The authors show that single-carrier or low-number-of-subcarriers modulations are very attractive competitors to the dramatically more complex and energy-inefficient traditional multi-carrier designs.

**ABSTRACT**

By trading coverage and hardware complexity for abundance of spectrum, sub-THz mobile access networks are expected to operate under highly directive and relatively spectrally inefficient transmission regimes, while still offering enormous capacity gains over current sub-6 GHz alternatives. Building on this assumption, and supported by extensive indoor directional channel measurements at 160 GHz, this study advocates the use of very simple modulation and equalization techniques for sub-THz mobile access. Specifically, we demonstrate that, under the aforementioned transmission regimes, little or no equalization is needed for scoring significant capacity gain targets. In particular, we show that single-carrier or low-number-of-subcarriers modulations are very attractive competitors to the dramatically more complex and energy-inefficient traditional multi-carrier designs.

**ENERGY-EFFICIENT SUB-THZ MOBILE ACCESS**

**SPECTRAL EFFICIENCY IS NEITHER NEEDED NOR WELCOME**

The exploitation of the large portions of available spectrum in the sub-THz band (90–300 GHz) is one of the most promising directions for enhancing the capacity of current mobile access networks [1, 2]. In contrast to current sub-6 GHz networks, for which a 100-fold capacity increase can only be achieved by means of extreme spatial multiplexing and very complex modulation schemes, sub-THz networks can score this ambitious goal by transmitting fewer simultaneous data streams with relatively low spectral efficiency ($\approx 1–3$ b/s/Hz). These observations are best illustrated by focusing on the following approximate formula for the network capacity:

$$ C = B \cdot M \cdot SE \text{ b/s/km}^2, \quad (1) $$

where $B$ is the signal bandwidth in Hertz, $M$ is the number of spatially multiplexed streams per square kilometer, and $SE$ is the per-stream spectral efficiency in bits per second per Hertz. In excellent conditions, current 5G sub-6 GHz networks approximately support $B \approx 100$ MHz, $M \approx 16$, and $SE \approx 3–6$ b/s/Hz by using massive multiple-input multiple-output (MIMO) arrays with 64 antennas and multi-carrier 256-quadrature amplitude modulation (QAM) signals. A 100-fold capacity increase at sub-6 GHz frequencies would require 100 times larger aggregate spectral efficiency (i.e., the product of $M$ and $SE$), which is very challenging to achieve due to the problematic interaction between $M$ and $SE$ caused by interference, and since $SE \approx 10$ b/s/Hz is already close to its practical limit caused by hardware imperfections. In contrast, by moving to sub-THz frequencies, for which bandwidths up to $B \approx 30$ GHz are conceivable, the same goal could be achieved with a dramatically more relaxed requirement on both $M$ and $SE$.

Admittedly, if the target 100-fold capacity increase must be realized in an energy-efficient manner, finding directional transmission regimes with very large bandwidth and spectral efficiency is a highly non-trivial task. For instance, the best known analytic tools do not cover the energy consumed by the hardware [3]. The present study focuses on sub-THz mobile access (i.e., on the exploration of the very large bandwidth extreme of this trade-off). In this regime, restriction to modulation schemes with low spectral efficiency is not only sufficient but also of paramount importance, since the resulting relaxation of the hardware requirements offers a unique opportunity for developing sub-THz transceivers with tolerable energy consumption [2].

**HIGHLY DIRECTIVE STEERABLE BEAMFORMING ANTENNAS**

To guarantee reasonable coverage at such high frequencies and large bandwidths with acceptable radiated power, highly directive antennas must be used [1]. For instance, upgrading an ideal sub-6 GHz free-space link through a 100-fold increase in frequency and bandwidth, while keeping the same coverage, radiated power, and target spectral efficiency, would require a directivity gain of about 60 dBi. For this reason, even considering significantly more relaxed coverage and spectral efficiency requirements than their sub-6 GHz counterparts, sub-THz mobile access networks will likely need directive antennas ($\approx 10–30$ dB) at both the transmit and receive ends. Furthermore, due to user mobility, high directivity must be dynamically realized via steerable beamforming antennas. This poses a series of remarkable technical challenges subject to extensive ongoing research, such as the...
energy-efficient design of this type of antennas and the so-called two-sided beam alignment problem [4, 5]. The present study assumes that high-gain steerable beamforming antennas are indeed feasible, and that a beam alignment procedure can be successfully performed. Under this assumption, the main focus is the evaluation of the possibly beneficial impact of using highly directive antennas on channel equalization.

