Distributed Deployment and Dual-Frequency Concepts to Strengthen Sub-THz Wireless Systems

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***Abstract*—The vast bandwidth available at sub-THz frequencies holds great promise for high-speed wireless access, precise localization, and advanced sensing applications. However, fundamental physical constraints and technological limitations make the deployment of reliable sub-THz networks challenging. We propose a new paradigm for sub-THz coverage by transmitting the RF signals over polymer microwave fibers (PMFs) that interconnect low-complexity radio units (RUs) in a daisy-chain configuration. The distributed architecture ensures that user equipments (UEs) connect to RUs in their proximity, reducing path loss and mitigating blocking. The RUs leverage low-complexity, compact integrated antenna modules. Additionally, dual-frequency *tandem operation* is proposed, integrating the sub-THz system with a sub-$10\,\mathrm{GHz}$ system that provides control signalling and a robust fallback solution for the sub-THz system. This proposed tandem architecture can open up the full potential of sub-THz technology and paves the way to cost- and energy-efficient, high-performance, real-time connectivity in dynamic environments.**

***Index Terms*—Sub-THz, distributed networks, dual-frequency, radio-over-fiber**

Fig. 1: The fragility of sub-THz links calls for new deployment approaches. A distributed deployment can strengthen the systems.

I. Introduction

Applications such as AR/XR and robotized factories require $\mathrm{Gbit/s}$ communication and accurate positioning. The large bandwidth available at sub-THz frequencies suggests that this band could provide a "highway to connectivity heaven". This has motivated R&D teams to progress technology, resulting in sub-THz channel models [1], hardware modules integrating many antennas and transceivers [2], and demonstrations of transmission at $>100\,\mathrm{Gbit/s}$ [3], [4]. These developments have demonstrated that very high throughputs can be achieved in sub-THz bands, in particular for static links. However, providing reliable coverage and consistent connectivity to non-static terminals at these frequencies is extremely difficult when compared to operation in sub-$10\,\mathrm{GHz}$ bands. Sub-THz links are fragile. The reasons lie in physics of propagation, blocking and Doppler especially, as explained in Section II, and in losses and intrinsic distortions introduced by high-frequency hardware that need to be mitigated, as elaborated in Section II-B. Hence, critical questions remain open: Can the potential of sub-THz be unleashed for applications in need of reliable links to non-static users? Or will sub-THz systems follow the same path as mmWave solutions, which in actual commercial deployments so far remain underused?

Distributed approaches have been proposed to cope with blockage, e.g. [5], however not considering how the distribution of sub-THz signals could be effectuated with a good cost versus signal loss compromise. In this paper, we present a new perspective on how to provide sub-THz connectivity based on low-complexity distribution of sub-THz signals with RF-over-polymer microwave fiber interconnecting compact radio units in a daisy-chain configuration (Fig. 2). Co-designed dual-frequency transmission and deployment approaches are proposed to mitigate propagation and implementation bottlenecks. The main contributions are:

- A dense deployment of RUs in a daisy-chain configuration connected with PMFs segments to bring the sub-THz signals close to the terminals, circumventing blocking. A RU, see Fig. 2, consists of only analog components. This solution makes a clean break with existing designs, for example the multipoint approach in [5] (cf. Section III).
- Novel radio-over-plastic fiber [6], specifically PMF, technology as a low-complexity and cost-efficient solution to distribute the sub-THz signals.
- Physically compact antennas distributed over an area to realize a sufficient link budget. The arrays integrated in

