Out-of-Band Information Aided mmWave/THz Beam Search: A Spatial Channel Similarity Perspective

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***Abstract*—The transition to higher frequency bands, e.g., millimeter-wave (mmWave) and terahertz (THz), will be capitalized on the long term for future wireless communications. One of challenges relates to rapid establishment of mmWave/THz links with low beam training overhead due to highly directional transmission. A promising solution is to take advantage of the coexistence of sub-6 GHz, mmWave, and THz wireless networks and to use out-of-band spatial information for enabling fast beam search. The success depends on the spatial similarity of radio channels across different frequency bands. In this article we promote a feasibility study of low-frequency spatial channel information assisted high-frequency beam search from a radio channel point of view. We develop multi-band channel similarity measure of desired beam directions extracted from radio channels, which are obtained via filtering propagation paths by different beampatterns at different frequencies. Measurement- and ray-tracing-based evaluations across multiple frequencies and environments are performed, which prove the usability of out-of-band information aided beam search strategy in line-of-sight (LOS) dominated scenario and even in non-LOS scenario. Finally, we discuss the challenges associated with exploiting spatial channel similarity.**

***Index Terms*—Beam search, beamforming impact, mmWave and THz, radio channel, spatial channel similarity.**

I. Introduction

THE use of the millimeter-wave (mmWave) and terahertz (THz) spectra is expected to provide unprecedented high data rates in 5G and 6G systems [1]. To establish reliable communication links with acceptable coverage in mmWave and THz frequency bands, large-scale antenna arrays are necessary to provide high beamforming gains and combat the propagation loss. Meanwhile, high sensitivity to blockage at mmWave and THz frequencies may cause performance degradation and severe overhead due to the more frequent beam mis-alignment and increasing need for beam refinement. Hence, using highly directive beam will significantly increase the complexity of beam management, which relies completely on accurate and timely acquisition of channel angular direction information [2]. For example, it is challenging to rapidly find a physical connection during *initial access* based on the existing exhaustive or hierarchical search strategy, which is realized via beam scanning over the entire angular space. Moreover, fine alignment of the transmitter (TX) and receiver (RX) beams along the dominant propagation paths is required for data plane transmission, and in turn, fast *beam tracking* schemes need further improvement to maintain satisfactory communication quality and help to avoid frequent beam training processes, especially in mobility scenarios. The former requires a large number of highly directional beams to cover all possible search space, leading to larger codebook size and higher beam training overhead for network access [3]. The latter requires efficient beam alignment completed within a very short time period, considering the short coherence time of dynamic mmWave/THz channels.

To deal with these challenges, out-of-band information aided beam search has attracted extensive attention to accelerate link establishment and control [4]. The out-of-band information, referring to the side channel information (e.g., directions of arrival/departure) collected via lower-frequency communication signals, is used to obtain coarse estimation of the beam pointing angles at higher frequency. Fortunately, modern radio transceivers are capable of supporting multi-band cooperation transmission, where the antennas and radio frequency (RF) hardware potentially operate at widely separated frequencies, even orders of magnitude. This provides the possibility of exploiting the spatial congruence across multi-band channels, along with the extraction of mmWave/THz channel directions from lower-band channels [5]–[7]. However, the use of out-of-band information for fast mmWave/THz beam search still poses a certain number of unsolved problems. For example, the usability of out-of-band information aided mmWave/THz beam search strategy depends on the degree of spatial channel similarity. We will consider related questions: how similar is the spatial power distribution of dominant propagation paths between low- and high-band channels? and when can low-band spatial channel information be used to roughly estimate potential beam directions at high frequency under realistic antenna beampattern constraints?