**The Impact of Directivity on Inter-Symbol Interference**

Many previous studies on millimeter-wave and THz systems already recognized that the use of highly directive antennas leads to radio channels (i.e., comprising the effect of the antennas) with considerably lower delay spread than the underlying propagation channels, and hence to radio channels for which simple modulation and equalization techniques are potentially sufficient [6–8]. This crucial observation can be explained by the so-called spatial filtering effect, which is illustrated in Fig. 1. As customary, we model the single-input single-output radio channel between two beamforming antennas by means of a channel impulse response \( h = (h_0, ..., h_L) \) with \( L \) taps, and a nominal signal-to-noise ratio (SNR) parameter. Then, by assuming standard coding techniques, and by treating inter-symbol interference as noise, an achievable spectral efficiency over this channel is

\[
\text{SE} = \log_2 \left(1 + \frac{|h_0|^2}{\sum_{l \neq 0} |h_l|^2 + \text{SNR}^{-1}}\right).
\]

(2)

where \( l_0 \) is the delay corresponding to the main peak of the power delay profile. Importantly, we remark that the above transmission scheme does not consider any form of digital equalization. For this reason, in the presence of significant inter-symbol interference, as depicted in Fig. 1a for the case of low antenna directivity, the spectral efficiency may be quite poor. However, when highly directive antennas are employed and most multipath components are consequently attenuated, as depicted in Fig. 1b, this simple scheme may be sufficient to achieve the relatively low target spectral efficiencies of sub-THz mobile access networks. Moreover, if needed, simple equalization techniques may be sufficient to suppress most of the residual inter-symbol interference and further improve upon Eq. 2. The reminder of this study is devoted to a deeper investigation of this intuition.

**The Impact of Directivity on Multi-User Interference**

The spectral efficiency expression in Eq. 2 based on treating inter-symbol interference as noise can be readily extended such that additional interference terms corresponding to the incoming signal of other users are included. Following the same spatial filtering argument as for inter-symbol interference, the use of highly directive antennas may significantly mitigate the impact of multi-user interference, provided that the interfering signal components do not overlap with the main desired signal component. In this work, for simplicity, we neglect multi-user interference by invoking the aforementioned spatial filtering effect, and by assuming the concurrent scheduling of users that are sufficiently separated in the angular domain. Therefore, the resulting capacity figures are only valid up to some maximum multiplexing gain \( M \) that, roughly speaking, depends on the antenna beamwidth and the angular distribution of the users.

**Objective, Methodology, and Organization of the Article**

Following the above discussion, the main objective of this study is to experimentally validate the claim that the combination of a relatively low target SE and the use of highly directive beamforming antennas may allow the use of simpler modulation and equalization techniques than in traditional designs, and hence leave room for significant energy savings. To this end, differently than in most related studies (see, e.g., [9, 10]), we follow an unconventional but more targeted methodology that integrates accurate measurement data with rigorous information theoretic arguments. More specifically, instead of extracting channel modeling parameters such as delay spread, we present the results of a measurement campaign directly in terms of theoretically achievable performance for different choices of modulation and equalization techniques. The reminder of this study is organized as follows. We illustrate the performed measurement campaign, and discuss how the obtained measurements can be used to approximate realistic sub-THz communication channels. We present the results of the measurement campaign in terms of achievable spectral efficiency and coded bit error rate (BER) for promising modulation and equalization techniques. Finally, we summarize the main conclusions and outline some possible future directions.

**Measurement Campaign**

This section illustrates the technical details of a measurement campaign aimed at characterizing the performance of simple modulation and equalization techniques for realistic indoor radio channels with 160 GHz carrier frequency, 4 GHz bandwidth, and directive beamforming antennas.

**Channel Sounder Setup**

The adopted channel sounder is based on the principle of time-domain channel measurement. Test and measurement equipment working in the millimeter-wave frequency range is expanded with active D-band front-ends that allow extension to carrier frequencies between 110 GHz and 170 GHz. The setup can be divided into transmitter (Tx) and receiver (Rx), where the Tx is kept fixed and the Rx is moved across different positions. The Tx consists of a signal generator (R&S® SMW200A) and an external D-Band front-end (R&S® FE170ST). The signal generator provides a perfect periodic correlation sequence (Frank-
The collected raw data are processed as follows. First, for each measurement position and scenario, a set of 500 calibrated channel impulse responses are extracted from the IQ samples, each corresponding to a single sounding sequence. Across the 500 measurements, a phase deviation is estimated under the assumption of a stationary radio channel. Thus, the common phase error of each sequence is compensated, and the 500 complex impulse responses are averaged, resulting in one common impulse response per measurement position with improved correlation gain. Finally, the obtained impulse responses are power normalized and synchronized with respect to the first peak. Accurate synchronization with sub-sample resolution is achieved via upsampling and cubic interpolation of the main peak. The resulting channel impulse responses correspond to channels as seen by a hypothetical communication system after phase and frequency offset compensation and time synchronization. Furthermore, since the impulse responses show a dynamic range of more than 60 dB, they can be considered as noise-free channel estimates for all SNR regions of practical communication systems.