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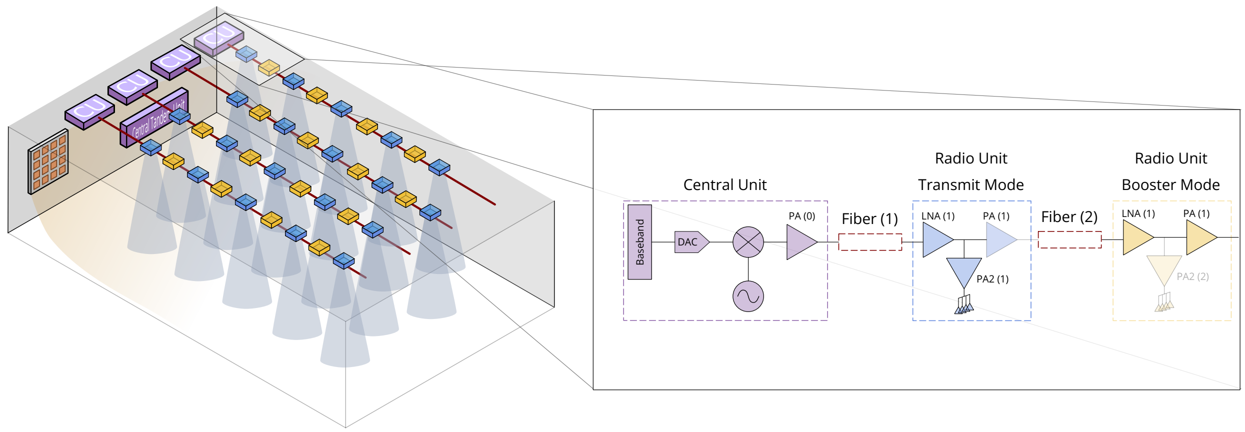

Fig. 2: A dense deployment of distributed low-complexity sub-THz radio units (RUs) and sub-10 GHz with dual-frequency operation. Block diagram of the sub-THz fiber-based infrastructure (the stripe), consisting of a central unit (CU), and multiple RUs connected with polymer microwave fibers (PMFs). As detailed in the close-up, a RU can be configured to transmit over the air (blue) or amplify the signal (yellow) to be carried further over the PMF to account for the losses.

RUs, each with only a small number of antennas, together form a sparse large array. Only one or a few RUs actively transmit at a given time, creating distinct beams that will "light up" following the allocation of RUs to user equipments (UEs). RUs realize rather broad beams that require less frequent updating and enable low-complexity integration.

- Dual-frequency "tandem" operation: while sub-THz band offers very high data throughput and sensing resolution, a complementary cooperating lower sub-10 GHz band offers support on the control plane and as a reliable "safety net".

II. Propagation and HW implementation: obstacles and mitigating them to reach the sub-THz highway

Wireless networks have been moving up in frequency in the quest for more capacity. This has been achieved to a large extent following the same deployment approach, i.e., using centrally located access points with similar radio frequency (RF) transceiver architectures and multi-carrier waveforms. While exploiting the same concepts has been successful for frequencies below sub-10 GHz, these approaches are problematic when moving up to the mmWave and sub-THz bands. As explained below, both radio propagation and hardware integration at these frequencies are substantially different and more challenging due to inherent physical limitations. The proposed deployment and signalling can mitigate these obstacles, strengthening the links.

A. Radio propagation at sub-THz: a cup of coffee can be the elephant in the room

Large-scale and small-scale fading at sub-THz impact performance in a drastically different way as compared to sub-10 GHz bands. While the physics are well understood, many reported studies underexpose the resulting impact on communication systems. This is the proverbial elephant in the room, as sketched in Fig. 1. In the following we discuss how the novel deployment and operation concepts address severe propagation effects.

Link budget. The effective aperture of an antenna is inversely proportional to the squared operating frequency. Hence, higher frequencies result in a smaller effective aperture, leading to increased loss. Specifically, when comparing transmissions at 140 GHz and 2.4 GHz, an additional loss of approximately 30 dB is incurred. Compensating for this loss, theoretically, is possible by using an antenna array with the same physical area, and thus more directive characteristics [7]. This would in the case above require the integration of $58 \times 58 = 3364$ antenna elements. In practice, the losses in interconnecting these antennas will counteract the gain to some extent, as explained in Section II-B. This many antennas in the array would result in a half-power beamwidth (HPBW) of under 2 degrees in the broadside, estimated from the array factor. Such narrow beams need very frequent tracking for non-static terminals, which is relaxed by the proposed deployment with relatively broad beams (crf. Section II-C).

