributed, $\mathbb{E}(\sigma) = \lambda^{-1}$	Horiz $\lambda^{-1} = 10.2°$; Vert $\lambda^{-1} = 0°$ (*)	Horiz $\lambda^{-1} = 10.5°$; Vert $\lambda^{-1} = 0°$ (*)
UE rms angular spread	σ is exponentially distributed, $\mathbb{E}(\sigma) = \lambda^{-1}$	Horiz $\lambda^{-1} = 15.5°$; Vert $\lambda^{-1} = 6.0°$	Horiz $\lambda^{-1} = 15.4°$; Vert $\lambda^{-1} = 3.5°$

Note: The model parameters are derived in [34] based on converting the directional measurements from the NYC data in [26], and assuming an isotropic (omnidirectional, unity gain) channel model with the 49 dB of antenna gains removed from the measurements.
(*) BS downtilt was fixed at 10 degree for all measurements, resulting in no measurable vertical angular spread at BS.

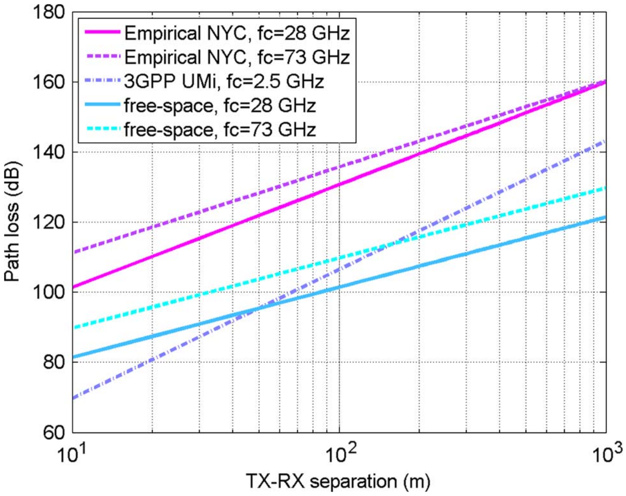


Fig. 8. ***Comparison of distance-based path loss models with unity gain antennas from [34]. The curves labeled "Empirical NYC" are the experimentally derived mmW models based on the NYC data [26]. These are compared to free space propagation for the same frequencies and the 3GPP UMi model [83] for 2.5 GHz.***

is given by

$$PL(d)\ [\mathrm{dB}] = 22.7 + 36.7 \log_{10}(d) + 26 \log_{10}(f_c) \quad (2)$$

where d is distance in meters and f_c is the carrier frequency in gigahertz. Fig. 8 plots this path loss model at $f_c = 2.5$ GHz. We see that our propagation models for unity gain antennas at both 28 and 73 GHz predict omnidirectional path losses that, for most of the distances, are approximately 20–25 dB higher than the 3GPP UMi model at 2.5 GHz. However, the wavelengths at 28 and 73 GHz are approximately 10–30 times smaller than at 2.5 GHz. Since, for a fixed antenna area, the beamforming gain grows with λ^{-2}, the increase in path loss can be entirely compensated by applying beamforming at either the transmitter or the receiver. In fact, the path loss can be more than compensated relative to today's cellular systems, with beamforming applied at both ends. We conclude that, barring outage events and maintaining the same physical antenna size, mmW propagation does not lead to any reduction in path loss relative to current cellular frequencies and, in fact, may be improved over today's systems. Moreover, further gains may be possible via spatial multiplexing, as we will see below.

D. Angular and Delay Spread Characteristics

The channel sounding system, with 10° beamwidth rotatable horn antennas and 400-MHz baseband signal bandwidth, enables high-resolution time and angular spread measurements. One of the key, and surprising, findings of our studies, was the presence of several distinct clusters of paths with significant angular and delay spread between the clusters. This observation provides strong evidence that—at least with the microcellular-type antennas in an urban canyon-type environment—mmW signals appear to propagate via several NLOS paths rather than a small number of LOS links. We note that these NLOS paths are arriving via reflections and scattering from different buildings and surfaces [26], [28]–[33], [78].

To illustrate the presence of multiple path clusters, the top panel of Fig. 9 shows the measured angular-of-arrival (AoA) power profile at a typical location in our 28-GHz measurements. At this location, we clearly see three angular clusters or "lobes" [31]—a common number observed over all locations. Similarly, the bottom panel shows the power delay profile, and we see that several clusters are apparent.