**ILLUSTRATIVE EXAMPLES OF MEASURED CHANNELS**

The exceptionally high dynamic range allows the observation of multipath components that are significantly smaller than the LoS path. Additionally, the temporal resolution resulting from the measurement bandwidth of 4 GHz allows the distinction of paths with a theoretical minimum distance of 0.25 ns. Figure 3 shows the measured power delay profile $|h|^2$ for three representative cases. The green plot refers to a measurement from the first scenario, at the distance of 18 m. Importantly, the green plot reveals the presence of a strong multipath component only 2 channel taps away from the LoS path, and it is a representative example of a channel with significant inter-symbol interference. This path is likely due to a ground reflection. The red and blue plots refer to two measurements from the second scenario, at a distance of 7 m and 1 m, respectively. In the red plot, the LoS path is clearly separable from the other paths, which all lie well below –30 dB. This is a representative example of a particularly well-behaved channel with negligible inter-symbol interference. In the blue plot, two relatively strong multipath components can be observed within a range of 0 dB and –30 dB, at a delay of 2 and 30 taps, respectively. Both correspondents, and especially the second path, may be caused by the interaction with the metal surfaces of the Tx and Rx devices themselves. This is a representative example of a channel with several signif-

**MEASUREMENT SCENARIO AND PROCEDURE**

The measurement campaign is conducted on the company premises of Rohde & Schwarz in Munich, Germany. As the venue, the rectangular atrium of a large building is used. The atrium’s dimensions are 15 m x 50 m with a height of approximately 20 m. The environment is mainly characterized by glass walls, a tiled floor, metallic surfaces (elevators), and concrete pillars. Figure 2 illustrates the measurement setup in terms of a floor plan, and the chosen Tx and Rx positions. For all positions, a line of sight (LoS) between the Tx and Rx was ensured, and the Tx and Rx antennas were aligned along the corresponding LoS direction. This corresponds to the assumed use case where the beams of the steerable antennas at the Tx and Rx are aligned. Two different measurement scenarios were considered, differing in the movement pattern within the atrium. In the first scenario, the Tx was placed centrally at the beginning of the atrium, and the Rx was moved longitudinally. Distances from 1 m up to 40 m were considered, resulting in 20 measurement positions. In the second scenario, a similar movement pattern was used along the diagonal line connecting two opposite corners of the atrium. Distances from 1 m to 46 m were considered, resulting in 26 measurement positions.

The first scenario was designed such that multipath components may be detectable, including ground reflections and reflections by, for example, the metal surfaces of the elevators. The second scenario was designed such that fewer multipath components should be detectable with respect to the first scenario. Nevertheless, the ground reflection may still be detectable.

For all positions, a line of sight (LoS) between the Tx and Rx is aligned. Two different scenarios were considered, resulting in 20 measurement positions. In the second scenario, a similar move-
significant multipath components with intermediate strengths that might influence the performance of a communication system. Due to the high dynamic range of the measurement setup, more multipath components are visible in all three channels below ~40 dB. Nonetheless, these components are so weak that they can be neglected for the low spectral efficiency regime.

Overall, all measured radio channels appear to be composed of only few relevant propagation paths with significant strength. These propagation paths, corresponding to the peaks of the power delay profiles, are mostly due to reflections captured by the main lobes of the antenna radiation patterns, and are generally located within 10–30 taps. This confirms the main intuition illustrated in Fig. 1. However, different than in the idealized model of Fig. 1, the channels exhibit additional taps in close proximity of the channel peaks, which are likely due to the chosen pulse shape. In fact, the measurements are hard band-limited; that is, they consider a sinc-like Nyquist pulse with pronounced side lobes, which contribute to inter-symbol interference in the (almost sure) case of the path delay being not perfectly aligned with the sampling grid.