Shadowing/blocking. To visualize the different blocking when transmitting at 140 GHz versus 2.4 GHz, consider the analogy of a coffee mug with a diameter of 7 cm versus an African elephant that gets 4 m long. These have similar sizes when expressed in number of wavelengths for the 140 GHz and 2.4 GHz bands, respectively. Moreover, the liquid in the cup behaves at sub-THz frequencies as an almost perfect reflector. To illustrate the consequences: suppose someone is holding a cup of coffee at 1 m on the line to the access point (AP) from a terminal, equipped with a uniform rectangular array (URA) of 1024 antennas, as illustrated in Fig. 1. With a HPBW of 7 degrees, the cup effectively becomes like an elephant in the room. This is a "bad luck" case, yet for example humans are more probable to create huge blockers, incurring a $\sim$40 dB loss at sub-THz frequencies. The proposed distributed deployment can circumvent such blockage, which is a main obstacle to consistent sub-THz connectivity.

Sensitivity to mobility. Doppler is much more severe due to the extremely short coherence time at sub-THz frequencies. Consider a person walking to the coffee machine at

$5\,\mathrm{km/h}$. When communicating using sub-THz frequencies, this person will experience a similar Doppler as sub-$10\,\mathrm{GHz}$ communication does in high-speed trains moving at $300\,\mathrm{km/h}$. The impact of high Doppler is that antenna beams need to be updated very frequently, in particular narrow beams created by large antenna arrays. The proposed deployment, which uses relatively broad beams oriented downward rather than sideways, offers improved resilience to the high Doppler effects characteristic of sub-THz frequencies.

Unreliable multipath. Multipath components create a safety net for communication links at sub-$10\,\mathrm{GHz}$ frequencies to maintain connectivity when the line-of-sight (LoS) is blocked. In sub-THz channels, multiple paths are scarce. Studies [8] reported 'it depends' whether this phenomenon will be significant. This can result in the worst of both worlds: multipath components (MPCs) cannot be relied on for overcoming blocking of the LoS, nor can one assume that there will be no MPCs to reduce equalizer complexity. A reflection from a wall can generate a strong MPC and be detrimental to the link quality unless an appropriate equalizer is used. Recent measurements confirm that significant MPCs primarily are received via strong side-beams of large arrays.

In conclusion, adopting the conventional central network deployment and transmission schemes that work well at sub-$10\,\mathrm{GHz}$ *is bound to lead to unreliable connectivity at sub-THz frequencies. In contrast, the proposed approach for sub-THz systems mitigate the obstacles to provide strong coverage.*

B. Integration challenges: small components, big losses

Progress on hardware operating at sub-THz frequencies has been impressive. Still, challenges remain significant. Those that are relaxed with the proposed approach are discussed next.

Amplifiers. It is difficult to make sub-THz amplifiers with high output power. At $140\,\mathrm{GHz}$, state-of-the-art amplifiers in commercially viable silicon technologies can provide $\sim 20\,\mathrm{dBm}$ of peak power [9]. This needs to be backed-off by $5\,\mathrm{dB}$ to $10\,\mathrm{dB}$ to transmit 1024-carrier OFDM waveforms. Furthermore, the efficiency is very low, less than $10\,\%$ under realistic conditions [9].

Phase noise. The amount of phase noise increases with the carrier frequency by $20\,\mathrm{dB}$ per decade. For high-bandwidth transmission at sub-THz, white phase noise will dominate the distortion. Traditional phase tracking techniques cannot mitigate this phase noise, as it is uncorrelated over time.

Antennas and Interconnects. Low-cost technologies like High-density Interconnect (HDI) printed circuit board (PCB) and Embedded Wafer Level Ball Grid Array (eWLB), which enable practical mass production, do not (yet) offer low-loss feeding networks and antenna implementations. For example, in its basic form, the redistribution layer (RDL) layer at the bottom of an eWLB package is used to implement feeding lines like coplanar waveguides, with insertion losses on the order of $0.5\,\mathrm{dB/mm}$. With a wavelength of $\sim 2\,\mathrm{mm}$, and the largest dimension of a typical array element being half a wavelength, the distribution of RF signals to many elements in a large array requires many mm's of feeding line (and hence many dB's of insertion loss). Therefore, the array gain from the use of more elements (ideally $3\,\mathrm{dB}$ for every doubling of the number of elements) is significantly degraded by practical feeding of these elements, potentially even nullifying the extra array gain.