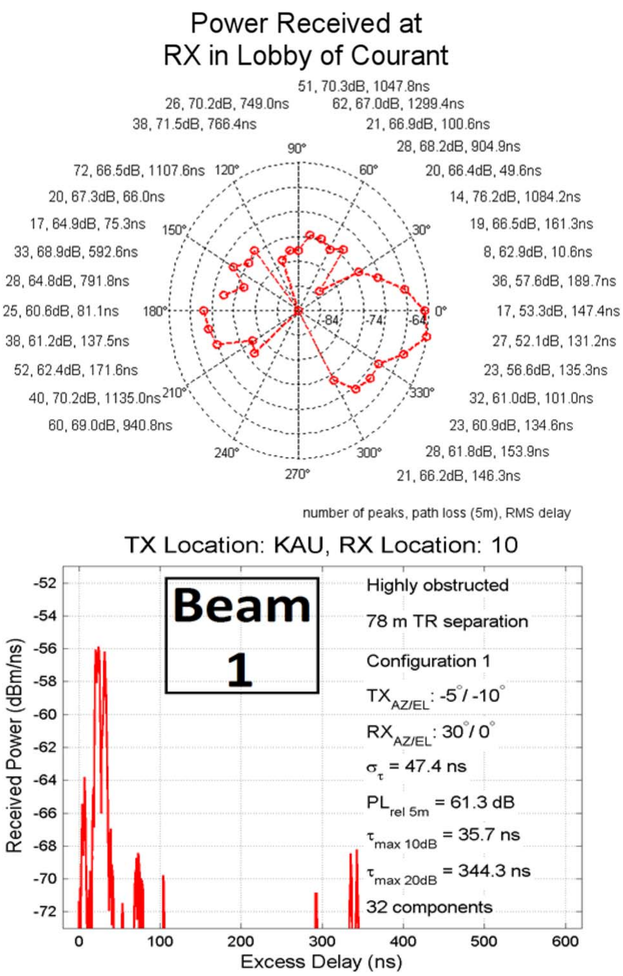


Fig. 9. ***(Top) AoA power profile measured in the courtyard outside a typical building in the 28-GHz measurement campaign. (Bottom) Power delay profile at a different location. Figures from [31] and [55].***

The presence of discrete clusters, each with relatively narrow angular and delay spread, will have certain implications for the receiver design that we discuss in Section V-E.

Akdeniz *et al.* [34] provide a detailed analysis of the statistical properties of the paths clusters, as based on the data [26], [28]–[33]. Some of the findings are as follows.

- The number of clusters is well modeled as a Poisson random variable with an average of approximately two clusters at each location. Due to the presence of multiple clusters and angular spread within clusters, many locations exhibit sufficient spatial diversity to support potentially two or even three spatial degrees of freedom. See [34] for more details.
- The angular spread (both between clusters and within clusters) occurs in the azimuth (horizontal) directions at both the transmitter and the receiver, indicating the presence of local scattering at both ends. Some vertical (elevation) angular spread is also observed at the receivers on the street, potentially from ground reflections. The root-mean-square (rms) beamspread within each cluster can vary significantly and is well modeled via an exponential distribution with similar parameters as current cellular models such as [83].
- The distribution of power among the path clusters is well modeled via a 3GPP model [83] where the fraction of powers in the K clusters are modeled as random variables $\gamma_1, \ldots, \gamma_K$ with

$$\gamma_k = \frac{\gamma_k'}{\sum_{j=1}^{K} \gamma_j'}, \qquad \gamma_k' = U_k^{r_\tau - 1} 10^{-0.1 Z_k} \tag{3}$$

  where the first random variable $U_k \sim U[0,1]$ is uniformly distributed and accounts for variations in delay between the clusters (clusters arriving with higher delay tend to have less power), and the second random variable $Z_k \sim \mathcal{N}(0, \zeta^2)$ is Gaussian and accounts for lognormal variations due to difference in shadowing on different clusters. The variables r_τ and ζ are constants fit to the observed power fractions. After fitting the parameters to the data, we found that the main cluster does not have the overwhelming majority of power. Significant power is often found in the second or even third strongest clusters, even considering attenuation due to longer propagation delay [34], again indicating the possibility of spatial multiplexing gains between a single BS and user equipment (UE).

E. Outage Probability

Due to the fact that mmW signals cannot penetrate many outdoor building walls, but are able to reflect and scatter off of them, signal reception in urban environments relies on either LOS links or strong reflections and scattering from building and ground surfaces. Therefore, a key risk in mmW cellular is outage caused by shadowing when no reflective or scattering paths can be found [31], [32].

To assess this outage probability, the study [34] used data from [26] and [28]–[33] which attempted to find signals of suitable strength at a number of locations up to 500 m from the transmitter. Interestingly, the analysis showed that signals were detectable at all 30 locations in Manhattan within 175 m from the cell. However, at locations at distances greater than 175 m, most locations experienced a signal outage. Since outage is highly environmentally dependent, one cannot generalize too much from these measurements. Actual outage may be more significant if there were more local obstacles, if a human were holding the receiver in a handheld device or, of course, if mobiles were indoor. We discuss some of these potential outage effects below.

IV. CAPACITY EVALUATION AND LESSONS LEARNED

Using the experimentally derived channel models from the NYC data [26], Akdeniz *et al.* [34] provided some simple system simulations to assess the potential urban mmW cellular systems. We summarize some of the key findings in that work along with other studies to estimate the possible capacity of mmW systems and identify the main design issues.

A. System Model

Our work here and the work in [34] follow a standard cellular evaluation methodology [83] where the BSs and UEs are randomly placed according to some statistical model, and the performance metrics were then measured over a number of random realizations of the network. Since the interest is in small cell networks, we followed a BS and UE distribution similar to the 3GPP UMi model in [83] with some parameters taken from [7] and [8]. The specific parameters are shown in Table 2. Observe that we have assumed an intersite distance (ISD) of 200 m, corresponding to a cell radius of 100 m. Also, the maximum transmit powers of 20 dBm at the UE and 30 dBm were taken from [7] and [8]. These transmit powers are reasonable since current CMOS RF power amplifiers in the mmW range exhibit peak efficiencies of at least 8%–20% [6], [84], [85].

We considered a network exclusively with mmW cells. Of course, in reality, mmW systems will be deployed with an overlay of conventional larger UHF/microwave cells. Thus, an actual mmW heterogeneous network will have a higher capacity, particularly in terms of cell edge rates. We discuss some of these issues in Section V-F.