Relation with Realistic Sub-THz Communication Channels
As already anticipated, in the remainder of this study we assess the performance of simple modulation and equalization techniques directly over the measured channel impulse responses. A natural question is to what extent do these impulse responses reflect the channel seen by a realistic communication system. First, we point out that the chosen antenna directivities (25 dBi and 6 dBi) can be reasonably implemented using steerable phased arrays of practical size and cost, and, as discussed earlier, are almost necessary to provide sufficient coverage at sub-THz frequencies. Note that since beam alignment is implemented by means of mechanical steering (a form of true-time-delay beamforming), our measurements are insensitive to the spatial wideband effect [11] for the LoS path. Nevertheless, the chosen antenna directivities and signal bandwidth fall into a regime where the spatial wideband effect is negligible for λ/2 spaced phased arrays, and therefore the measurements are also representative of more practical beamforming implementations. Second, we argue that the chosen pulse shape still produces good approximations of realistic communication channels. In fact, although practical communication systems may consider pulses with faster decay, such as root raised cosine pulses, the difference would be mostly noticeable for the weaker secondary paths, since accurate time recovery is performed with respect to the main peak.

Finally, we remark that the current channel impulse responses are representative of a system with 4 GHz communication bandwidth, which is a reasonable choice for early prototypes of sub-THz mobile access networks. Nevertheless, this bandwidth is already sufficient to capture the main impact of the absolute delay spread with a sub-nanosecond resolution. Therefore, the results in this study could also be approximately extended to systems with higher bandwidths, provided that the delay spread expressed in number of channel taps is scaled accordingly.

Measurement Results
In this section, we present the results of our measurement campaign in terms of achievable performance of promising modulation and equalization techniques over the measured channels. In particular, motivated by the importance of ener-
gy-efficient designs, we study two alternatives to traditional implementations of multi-carrier modulation based on orthogonal frequency-division multiplexing (OFDM). Multi-carrier modulation is known to approach the fundamental spectral efficiency limits of inter-symbol interference channels with a relatively simple equalization effort, provided that the number of subcarriers is large enough. However, its main drawback is the known issue of producing signals with peak-to-average-power ratio (PAPR) proportional to the number of subcarriers, which needs to be compensated for by significantly reducing the energy efficiency of the transceiver front-end. Therefore, we consider single-carrier modulation with linear equalization and multi-carrier modulation with a low number of subcarriers. We then show that both alternatives achieve spectral efficiencies of about 1–3 b/s/Hz over all measured channels. Hence, both schemes may be sufficient to score the target capacity gains in a more energy-efficient manner.

**Single-Carrier with Linear Equalization**

We first consider single-carrier modulation followed by an N-tap linear equalizer. An achievable spectral efficiency is given by Eq. 2, with h replaced by its convolution with the equalizer impulse response. We compute the optimal equalizer coefficients in terms of spectral efficiency (i.e., maximizing the corresponding Rayleigh quotient appearing in Eq. 2). The solution takes the form of a standard linear minimum mean square error equalizer. We set $l_0$ as the delay of the main peak of the original power delay profile, plus an additional offset which is tuned such that the equalizer focuses on the optimal number of precursors and postcursors (in practice, only one or two postcursors are relevant).

Figure 4 reports the resulting achievable spectral efficiency over the measured channels as a function of the number of taps $N$, where $N = 1$ stands for no equalization and assuming SNR = 6 dB. Since the channel impulse responses are normalized, the SNR parameter can be interpreted as a receive SNR comprising transmit power, path loss, beamforming gain, and receiver noise. The dashed line shows the so-called matched filter upper bound, equivalent to the capacity of an AWGN channel with the same SNR, which provides an upper bound on the achievable spectral efficiency. We remark that this bound is generally not achievable and may be even quite far from the achievable performance under ideal equalization in channels with significant inter-symbol interference. The chosen SNR is in the high range of what is expected to be practically feasible at the edge of a sub-THz mobile access network. Furthermore, it leads to an upper bound within the spectral efficiency regime of interest (i.e., 1–3 b/s/Hz). For lower SNR values, the gains of the equalization decrease until they become negligible. A higher SNR improves performance for all choices of number of taps $N$, up to saturation points driven by the uncompensated inter-symbol interference for the given choice of $N$.