C. Mitigating the obstacles to the sub-THz highway

Adequate system-level designs can mitigate obstacles at sub-THz frequencies that make the links fragile. We highlight two key choices that blend well with the proposed deployment approach, further elaborated in Section III.

Selecting hardware-friendly waveforms. Multi-carrier waveforms modulated with higher-order constellations are adopted to offer a high spectral efficiency and cope with multipath fading, at the expense of a high peak-to-average power ratio (PAPR). In contrast, we advocate using waveforms requiring low dynamic range that are robust to non-linear distortions and low-order constellations for sub-THz connectivity. These are hardware-friendly and allow relaxation of the requirements of (i) the amplifiers, which can be operated with less back-off; (ii) the oscillators, which inevitably introduce white phase noise; and (iii) the data converters, whose resolution can be lowered, reducing complexity and energy consumption. The high available bandwidth, realistically considered $20\,\mathrm{GHz}$ in this paper, can ensure $>10\,\mathrm{Gbit/s}$ on each PMF even with these low-spectral efficienct waveforms. Local network capacity can be scaled up linearly with number of PMF stripes to $\sim\,\mathrm{Tbit/s}$ in large venues.

Providing coverage with many broad-beams. Many arrays, each with a small number of antennas, can provide stable coverage for non-static users. This approach can cope with both propagation and hardware integration challenges at sub-THz: (i) the link budget is less sensitive to user movement thanks to the broader beams and less prone to multi-path as the arrays serve as a spatial filter without high sidelobes, and (ii) the implementation does not suffer from the large interconnect losses coming with arrays with many antenna elements.

III. Strengthening sub-THz links concept I – Dense deployments to make friends with physics

The novel paradigm brings the 'wireless sub-THz entry point' to the proximity of the UEs through transmission of the RF signals over PMFs, hosting RUs connected in a daisy-chain topology. This results in a distributed, dense deployment of sub-THz RUs equipped with antenna arrays with relatively few elements, creating favorable conditions for providing reliable high-throughput coverage. This architecture, sketched in Fig. 2, is reminiscent of a spot-based lighting system, where users are served by the nearest source(s). Such deployment can overcome propagation obstacles outlined in Section II by reducing the link distance, decreasing the risk of blocking, and lowering the beam steering complexity and update rate, as also pointed out in [10]. The deployment can ensure that a UE at every location is serviced by at least two RUs, as illustrated in Fig. 3. This enhances resilience to blocking of the LoS to the nearest RU. The sub-THz signals are distributed via RUs over a polymer microwave fiber (PMF). This in contrast to radio-over-fiber (RoF), where RF signals are converted to

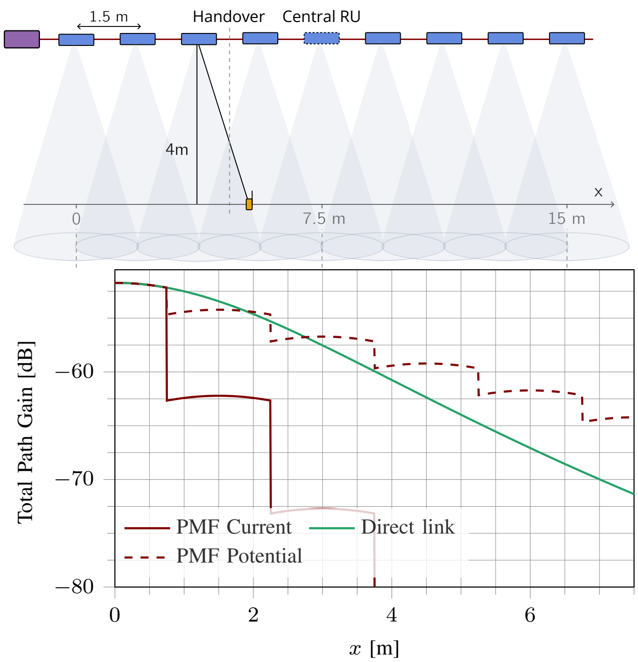

Fig. 3: Signal degradation over the air and over the fiber in the considered sub-THz system. Distributed RUs outperform a single central RU approach, mitigating LoS blocking and improving the path gain over the air. Every 1.5 m a RU acts as a boost unit to amplify the signal. On the fiber, the first couple of meters, the signal is noise-limited and transitions to a distortion-limited regime after approximately 9 m.

optical signals, which are carried over an (optical) fiber. The PMF enables low-complexity deployment [6] and avoids the need for many high-frequency transceivers or optical-electrical converters. However, it also brings limitations as no digital baseband signals are available at the RUs.