To model the beamforming, which is essential in mmW systems, we followed a conservative model, making the simplifying assumption that only single stream processing (i.e., no single-user or multiuser spatial multiplexing) was

Table 2 Default Network Parameters From [34]

Parameter	Description
BS layout and sectorization	Hexagonally arranged cell sites placed in a 2km x 2km square area with three cells per site.
UE layout	Uniformly dropped in area with average of 10 UEs per BS cell (i.e. 30 UEs per cell site).
Inter-site distance (ISD)	200 m
Carrier frequency	28 and 73 GHz
Duplex mode	TDD
Transmit power	20 dBm (uplink), 30 dBm (downlink)
Noise figure	5 dB (BS), 7 dB (UE)
BS antenna	8x8 $\lambda/2$ uniform linear array
UE antenna	4x4 $\lambda/2$ uniform linear array for 28 GHz and 8x8 array for 73 GHz.
Beamforming	Long-term beamforming without single-user or multi-user spatial multiplexing

used. Of course, intercell coordinated beamforming and multiple-input–multiple-output (MIMO) spatial multiplexing [23], [86] may offer further gains, particularly for mobiles close to the cell. Although these gains are not considered here, following [55], we considered multibeam combining that can capture energy from optimally noncoherently combining multiple spatial directions to obtain capacity results here and in [34]. However, we only considered long-term beamforming [87] to avoid tracking of small-scale fading, which may be slightly challenging at very high Doppler frequencies (e.g., bullet trains) at mmW.

Both downlink and uplink assumed proportional fair scheduling with full buffer traffic. In the uplink, it is important to recognize that different multiple-access schemes result in different capacities. If the BS allows one UE to transmit for a portion of time in the whole band, the total receive power will be limited to that offered by a single user. If multiple UEs are allowed to transmit at the same time but on different subbands, then the total receive power will be greater, which is advantageous for users that are not bandwidth limited. The simulations below thus assume that subband frequency-division multiple access (FDMA) is possible. As we discuss in Section V-B, this enables much greater capacity as well as other benefits at the MAC layer. However, realizing such multiple-access systems presents certain challenges in the baseband front–end, which are also discussed.

B. SINR and Rate Distributions

We plot signal-to-interference-plus-noise ratio (SINR) and rate distributions in Figs. 10 and 11, respectively. The distributions are plotted for both 28 and 73 GHz and for 4×4 and 8×8 arrays at the UE. The BS antenna array is held at 8×8 for all cases, although we expect future mmW BSs to have thousands of antenna element leading to much greater gains and directionality. Some of the key statistics are listed in Table 3. More details can be found in [34].

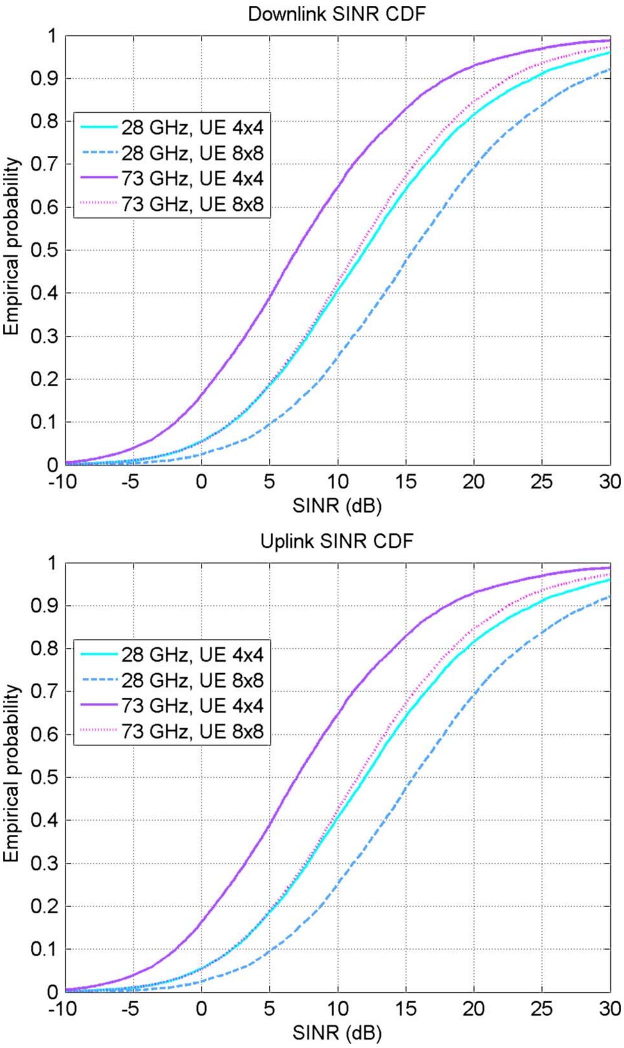


Fig. 10. ***Downlink (top plot)/uplink (bottom plot) SINR CDF at 28 and 73 GHz with 4 × 4 and 8 × 8 antenna arrays at the UE. The BS antenna array is held at 8 × 8. Figure from [34] based on measurement data in [26].***

There are two immediate conclusions we can draw from the curves. First, based on this evaluation, the sheer capacity of a potential mmW system is enormous. Cell capacities are often greater than 1 Gb/s and the users with the lowest 5% cell edge rates experience greater than 10 Mb/s. These rates would likely satisfy many of the envisioned requirements for beyond 4G systems such as [5] and [66].