To address the questions, we focus on the feasibility study of using lower-frequency channel direction information for upper-frequency beam search from the viewpoint of multi-band spatial channel similarity. The degree of similarity indicates whether beam search in one band can benefit from leveraging channel information in another band. Empirical results prove that the spatial channel similarity from microwave to THz bands can be visually assessed via direct comparison of power angular spectra (PAS) [7], [8]. The level of similarity, however, strictly depends on the propagation environments and antenna systems used in the measurements. For instance,

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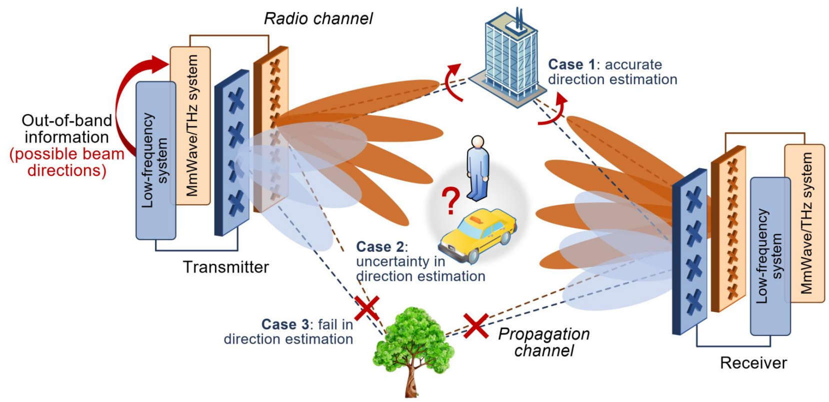


Fig. 1. The schematic of using out-of-band spatial channel information for fast mmWave/THz beam search.

the improvement of channel spatial resolution, benefited from using much larger antenna array at higher frequency, results in increased capability of distinguishing multipath components (MPCs) compared that on low-band channels and smaller arrays. Meanwhile, a wide beampattern typical with low frequency antennas is likely to cause the ambiguity of two adjacent beam directions and lead to inaccurate estimation of potential beam directions in mmWave/THz bands. Hence, the channel similarity measure must account for the interaction between propagation channels and RF systems, e.g., antenna geometry and beamforming configurations. On the other hand, a standard metric is needed to represent the degree of similarity across different frequency bands. It helps to analyze the frequency-dependent behavior of multi-band channels with a fair comparison of spatial profiles, as well as the dominant channel directions. Even more, it contributes to determining whether to leverage low-frequency channel information for fast mmWave/THz beam search under different channel conditions.

In this article we first briefly present the basic concept of out-of-band information assisted mmWave/THz beam search approach. We detail our proposed metrics to measure multi-band spatial channel similarity. A feasibility study of spatial channel similarity is presented with selected results across different environments and frequencies. Finally, we outline the key challenges of exploiting channel similarity and conclude this work.

II. Out-of-Band Information Assisted Beam Search

The idea of using out-of-band channel to aid in acquisition of mmWave/THz spatial channel information has been proposed for efficient channel estimation and beam training (also called as beam selection) [4]. For the communication links simultaneously using multiple well-separated frequency bands (e.g., by dozens or hundreds of gigahertz), the number of antenna elements used in lower band is expected to be much smaller than that in higher band as shown in Fig. 1, due to physical size constraints. Electrically smaller antenna arrays mean wider beampatterns. Hence, low-frequency beam search can be performed with lower training overhead and computational complexity due to the use of less directive beampattern. Some recent works have started to use low-frequency information for high-frequency covariance estimation [6] or codebook design [5].

In this article, we focus on mmWave/THz beam search using out-of-band channel direction information. Specifically, in the phase of idle mode, potential user directions extracted from low-frequency signals can be used for coarse estimation of strongest sector or beam space and the number of required stages in hierarchical beam training protocols will be accordingly reduced at high frequency. In the phase of connected mode, estimated side spatial channel information from low-frequency communication systems are regarded as prior information to direct the beams in higher frequency band. The coarse estimation of the angles of arrival/departure of strong propagation paths at sub-6 GHz will be used to configure mmWave/THz communication links via the best beam pairs. Without consuming the mmWave/THz communication resources, this protocol can help to reduce the beam training overhead by avoiding unnecessarily sweeping through the entire beam space. Let us take a simplified example. Assume there is at both link ends, say, 120° and 80° angular sectors to be searched in azimuth and elevation, respectively. Furthermore, assume there are two dominant paths within the beam space of interest and high-frequency directive beams must scan with at maximum 10° angle increment. Using codebook-based exhaustive beam search strategy [3], $(12 \cdot 8)^2 = 9216$ beam pairs is needed without any prior information. Otherwise, if low-frequency channel provides a coarse estimation of beam directions, we can limit the number of beam vectors in the codebook when using narrow beam with beamwidth of 10° to search in limited 20° angular space around the estimated directions. The corresponding figure would be $(4 \cdot 2)^2 = 64$, which achieves 144-fold ratio of beam search effort improvement when using the out-of-band information.