For resource allocation, user scheduling, handovers between RUs, and minimal on-switching of sub-THz hardware, we propose a dedicated control channel operating at sub-10 GHz that offers reliable coverage, as explained in Section IV. Dual-frequency operation of networks whereby mmWave transmission is assisted by lower frequencies has been investigated before, for example in [11]. However, most developments, such as Wi-Fi systems, are based on co-located dual-frequency centrally deployed access points with both carriers optimized for data transmission. Hence, the mmWave channel offers a high-speed data pipe when conditions allow, which in reality turns out to be rather rarely. In contrast, we propose distinct deployments for the lower and higher frequencies and aim for consistent high-data rate support enabled by the very high bandwidth available at sub-THz frequencies. The inevitable cost overhead of distributed deployment can be justified by the use of PMF-based infrastructure, which offers a cost-efficient solution as detailed at the end of this section.

In the following, we zoom in on the transmission of sub-THz signals over-the-fiber and over-the-air, respectively.

A. Transmitting sub-THz signals over PMF

Figure 2 illustrates the sub-THz fiber-based structure, i.e, the *stripe*. It consists of a central unit, delivering a sub-THz signal on a PMF, to a set of RUs that can transmit the signal over the air. RUs may also be configured to operate in booster mode, with the sole purpose of amplifying the signal along the fibre, as indicated in Fig. 2. Disabling a RU will disable all subsequent RUs, saving power on the non-activated hardware. We restrict the discussion to the downlink operation here; the uplink is similar but in reverse order.

Central unit: The central unit creates the baseband signals, and upconverts to sub-THz frequencies. Then the signal is amplified in a power amplifier, and fed into the PMF.

PMF: The PMF transports the sub-THz signal along the stripe. The signal gets attenuated along the PMF, typically in the order of 3 dB per meter and with an additional 3 dB loss in the chip-to-PMF transition, i.e., coupler [6][12]. Possibly, signals could get spectrally distorted along the way depending on the waveguide design, which may be tailored to avoid this.

Radio units: At chosen intervals, radio units amplify the signal from the PMF and feed to an antenna (or a phased array). When a RU is activated to transmit to a UE, the signal is switched to the antennas. When the RU is not transmitting or receiving, it acts in booster mode as depicted in Fig. 2.

The signal generation and transmission over the stripe is affected by impairments that can drastically degrade the signal quality. Two important impairments are *phase noise*, created in the central unit, and *amplifier nonlinearity* in the RUs. Both degrade the signal quality, and the nonlinearities also lead to spectral regrowth, potentially breaking spectral mask requirements. A key limiting factor is the need to restrict the gain of a RU to below $\sim$30 dB to prevent self-oscillations. These oscillations can occur when signals emitted from the RU are picked up by the PMF-to-chip transition coupler at the input. In practice, maintaining an output-to-input coupling below 30 dB at these frequencies is extremely challenging. There is a delicate balance between noise and distortion contributions along the PMF. Feeding a too-strong RF signal into the PMF will quickly build up nonlinear intermodulation distortion. On the other hand, a too-low RF signal will drown in the noise added by each RU. Figure 3 illustrates a case where the RF signal power has been adjusted to balance signal-to-noise (S/N) and signal-to-distortion (S/IMD) performance. The signal distortion in the first part of the PMF is dominated by noise. Further along the stripe, the nonlinear distortion becomes the main limiting factor. Overall, the example demonstrates more than 30 dB signal-to-noise and distortion ratio within the considered 15 m PMF.