Second, for the same number of antenna elements, the rates for 73 GHz are approximately half the rates for 28 GHz. However, a 4×4 $\lambda/2$-array at 28 GHz would take about the same area as an 8×8 $\lambda/2$ array at 73 GHz. Both would be roughly 1.5×1.5 cm^2, which could be easily accommodated in a handheld mobile device. In addition, we see that 73-GHz

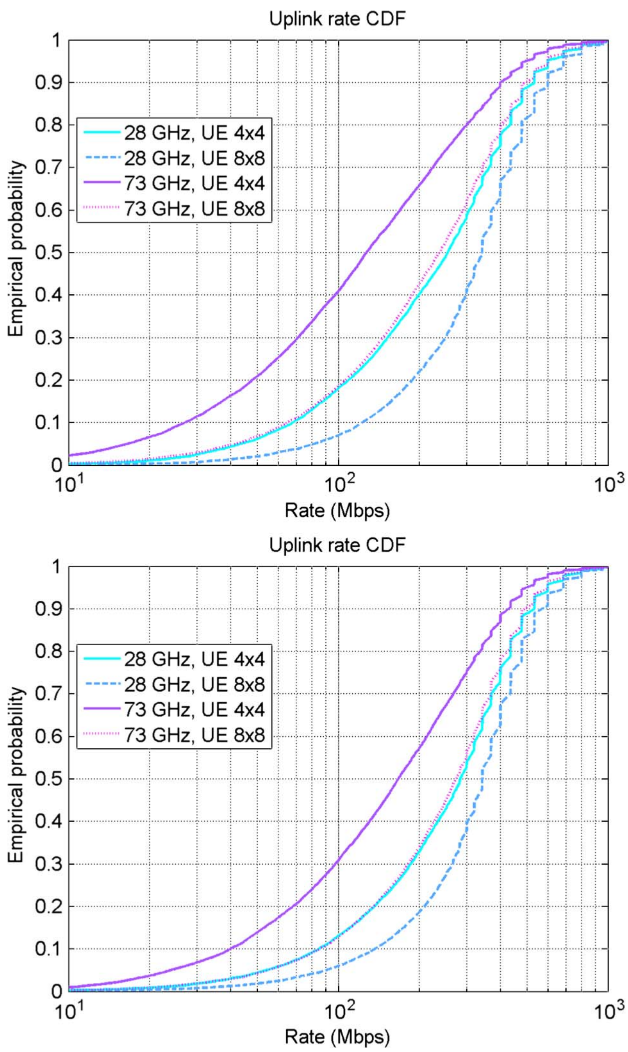


Fig. 11. ***Downlink (top plot)/uplink (bottom plot) rate CDF at 28 and 73 GHz with 4 $\times$ 4 and 8 $\times$ 8 antenna arrays at the UE. The BS antenna array is held at 8 $\times$ 8. Figure from [34] based on measurement data in [26].***

8 $\times$ 8 rate and signal-to-noise ratio (SNR) distributions are very close to the 28-GHz 4 $\times$ 4 distributions, which is reasonable since we are keeping the UE antenna size approximately constant. Thus, we can conclude that the loss from going to the higher frequencies can be made up from larger numbers of antenna elements without increasing the physical antenna area.

C. Comparison to 4G Capacity

We can compare the SINR distributions in Fig. 10 to those of a traditional cellular network. Although the SINR distribution for a cellular network in a traditional UHF or microwave band is not plotted here, the SINR distributions in Fig. 10 are actually slightly better than those found in cellular evaluation studies [83]. For example, in Fig. 10, only about 10% of the mobiles appear under 0 dB, which is a lower fraction than typical cellular deployments. We conclude that, although mmW systems have an omnidirectional path loss that is 20–25 dB worse than conventional microwave frequencies, short cell radii combined with highly directional beams are able to completely compensate for the loss, and, in fact, improve upon today's systems.

We can also compare the capacity and cell edge rates using the numbers in Table 3. The LTE capacity numbers are taken from the average of industry reported evaluations given in [83] (specifically Table 10.1.1.1-1 for the downlink and Table 1.1.1.3-1 for the uplink). The LTE evaluations include advanced techniques such as spatial-division multiple access (SDMA), although not coordinated multipoint. For the mmW capacity, we assumed 50-50 uplink–downlink (UL–DL) TDD split and a 20% control overhead in both UL and DL directions.

Under these assumptions, we see from Table 3 that the spectral efficiency of the mmW system for either the 28-GHz 4 $\times$ 4 array or the 73-GHz 8 $\times$ 8 array is roughly comparable to state-of-the art LTE systems.[2] Due to its larger bandwidth, we see in Table 3 (cell capacity) that the mmW systems offer a significant 20-fold increase of overall cell capacity. Moreover, this is a basic mmW system with no spatial multiplexing or other advanced techniques; we expect even higher gains when advanced technologies are applied to optimize the mmW system.

While the 5% cell edge rates are less dramatic, they still offer a ninefold to tenfold increase. This indicates a significant limitation of mmW systems under NLOS propagation; edge of cell users become power limited and are unable to fully exploit the increased spectrum. Thus, other features, such as the use of repeaters/relays, will be needed to achieve a more uniform performance in mmW systems in these scenarios.

D. Interference Versus Thermal Noise

A hallmark of current small cell systems in urban environments is that they are overwhelmingly interference limited, with the rate being limited by bandwidth, and not power. Our studies reveal that mmW small cell systems represent a departure from this model. For example, Fig. 12 plots the distribution of the interference-to-noise ratio (INR) for both uplink and downlink in our simulation of the mmW system at 28 GHz. We see that interference is not dominant. In fact, for the majority of mobiles, thermal noise is comparable or even larger, particularly in the downlink.

At the same time, although interference is not dominant, many of the mobiles are in a bandwidth-limited,

[2]Note that the spectral efficiency for the mmW system is quoted including the 20% overhead, but not the 50% UL–DL duplexing loss. Hence, the cell capacity in Table 3 is $C = 0.5\rho W$, where ρ is the spectral efficiency and W is the baseband bandwidth.