As we can see, 50 percent of the measured channels are so well behaved that no equalization is actually needed to approach almost ideal performance. Furthermore, reliable communication above 1 b/s/Hz without equalization is theoretically possible in the vast majority of the cases. However, in the other 50 percent of the cases, the inter-symbol interference caused by strong paths in close vicinity of the main peak causes large variations from the ideal performance. In a few extreme cases, the achievable spectral efficiency may even drop below 1 b/s/Hz. Fortunately, this residual inter-symbol interference can be significantly mitigated by using only 5–6 equalization taps, for which the achievable spectral efficiency is consistently kept above 1.4 b/s/Hz. One important comment here is that in all measured channels, further spectral efficiency gains can only be observed after adding several tens or even
hundreds of equalization taps (i.e., when the filter length reaches the weaker multipath components located far away from the main peak). Nevertheless, these gains are negligible and do not justify the longer equalizers.

As a final remark, we recall that the above figures are valid for a 4 GHz communication bandwidth (i.e., for theoretical rates on the order of 4 Gb/s/stream). If higher bandwidths are used, and the target SNR is kept to the same value, the number of required equalization taps for each measurement point may increase proportionally, reaching a few tens of taps in the worst cases. Still, the main message of this section would continue holding: that is, single-carrier modulation and a simple linear equalizer may be sufficient to score the target capacity goals in the considered indoor scenario.

**Multi-Carrier with a Low Number of Subcarriers**

In this section, we consider multi-carrier modulation based on a standard OFDM implementation with \( K \) subcarriers and a cyclic prefix of length \( Q \). In contrast to traditional designs, we study the effect of choosing a prefix length much shorter than the delay spread (i.e., we focus on \( Q \ll 1 \)). In this regime, the channel in the subcarrier domain suffers from both inter-carrier interference (ICI) and inter-block interference (IBI) \([12]\). By following similar arguments as for the single-carrier case (i.e., by treating ICI and IBI as noise), an achievable spectral efficiency is given by the sum of \( K \) expressions similar to Eq. \( 2 \), where the signal and inter-symbol interference terms are replaced by the appropriate channel coefficients in the subcarrier domain, and a pre-log factor that takes into account the prefix overhead. For all tested numbers of subcarriers \( K \), we optimize the prefix length \( Q \). Furthermore, similar to the single-carrier case, we consider a block-boundary detection stage such that the prefix is optimally centered with respect to the main channel peak.

Interestingly, for all tested numbers of subcarriers, the gains of adding a cyclic prefix in terms of ICI and IBI mitigation are minor and outweighed by the multiplicative spectral efficiency losses due to the overhead. As a consequence, we focus on an unconventional implementation with no prefix (\( Q = 0 \)), as proposed in \([12]\). However, different than \([12]\), we do not consider additional equalization stages, and simply treat ICI and IBI as noise. Similar to the single-carrier case, Fig. \( 5 \) reports the resulting achievable spectral efficiency over the measured channels as a function of the number of subcarriers \( K \) and by assuming \( \text{SNR} \approx 6 \text{ dB} \). We notice that very few subcarriers are needed to achieve spectral efficiencies significantly higher than 1 b/s/Hz in all measured channels and are often sufficient to approach the ideal performance limit. An informal explanation is that even without a cyclic prefix, the inter-symbol interference is spread over multiple subcarriers and pushed toward the noise floor as \( K \) increases. Furthermore, at the price of a higher PAPR and hence of more stringent hardware efficiency requirements, we observe that the proposed multi-carrier modulation with \( K \geq 16 \) achieves better spectral efficiencies (in both median and worst case) than single-carrier modulation even for a large number of equalization taps (we tested up to \( N = 256 \) equalization taps).

**Performance of a Complete System**

In this section, we show that reliable communication at 1 b/s/Hz over the measured channels is indeed feasible by using simple modulation and equalization techniques. Specifically, we run a numerical simulation of a system employing single-carrier quadrature phase shift keying (QPSK) modulated signals, linear minimum mean square error equalization with \( N = 7 \) taps (two of which are postcursors), and standard low-density parity check (LDPC) codes. The LDPC code has a rate of 1/2 and a 1296-bit block length, and uses the parity check matrix as defined in the IEEE 802.11n standard. The LDPC decoder is tuned by treating inter-symboll interference as additive Gaussian noise with the same power and uses a belief propagation algorithm. The simulated transmit signals are distorted by the measured channel impulse responses, and Gaussian noise is added according to the SNR parameter. Figure \( 6 \) reports the performance in terms of coded BER for all measured channels as a function of the SNR. For reference, we also report the corresponding uncoded BER curves, and a lower bound on the minimum SNR for reliable communication at 1 b/s/Hz, obtained from the aforementioned matched filter upper bound on the achievable spectral efficiency (Shannon limit). Remarkably, the gap between the obtained BER curves and the (not necessarily achievable) Shannon limit is in the vast majority of cases between 2.5–4 dB, a range that is in line with the typical gap from capacity of LDPC codes on AWGN channels. Furthermore, letting SNR \( \approx 6 \text{ dB} \) allows for reliable communication even for the worst case channels, as predicted by Fig. 4. This confirms that for low target spectral efficiencies, inter-symbol interference can indeed be successfully mitigated by means of simple equalization techniques, at the point when it can be treated as noise and further mitigated by standard codes for the AWGN channel.