Energy consumption estimation. Excellent energy efficiency, <10 pJ/bit [4] has been achieved for Gbit/s wireless sub-THz links. However, this is reported for short distances (cm-level) only or with very directive antennas on fixed links, making the comparison with sub-10 GHz transmission not entirely fair. It is important to acknowledge that the energy consumption of sub-THz transmission is impacted by high losses of components and amplifiers, with a typical efficiency $<$10 % in state-of-the-art designs [9]. In contrast, current sub-10 GHz power amplifiers (PAs) reach $>$50 % efficiency.

Sub-THz systems must overcome blocking and shadowing that induce losses of 40 dB and higher. While this problem cannot be solved by increasing the transmit power, our proposed distributed deployment addresses it. However, the solution comes at the expense of energy consumption in RUs that need to boost the signals to compensate for losses on the PMF. In fully LoS conditions, a central deployment will consume less energy, as illustrated in Fig. 4 , given the current losses in PMF fibers.

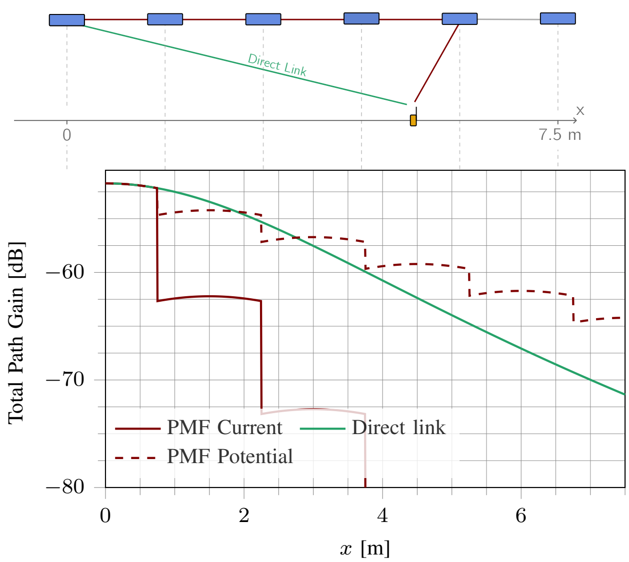

Fig. 4: Path gain comparison between a direct over-the-air link (**??**) and the proposed distributed deployment using PMFs. In the distributed case, the total loss accumulates from both the fiber segments (and couplers) and the over-the-air propagation. Current technology **??** offers a fiber attenuation of $3\,\mathrm{dB/m}$ and a $3\,\mathrm{dB}$ loss per coupler, which experiences significantly path loss. With lower losses (e.g., a PMFs with $1\,\mathrm{dB/m}$ loss and a $0.5\,\mathrm{dB}$ coupling loss as in **??**), the distributed deployment could become more energy-efficient than a central deployment.

Based on efficiency numbers for state-of-the-art amplifiers [9], and assuming $10\,\mathrm{mW}$ peak output power and class A operation at sub-THz, each RU, whether in transmit or in booster mode, is expected to consume $\sim\!500\,\mathrm{mW}$. The total energy consumption will be determined by the CU-to-UE distance, since inactive RUs can be disabled. Energy consumption scales linearly with stripe length well beyond $100\,\mathrm{m}$. Since inactive RUs will be disabled, the average distance from the CU to the UEs determines the energy consumption. The full transceiver functionality in the CU could consume as little as $100\,\mathrm{mW}$ in transmit or receive mode [4]. This yields a total power consumption of $\sim\!5\,\mathrm{W}$ for a $15\,\mathrm{m}$ stripe. When transmitting $20\,\mathrm{Gbit/s}$ over an individual PMF – achievable with a 'gentle' low-constellation waveform in $20\,\mathrm{GHz}$ bandwidth – the energy efficiency of the sub-THz transmission is estimated to be $\sim\!200\,\mathrm{pJ/bit}$[1]. This shows that, in absolute terms, the energy required to provide multi-Gbit/s wireless data transmission is very reasonable. For example in a factory or a stadium, when compared to other consumers such as lighting and machinery, it would not incur a significant increase.

[1]Note that digital baseband power is not included in this estimate. We expect its contribution in energy/bit is rather agnostic to the operating frequency.