Table 3 Conservative mmW and LTE Cell Capacity/Cell Edge Rate Comparison From [34] Based on Isotropic Channel Models Derived From Measurement Data in [26]

System	BW & Duplex	BS antenna	UE antenna	fc (GHz)	Spec. eff (bps/Hz)		Cell capacity (Mbps)		5% Cell edge rate (Mbps)	
					DL	UL	DL	UL	DL	UL
mmW	1 GHz TDD	8x8	4x4	28	2.25	2.38	1130	1190	17.4	21.6
		8x8	8x8	28	2.83	2.84	1420	1420	32.7	36.3
		8x8	4x4	73	1.45	1.65	730	830	6.6	9.6
		8x8	8x8	73	2.15	2.31	1080	1160	16.6	22.1
LTE	20+20 MHz FDD	2 TX, 4 RX	2	2.5	2.69	2.36	53.8	47.2	1.80	1.94

Note 1. Assumes 20% overhead and 50% UL-DL duty cycle for the mmW system
Note 2. Long-term, non-coherent beamforming are assumed at both the BS and UE in the mmW system. However, the mmW results assume no spatial multiplexing gains, whereas the LTE results from [83] include spatial multiplexing and beamforming.

rather than power-limited regime. For example, Table 3 shows that the average spectral efficiency is approximately 2.1–2.4 b/s/Hz in the uplink and downlink for 4×4 28-GHz or 8×8 73-GHz systems. We find from Table 3 that, if spatial multiplexing is not exploited, links will be bandwidth limited and not power limited, even though interference is not dominant. We conclude that, without spatial multiplexing, mmW systems would represent a new network operating point not seen in current urban cellular deployments: large numbers of mobiles would experience relatively high SINR in directionally isolated links. In a sense, mmW takes us "back to the future" when cellular was first deployed in virgin spectrum.

Of course, without exploiting, spatial multiplexing systems would not benefit from all the degrees of freedom.

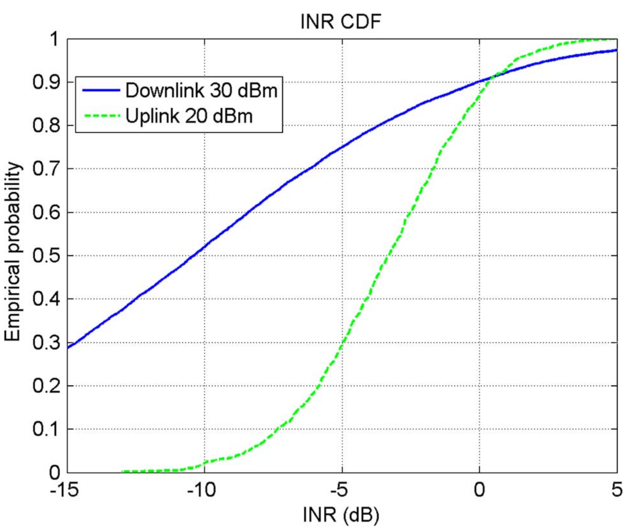


Fig. 12. ***Interference-to-noise ratio in the uplink and downlink for 28 GHz with a 4×4 UE antenna array.***

We have not yet evaluated single-user or multiuser MIMO, but such techniques would lower the SINR per stream for the higher SINR mobiles. However, the INR distribution would not significantly change since the total transmit power would be constant. Therefore, the links would remain limited by thermal noise rather than interference.

E. Effects of Outage

As mentioned above, one of the significant risks of mmW systems is the presence of outage; the fact that there is a nonzero probability that the signal from a given BS can be too weak to be detectable.

To quantify this effect, Akdeniz *et al.* [34] estimated the capacity under various outage probability models. The simulations above assumed that at distances greater than a threshold of $T = 175$ m, the signal would not be detectable, and, hence, the link would be in outage. This assumption was based on the data we observed in [26] and [28]–[33]. However, as discussed in Section III-E, mobiles in other environments may experience outages closer to the cell, particularly if there is a lot of ground clutter or the humans themselves blocking the signal. To model this scenario, Akdeniz *et al.* [34] considered a hypothetical outage model, loosely based on [83], where there was a significant outage probability even close to the cell. For example, in this model (called a "soft outage" for reasons explained in [34]), there was approximately a 20% probability that a link to a cell would be in outage even when it was only 80 m from the cell.

Interestingly, under this more conservative outage model, the average cell capacity was not significantly reduced. However, both uplink and downlink 5% cell edge rates fell by a dramatic 50%. This reduction shows that mmW systems are robust enough that mobiles in outage to any one cell will still be able to establish a connection to another cell. On the other hand, in environments where the outages close to the cell are frequent, the gains of

mmW systems will not be nearly as uniform, with cell edge users suffering significantly.

F. Other Studies

Although our study here and in [34] was the first to use the experimentally derived omnidirectional channel models from the directional data in [26], the results in [34] roughly corroborate the findings of very high capacity from mmW systems predicted in several earlier analyses. For example, the study in [7] estimated approximately 300 Mb/s per cell throughput in a 500-MHz system. This capacity corresponds to a somewhat lower spectral efficiency than what we show here and in [34], but the study in [7] assumed only minimal beamforming at the receiver (either no beamforming or a 2×2 array) and a much larger cell radius of 250 m.

In [9], ray-tracing software is used to analyze a mmW campus network, and a median total system capacity of 32 Gb/s with five cell sites, each cell site having four cells, is found. Since the bandwidth in that study was 2 GHz, the spectral efficiency was approximately 2/5/4/2 3 = 0.8 b/s/Hz/cell. This number again is lower than our predictions, but [9] was limited to quadrature phase-shift keying (QPSK) modulation. Somewhat higher capacity numbers were found in a followup study [65] in both campus and urban environments. A later study presented in [66] predicted average spectral efficiencies of almost 1.5 b/s/Hz in a 2-GHz system in an urban grid deployment, a number only slightly lower than our value of 2.3–2.8 b/s/Hz. In all these studies, the cell edge rates compare similarly to the predicted values in [34], assuming one normalizes to the number of users in each cell.