To motivate this idea, it is primary to exploit spatial channel similarity between two frequency bands having remarkable frequency gap. From a propagation channel view, mmWave/THz channels become more sparse and specular in comparison with low-frequency channels due to the decrease in wavelength [1]. There is enough evidence from channel measurements that propagation mechanisms will not significantly change with frequency increasing except for the reduction of received power, delay spread, and angular spread [9]. In

Fig. 1, spatial characteristics of line-of-sight (LOS) component and well-separated clusters are congruent between low- and high-frequency bands (i.e., *Case* 1). Accurate estimation of the beam directions in mmWave/THz band can be thus realized by using low-frequency channel information. However, some degree of spatial disagreement can be observed when high-frequency signals experience much higher transmission loss (i.e., *Case* 3). For example, significant foliage attenuation at high frequency results in less strong beam directions [10] and thus, it will cause wrong decision on beam direction estimation when blindly using low-frequency channel information. Besides, the parameters used to characterize a radio channel depend not only on the operating frequency band, but also on the type of the observing antenna and RF front-end, such as antenna geometry and beamforming scheme. MmWave/THz high-gain antenna arrays, mechanically capable of containing more antenna elements, could radiate more sharpened beampatterns to achieve high beamforming gains and consequently high angular resolution. Conversely, a wider beam used in low-frequency system undermines its capability to distinguish the adjacent clusters (i.e., *Case* 2), which leads to the uncertainty in beam direction estimation.

The feasibility of out-of-band spatial information assisted mmWave/THz beam search for specific frequency combination and environment strongly depends on the radio channel similarity, which needs further evaluations with a standard similarity metric.

III. Multi-Band Spatial Channel Similarity

In this section, we introduce two proposed metrics to measure the spatial similarity of multi-band radio channels. The former characterizes the channel similarity from a statistics point of view by directly comparing the normalized PAS. The latter relies on the extracted strong channel directions, which is more practical and straightforward in terms of using low-frequency spatial information for fast high-frequency beam search.

A. Statistical Channel Similarity Measure

Existing quasi-static channel measurement results show significant spatial congruence between two widely separated frequency bands based on visual inspection [7], [8], yet lacking a standard metric to characterize the degree of channel similarity. The simplest way is to directly compare the multi-band PAS of radio channels. The practical antenna beampatterns at different frequencies will be first taken into account via filtering the PAS of propagation channels by desired beampatterns. It means that the selected beampattern is first steered to a specific direction and the resulting power is calculated as the sum power of all observable MPCs weighted with beam gains within the corresponding beamwidth. The filtered PAS represents the spatial power distribution of radio channel. However, remarkable received power difference between two PAS can be observed, which is introduced by wave propagation and system configurations (only impact measurement results). Thus, both low- and high-frequency spectra are normalized to the sum power of unity for a fair comparison. The other benefit of using this approach is that normalized PAS can be interpreted as probability density function (PDF) and in turn, the total variation distance, calculated as the cumulative difference between two probability distributions (i.e., normalized PAS), is defined as a statistical measure of spatial channel similarity. Its conversion on a percentage basis is called as PAS similarity percentage (PSP), whereby the closer the value is to 100%, the more similar the spatial profiles of low- and high-frequency radio channels.