B. Transmitting the sub-THz signals over the air

The PMF deployment with many distributed RUs boosts the signals along the fiber and brings the antennas close to the UE, thereby reducing the LoS propagation distance and hence the path loss over the air; most importantly, it creates redundant links to cope with blocking. The spot-beam coverage also reduces scan loss, since the smaller coverage means that the direction to the UE is closer to the broadside of the antenna.

To demonstrate this with an example based on data from real PMF prototypes and sub-THz RF component implementations [6], [7], we consider a conference room (Fig. 3), where a $15\,\mathrm{m}$-long stripe runs along the length of the room, with each RU providing $3\,\mathrm{m}$ of coverage along the horizontal (x)-axis. If the UE is located $4\,\mathrm{m}$ below the stripe, with an antenna gain of $18\,\mathrm{dBi}$ (4×4 patch array with element gain of $6\,\mathrm{dBi}$ and array gain of $12\,\mathrm{dB}$), the path loss at different positions is shown in Fig. 3. It is assumed that handover occurs when the UE is between two RUs. The RU also has 4×4 patch array giving $18\,\mathrm{dBi}$ antenna gain. For comparison, the path loss of a system with only one centralized RU at the center of the room is also shown in Fig. 3, for both an unsteered and steered case.

As can be seen, the increase in path gain (with respect to the centralized RU) begins when the handover occurs at $x = 1\,\mathrm{m}$, with the excess loss caused by both the increase of over-the-air distance (path loss) and direction to broadside (scan loss). The path loss of the distributed RUs remains stable, with regular handovers occurring along the x-axis in multiples of $1\,\mathrm{m}$. In fact, near the edge of the room, the maximum path loss from the central 4×4 patch array is the same as in the deployment with only single patch antennas along the stripe. This means that the distributed RU can be equipped with a single patch element and still provide the same link budget as the centralized system with a 4×4 patch array at the RU. The single-element antenna approach implies a simpler, and often also more compact, design. It does not require beam scanning and avoids the complexity and losses coming with phase shifting and feeding network. The unsteered stripe case could also be interpreted as a high-gain single antenna [7].

Finally, the distributed RUs also offer larger probability of LoS propagation as the closest RU is located at a higher elevation angle with respect to the UE, compared to the centralized case. The overlapping coverage further increases the probability of LoS propagation.

Cost considerations. The envisioned ease of installation of the PMF is a major benefit. Ultimately, the fibers could be deployed by simply gluing them as stripes of tape that embed the (very small) RUs. Installation costs can be safely assumed to be the dominant cost of any wireless infrastructure with a distributed topology. The latter is the only viable option for providing consistent coverage at sub-THz, as explained above. An alternative could be to deploy optical fibers, which present a low-loss solution yet would require many expensive optical-electrical converters. Bringing the digital baseband signals to the distributed entities would require many costly full sub-THz front-ends; as direct electrical interconnects cannot support the bandwidth required for multi-$\mathrm{Gbit/s}$ datarates, this is not a viable alternative. Note that no quantitative cost estimates are provided as these depend highly on market demand and volume.

IV. Strengthening sub-THz links Concept II – Dual-frequency for reliability, efficiency, and capacity

Fundamental properties of lower and higher bands in a dual-band system are complementary. Lower bands offer more modest throughput – due to comparatively lower bandwidth – but higher link robustness, that is, less sensitivity to blockage, and Doppler. Operation at higher bands has precisely opposite qualities: high throughput but higher fragility of the links. Hence, it is natural for lower and higher bands to take on complementary roles in a dual-band system.

Control data typically requires high link robustness and should be transmitted on the sub-10 GHz band: scheduling, configuration of transmission and reception, handovers between RUs, wake-up functionality for stripes temporarily put in sleep mode, etc. Lower bands can also be used to transmit data that require high reliability. On the other hand, the connection at the sub-THz band should almost exclusively be used for data transmissions. Non-data signaling at higher bands should be limited to signals that cannot be sent at the lower band, e.g., transmission of pilots for estimation and tracking of RF impairments. Moving the control signaling to the lower band not only ensures the necessary robustness but may also reduce the control signaling overhead and latency, e.g., through the selection of the best RU and associated beams at sub-THz learned at sub-10 GHz.