In a different work, Akoum *et al.* [22] used a stochastic geometry analysis and predicted almost 5.4 b/s/Hz, which is almost twice our estimated spectral efficiency. However, that work assumed that all links can operate at the Shannon limit with no maximum spectral efficiency.

This comparison illustrates that, in a number of different scenarios and analysis methods, the absolute spectral efficiency and cell edge rate numbers are roughly comparable with estimates here and in [34] that used experimentally derived channel models. Thus, the broad message remains the same: under a wide variety of simulation assumptions, mmW systems can offer orders of magnitude increases in capacity and cell edge rate over state-of-the-art systems in current cellular bands.

V. KEY DESIGN ISSUES AND DIRECTIONS FOR mmW 5G

The above preliminary results show that while mmW bands offer tremendous potential for capacity, cellular systems may need to be significantly redesigned. In this section, we identify several key design issues that need to be addressed from a systems perspective if the full gains of mmW cellular systems are to be achieved.

A. Directional Transmissions and Broadcast Signaling

The most obvious implication of the above results is that the gains of the mmW system depend on highly directional transmissions. As we discussed above, directionality gains with appropriate beamforming can completely compensate for, and even further reduce, any increase in the omnidirectional path loss with frequency. Indeed, once we account for directional gains enabled by smaller wavelengths, the path loss, SNR, and rate distributions in the mmW range compare favorably with (and may improve upon) those in current cellular frequencies.

One particular challenge for relying on highly directional transmissions in cellular systems is the design of the synchronization and broadcast signals used in the initial cell search. Both BSs and mobiles may need to scan over a range of angles before these signals can be detected. This "spatial searching" may delay BS detection in handovers—a point made in a recent paper [88]. Moreover, even after a mobile has detected a BS, detection of initial random access signals from the mobile may be delayed since the BS may need to be aligned in the correct direction.

A related issue is supporting intermittent communication [say through discontinuous reception and transmission (DRX and DTX) modes] which has been essential in standards such as LTE for providing low power consumption with "always on" connectivity [89]. In order that either a mobile or a BS can quickly begin transmitting, channel state information in the form of the spatial directions will need to be maintained at the transmitter. If cells are small, even the second-order spatial statistics of the channel may change relatively fast implying that some sort of intermittent transmissions may need to be performed to track the channel state.

B. Multiple-Access and Front–End/Baseband Considerations

With small cells, the need for future spectrum/bandwidth flexibility, support for beamforming and low cost, TDD is an attractive duplexing strategy for mmW. Our analysis in Table 3 assumes TDD for mmW.

However, closely related to the issue of directional transmissions is how to support FDMA within the TDD time slots. Current cellular systems use digital processing for MIMO and beamforming. However, with the large numbers of antennas and wide bandwidths, it is simply not practical from a power or cost perspective to place high-resolution, wideband A/D converters on each antenna element in the mmW range [6]–[8]. Most commercial designs have thus assumed phased-array architectures where signals are combined either in free space or RF with phase shifters [90]–[92] or at IF [93]–[95] prior to the A/D conversion. A limitation of such architectures is that they

will forgo the support of spatial multiplexing and multiuser transmissions within the TDD time slots and require time-division multiple access (TDMA) with only one user within a time slot being scheduled at a time. In particular, FDMA transmissions within the same time slot as supported in LTE through resource blocks will not be possible; see Fig. 13.

Enabling granular allocations in frequency is one of the main hallmarks of LTE, and sacrificing this capability by restricting to TDMA scheduling will bear significant costs in mmW.

- Uplink power: Restricting to TDMA scheduling within a TDD time slot implies that the power of only UE can be received at a time. Since mobiles at the cell edge may be power limited, this reduction of power can significantly reduce capacity. For example, according to the uplink rate cumulative distribution function shown in Fig. 14, one can easily see an order of magnitude improvement when multiuser transmission is enabled by FDMA, compared to a baseline TDMA, both assuming TDD.
- Support for small packets: Supporting multiuser transmissions will also be essential to efficiently support messages with small payloads and is needed for low latency machine-to-machine communications [96]. Specifically, when only one UE can transmit or receive at a time, it must be allocated in the entire bandwidth in a TDD slot, which is extremely wasteful for small packets. As an example, in the design of [8], the transmission time interval (TTI) is 125 μs. Thus, a 1-GHz allocation at this TTI will have approximately 125 000 degrees of freedom. Such large transport blocks would be terribly inefficient, for example, for transport control protocol acknowledgment as well as other control signaling.

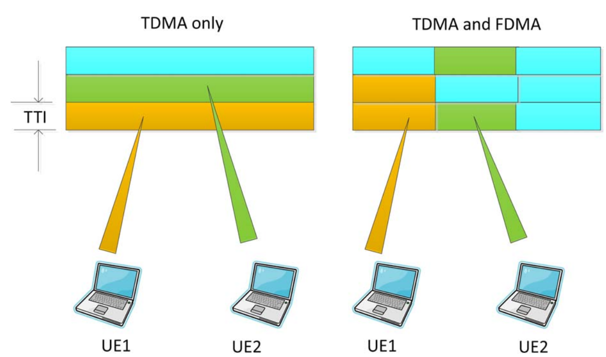


Fig. 13. ***Multiple access: Enabling FDMA (within a TDD time slot), where multiple UEs can be scheduled at a time, can offer numerous benefits in mmW systems, including improved power in the uplink, more efficient transmission of small packets, and reduced UE power consumption. A key design issue is how to support FDMA in TDD with mmW front-ends that perform beamsteering in analog.***