**Conclusion**

Our results corroborate the attractiveness of simple and energy-efficient alternatives to traditional OFDM-based designs in sub-THz mobile access networks. In particular, our results strengthen the claim that single-carrier modulation is a promising solution for the early development of these networks, where energy efficiency is a major limiting factor. Then our results suggest that an evolution toward more capable networks can be accomplished by gradually increasing the number of subcarriers in an unconventional OFDM implementation. Our methodology integrates accurate experimental data with rigorous information theoretic arguments. The integration of these approaches is particularly effective, since our channel measurements closely approximate the impulse response as seen by a hypothetical but realistic sub-THz communication system in the same indoor environment, and with the same signal bandwidth (4 GHz), carrier frequency (160 GHz), and antenna directivities at the access point (25 dB) and user equipments (6 dB). To further test the robustness of our analysis, future works should explore different system parameters. For instance, even though some preliminary conclusions can already be extrapolated from this.
study, a direct performance evaluation for larger bandwidths is desirable. Perhaps most importantly, future works should also cover different environments with more reflections and possibly a higher number of multipath components. Furthermore, non-line-of-sight propagation and the effect of multi-user interference are interesting additions to the analysis.

REFERENCES

[1] S. T. Rappaport et al., “Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond,” IEEE Access, vol. 7, 2019, pp. 78,729–57.
[2] N. Rajatheva et al., “Scoring the Terabit’s Goal: Broadband Connectivity in 6G,” arXiv preprint arXiv:2008.07220, 2020.
[3] S. Verdú, “Spectral Efficiency in the Wideband Regime,” IEEE Trans. Info. Theory, vol. 48, no. 6, 2002, pp. 1319–43.
[4] H. Yan et al., “Performance, Power, and Area Design Trade-Offs in Millimeter-Wave Transmitter Beamforming Architectures,” IEEE Circuits Sys. Mag., vol. 19, no. 2, 2019, pp. 33–58.
[5] X. Song, T. Kühne, and G. Caire, “Fully/Partially-Connected Hybrid Beamforming Architectures for mmwave MU-MIMO,” IEEE Trans. Wireless Commun., vol. 19, no. 3, 2020, pp. 1734–69.
[6] R. Sun et al., “Millimeter-Wave Radio Channels vs. Synthe- sis Beamwidth,” IEEE Commun. Mag., vol. 56, no. 12, Dec. 2018, pp. 53–59.
[7] R. Pietrievicz et al., “Performance Analysis of Future Multi- gigabit Wireless Communication Systems at THz Frequen- cies with Highly Directive Antennas in Realistic Indoor Environments,” IEEE J. Sel. Topics Quantum Electron., vol. 14, no. 2, 2008, pp. 421–30.
[8] H. Sarieddeen, M.-S. Alouini, and T. Y. Al-Naffouri, “An Overview of Signal Processing Techniques for Terahertz Communications,” Proc. IEEE, vol. 109, no. 10, 2021, pp. 1628–65.
[9] J. Gomez-Ponce et al., “Directionally Resolved Measurement and Modeling of THz Band Propagation Channels,” IEEE Open J. Antennas and Propagation, vol. 3, 2022, pp. 663–86.
[10] Y. Xing, T. S. Rappaport, and A. Ghosh, “Millimeter Wave and Sub-THz Indoor Radio Propagation Channel Measurements, Models, and Comparisons in an Office Environment,” IEEE Commun. Lett., vol. 25, no. 10, 2021, pp. 3151–55.
[11] B. Wang et al., “Spatial-Wideband Effect in Massive MIMO with Application in mmWave Systems,” IEEE Commun. Mag., vol. 56, no. 12, Dec. 2018, pp. 134–41.
[12] M. Toeltsch and A. F. Molisch, “Efficient OFDM Transmission Without Cyclic Prefixes for Frequency-Selective Channels,” Proc. 11th IEEE Int. Symp. Personal Indoor and Mobile Radio Commun., 2000, vol. 2, pp. 1363–67.

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