To understand the underlying problem, note that since higher bands typically use phased antenna arrays with few transceiver chains, beamforming in several directions simultaneously may be infeasible. Instead, focused beams can be directed only in a single direction at a given time. Finding the best RU and beam to serve the UE then entails sending one pilot signal per RU and candidate beam in a separate time slot, and the UE performing measurements on each pilot signal and providing a measurement report. Assuming N_{RU} candidate RUs and N_b candidate beams per RU, the described procedure requires $N_{RU}N_b$ time slots for sending the downlink pilots, plus UE processing and reporting time. If the number of RUs and beams per RU is large the described procedure could end up consuming a substantial amount of downlink resources and result in large latency.

Lower bands can be conveniently used for improving the efficiency of the above procedure. The solution entails two stages, a learning phase, which can be performed as for example proposed in [13], and an exploitation phase:

1) During the learning phase, a legacy measurement and reporting scheme is performed at the sub-THz band. Simultaneously, the dual-band UE sends uplink pilots at sub-10 GHz band to estimate the channel. The sub-10 GHz channel and information about the best sub-THz RU/beam combination provide a data point particular to where the dual-band UE is located. This data point is used by the network to learn the mapping from the channel at sub-10 GHz to the choice of the best RU/beam at sub-THz. Collection of data points in the learning phase continues over time and UE positions until satisfactory performance of the model is achieved.
2) In the exploitation phase, when there is need to choose a new RU or beam, the UE first sends an uplink pilot in the sub-10 GHz band. Using the model inferred in the learning phase, the network infers the list of sub-THz RUs/beams most likely to be the best for serving the UE. This list can be utilized for a more concentrated RU/beam search, or the best high frequency RU/beam as suggested by the model could be used directly for data transmissions without measurements.

Supervised methods using standard machine learning solutions (e.g., deep feedforward or convolutional neural networks) can be used to learn the mapping from sub-10 GHz channels to the best sub-THz RUs and beams [14]. During training, the sub-10 GHz channel responses represent features. The best sub-THz RUs along with the best beam represent a label in a feature-label pair. The size of the dataset for training is determined by the coverage area, wavelength, and correlation properties of the sub-10 GHz channel. For example, sampling a coverage area of 50×50 meters on a regular 2D grid with $5\,\lambda$ spacing at 6 GHz yields 40 000 samples. Preliminary results [15] suggest that a significant reduction in overhead for finding the best sub-THz RUs can be achieved with this approach.

One challenge with the dual-band operation is the need for tight synchronization and coordination between the two bands. This can be accomplished by having the sub-10 GHz and sub-THz systems share the same digital baseband and scheduler. Moreover, the time-domain structure of the two subsystems should be designed such that joint scheduling is facilitated. For example, each timeslot in the sub-10 GHz system could contain an integer number of sub-THz slots.

V. Conclusions and R&D directions

Sub-THz systems will not offer robust services to non-static terminals when deployed similarly as sub-10 GHz systems. We have presented a novel dense RF-over-PMF-based distribution of sub-THz signals and dual-frequency concept for offering robust sub-THz connectivity. This system provides a low-cost solution for a distributed deployment and circumvents propagation and hardware obstacles encountered at sub-THz frequencies. The proposed approach offers an interesting potential to strengthen sub-THz links. The system can extend coverage to non-static UEs over tens of meters with an energy efficiency in the order of a few $100\,\mathrm{pJ/bit}$.

Further technological innovation is needed to advance the concept towards actual implementation:

- Lower loss fibres and couplers should be designed to improve the link budget over the PMF. This would require less amplification of RUs in booster mode, lowering energy consumption.
- Efficient algorithms are needed to enable transmission of waveforms with non-linear and noisy hardware. Appropriate waveforms are required to relax both hardware and algorithmic complexity.

- Approaches leveraging the same dual-frequency dense deployment concepts should be developed to support emerging applications that require position information.

After decades of R&D on wireless transmission at mmWave and above, these systems have so far only found success on fixed or very short links. Other trajectories are needed to conquer new territories. While significant technological progress is needed to prepare our proposed dual-frequency approach for actual deployment, we think that this is the way forward to exploit the large bandwidths at sub-THz bands.

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