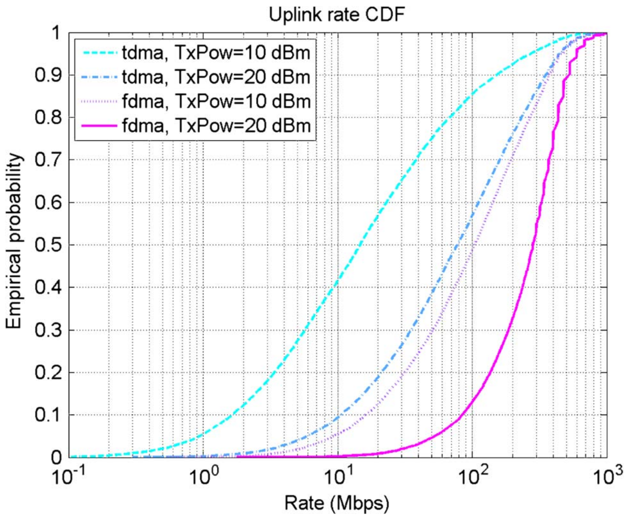


Fig. 14. ***Power loss with TDMA only: Designs that do not enable multiple users to be scheduled at the same time can suffer a significant penalty in capacity in the uplink due to loss of power. Shown here is the rate distribution comparing FDMA and TDMA scheduling using beamforming with the 28-GHz isotropic channel model.***

- Power consumption: From a power consumption perspective, it may be preferable for individual UEs to only process only a smaller portion (say 100 MHz) of the band during a time slot. Such subband allocations can reduce the power consumption of the baseband processing, which generally scales linearly in the bandwidth.

Thus, a key design issue facing 5G mmW systems is how to support multiple access while enabling low power consumption, particularly at the UE. One promising route has been the use of compressed sensing and other advanced low-bit rate technologies, suggested in [97].

In addition, one may consider other SDMA algorithms that optimally exploit a smaller number of beams. For example, each UE can still support only one digital stream, potentially on a subband for low power consumption. The BS, which would generally have somewhat higher power capacity, could support a smaller number, say K, beams. Then, to support N UEs with $K<N$, the BS can simply select the K beams to span the "best" K-dimensional subspace to capture the most energy of the N users.

C. Directional Relaying and Dynamic Duplexing

Another key design issue for mmW cellular systems is support for repeaters/relays—a feature that can be particularly valuable due to the need for range extension. In current cellular systems, relaying has been primarily used both for coverage extension and, to a lesser extent, capacity expansion when backhaul is not available [99]–[101]. Although significant research went into enabling relaying in 3GPP LTE-Advanced [102], the projected gains have been modest. In dense interference-limited environments, the

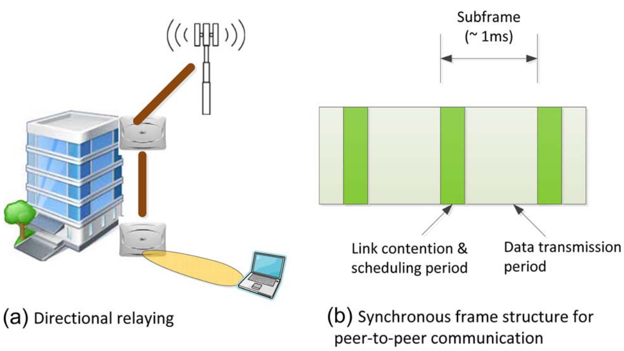


Fig. 15. ***Directional mmW relaying. (a) Multihop directional relaying can provide wireless backhaul and extend coverage of mmW signals in the presence of clutter and shadowing. (b) A synchronous peer-to-peer frame structure along the lines of [98] can enable fast coordination and resource allocation across relays, BSs, and mobiles with dynamic duplexing.***

loss in degrees of freedom with half-duplex constraints and multiple transmissions is typically not worth the increase in received power from shorter range.

With regards to relaying, mmW networks may be fundamentally different. As discussed above, one of the greatest challenges for mmW systems is that mobiles may be in outage to the closest cell, dramatically reducing the cell edge rate. In these cases, relaying may be necessary to selectively extend coverage to certain users and provide a more uniform quality of service throughout the network. Furthermore, given the inability of mmW signals to penetrate indoors, relaying would also be essential to provide seamless indoor/outdoor coverage and coverage in and around vehicles, airplanes, etc. Relaying may also be valuable for backhaul to picocells when fiber connectivity is not available [37]–[39]. Depending on the cell locations, some of these mmW links may be in the clutter and require NLOS connectivity similar to the access links; see, for example, Fig. 15(a).

In order to obtain the full advantages of relaying, cellular systems may need to be significantly redesigned. Cellular systems have traditionally followed a basic paradigm dividing networks into distinct BSs and mobiles, with relays typically being added as an afterthought. However, given the central role that relaying may play in the mmW range for both the access link and for backhaul, it may be worth investigating new peer-to-peer topologies, such as Qualcomm's FlashLinQ system [98], where there is less centralized scheduling and where frequency band and time slots are not statically preallocated to traffic in any one direction. As shown in Fig. 15(b), one may consider symmetric frame structures that are common in the uplink and downlink. The directions of the links would not necessarily need to be synchronized across the network, and a periodic contention period can be used to reassign the directions of the links as necessary. Such a design would be a significant departure from the uplink–downlink in current LTE systems, but would enable much greater flexibility for multihop networks and integrated systems for both access and backhaul.

D. An End to Interference?

As mentioned above, current cellular networks in dense urban deployments are overwhelmingly interference limited. At a high level, mitigating this interference can be seen as the driving motivation behind many of the advanced technologies introduced into cellular systems in the last decade. These techniques include coordinated multipoint, intercellular interference coordination and more forward-looking concepts such as interference alignment.

One of the striking conclusions of the above analysis is that many of these techniques may have much more limited gains in the mmW space. As we saw, for many mobiles, thermal noise is significantly larger than interference. That is, in mmW systems with appropriate beamforming, links become directionally isolated and intercellular interference is greatly reduced. This fact implies that point-to-point, rather than network, technologies may play a much larger role in achieving capacity gains in these systems.

E. Exploiting Channel Sparsity and Compressed Sensing

As described in Section II-B, one possible challenge in mmW system is the high Doppler. In general, Doppler spread is a function of the total angular dispersion, carrier frequency, and mobile velocity [54]. Thus, due to the high carrier frequencies and significant local scattering, one might initially think that the total Doppler spread in mmW systems will be high and potentially difficult to track.

However, the measurements reviewed in Section III revealed that signals generally arrive on a small number of path clusters, each with relatively small angular spread. Directional antennas will further reduce the multipath angular spread [103]. This property implies that the individually resolvable multipath components will vary very slowly, a fact confirmed directly in our experiments in [26]. This is good news.

To understand how to exploit these slow variations for tracking the channel, first observe that the narrowband channel response at any particular frequency could be described as

$$h(t) = \sum_{k=1}^{K} g_k(t) e^{2\pi i f_d \cos(\theta_k) t} \tag{4}$$

where K is the number of clusters, f_d is the maximum Doppler shift, θ_k is the central angle of arrival of the

cluster, and $g_k(t)$ is the time-varying gain of the channel related to the angular spread *within* the cluster. Since the angular spread within each cluster is small, the cluster gains $g_k(t)$ will generally be slowly varying even though the aggregate channel $h(t)$ may have much higher variations. Moreover, the angles of arrival θ_k are also typically slowly varying since they are a result of the large-scale scattering environment and do not change with small-scale mobility. This fact suggests that even though $h(t)$ may change rapidly, the parametrization (4) may enable more accurate tracking, particularly since the number of clusters K tends to be small (K is typically 1–5 in our measurements).

The parametrization (4) is fundamentally *nonlinear* and analogous to the types of models used in finite rate of innovation models [104] and compressed sensing-based channel estimation and channel sounding [105]–[108]. The extension of these methods to very wideband systems with large numbers of antennas may, therefore, have significant value.

F. Heterogeneous Networking Issues

As described in Section II-C, mmW systems cannot be deployed in a standalone manner. To provide uniform, reliable coverage, fallback to cellular systems in conventional UHF or microwave frequencies will be necessary. While support for heterogeneous networks has been a key design goal in recent cellular standards, mmW systems will push the need for support for heterogeneous networks in several new directions.

Most importantly, the heterogeneous network support in mmW will require cell selections and path switching at much faster rates than current cellular systems. Due to their vulnerability to shadowing, mmW signals to any one cell will be inherently unreliable and can rapidly change with small motions of the users or the user's environment. One avenue to explore is the use of *carrier aggregation* techniques [109], [110] where mobiles can connect to multiple BSs simultaneously. Carrier aggregation was introduced in release 10 of 3GPP LTE-Advanced primarily to increase peak throughputs. For mmW systems, carrier aggregation could provide macrodiversity, but would require support for path switching and scheduling in the network.

A second issue in the evolution of HetNets for mmW will be multioperator support. Indoor cells and cells mounted on private buildings may be better operated by a third party who would then provide roaming support for carriers from multiple subscribers. While roaming is commonly used in current networks, the time scales for mmW roaming would be much faster. In addition, with carrier aggregation, it may be desirable for a mobile to be connected to cells from different operators simultaneously.

Further complicating matters is the fact that, given the large amount of spectrum, a single operator may not be able to fully utilize the bandwidth. Thus, the model where a single operator has exclusive rights to a bandwidth may not lead to the most efficient use of the spectrum. However, support for multiple operators sharing spectrum will need much more sophisticated intercell interference coordination mechanisms, especially with directionality. Future clearing houses will provide such measurement and management for multiple carriers and their users.

VI. CONCLUSION

Millimeter systems offer tremendous potential with orders of magnitude greater spectrum and further gains from high-dimensional antenna arrays. To assess the feasibility of mmW systems, we have presented some initial propagation measurements in NYC—a challenging environment, but representative of likely initial deployments. Our measurements and capacity analysis have revealed several surprising features: Through reflections and scattering, mmW signals are potentially viable at distances of 100–200 m, even in completely NLOS settings. Moreover, with modest assumptions on beamforming, our capacity analysis has indicated that mmW systems can offer at least an order of magnitude in capacity over current state-of-the-art LTE systems, at least for outdoor coverage.

Potential mmW cellular systems may need to be significantly redesigned relative to current 4G systems to obtain the full potential of mmW bands. In particular, the heavy reliance on directional transmissions and beamforming will necessitate reconsideration of many basic procedures such as cell search, synchronization, random access, and intermittent communication. Multiple access and channelization also become tied to front–end requirements, particularly with regard to analog beamforming and A/D conversion.

In addition, directional isolation between links suggests that interference mitigation, which has been a dominant driver for new cellular technologies in the last decade, may have a less significant impact in mmW. On the other hand, technologies such as carrier aggregation and multihop relaying that have had only modest benefits in current cellular networks may play a very prominent role in the mmW space. These design issues—though stemming from carrier frequency—span all the layers of communication stack and will present a challenging, but exciting, set of research problems that can ultimately revolutionize cellular communication. ■

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