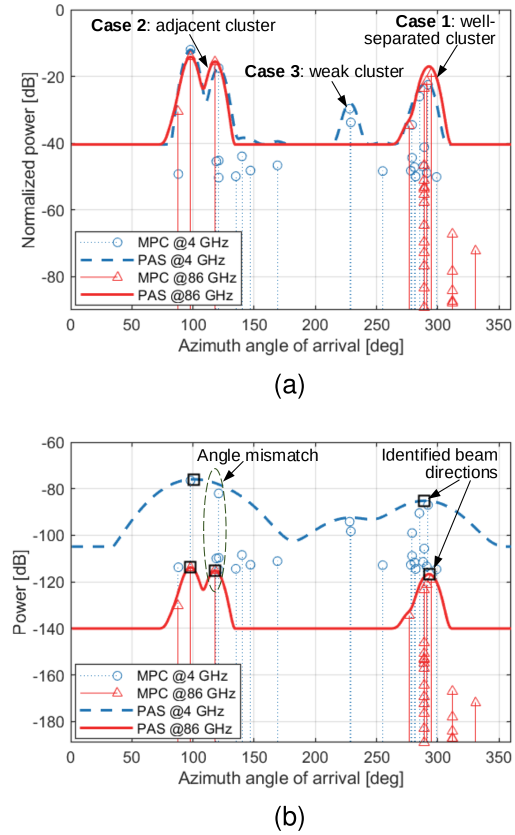


Fig. 2. Illustration of two proposed spatial channel similarity metrics using the same channel data sample. (a) PSP. (b) Best Desired Beam Direction.

Fig. 2a depicts an example of normalized MPCs at 4 GHz and 86 GHz from point cloud ray-tracing [11], where the dominant channel directions in azimuth plane are consistent at two frequencies. By comparing the normalized PAS of the radio channels, which are filtered by the same 3GPP beampatterns [9] with 30 dB peak to minimum gain ratio and 10° half-power beamwidth (HPBW), the corresponding value of PSP is 70.4%. The PSP metric represents the overall channel gain similarity over all directions in 360° azimuth plane. However, smaller PSP does not necessarily mean low level of channel similarity if we only focus on the reuse of the angles of arrival/departure of dominant paths. For instance, despite smaller PSP value for the case shown in Fig. 2a, the strong channel directions are consistent between 4 GHz and 86 GHz, indicating that side information could still be employed to aid high-frequency beam search. Hence, a more practical metric with respect to the channel directions has been promoted that considers the extraction and translation of spatial channel information from one band to another band.

B. Beam Direction-Based Channel Similarity Measure

Following the aforementioned procedure, the PAS of propagation channel are again first filtered with the desired beampatterns to involve the impact of practical antenna designs. Using the methods developed in [12], the sets of desired beam directions can be extracted based on the PAS of radio channels. Then we calculate the sum power of high-frequency beamformed PAS at low- and high-frequency beam pointing angles, respectively. Their power ratio represents how much potential channel gain is lost if the low-frequency channel direction information is used for high-frequency beam search, instead of choosing its own channel information. In general, the power ratio (in dB) is less than or equal to 0 dB, considering more potential beam directions can be exploited at high frequencies due to using larger antenna arrays. The increasing angular resolution makes it possible to distinguish the physical scatterers with very small angular separation. Note that the closer the value is to 0 dB, the better available out-of-band spatial information can be extracted to aid beam search at high frequencies. Moreover, a direction extracted from low-frequency channel is interpreted as useless or *false* direction for high-frequency beam search, if the high-frequency antenna cannot collect significant power when steered to that direction. Comparing the numbers of false directions and all proposed directions, we can conclude whether low-frequency spatial information can be used for high-frequency beam search in such a scenario.

Fig. 2b illustrates the estimation results of the best desired beam directions using the same propagation data as depicted in Fig. 2a, but using different beampatterns to characterize radio channels at different frequencies. Under the reasonable assumption that low-frequency antenna system presumably has smaller electrical size, corresponding to lower antenna gain and larger beamwidth of the main lobe, the 3GPP beampatterns with the HPBW of $40°$ and $10°$ are utilized to form the radio channels at 4 GHz and 86 GHz, respectively. More desired beam directions can be detected at 86 GHz because of narrower beam, which is able to distinguish close channel directions without angle ambiguities as we expected. The mentioned power ratio and the number of false directions in Fig. 2b are -2.81 dB and 0, respectively. Good spatial congruence indicates that side information from 4 GHz channel can be leveraged for coarse estimation of best desired beam directions at 84 GHz, despite existing slight angle mismatch between beamformed channels. Hereafter, different pratical beampatterns (in particular beamwidths) are utilized in different frequency bands to investigate their impact on the degree of channel similarity. Moreover, higher-frequency systems tend to use wider bandwidths which provide higher delay resolution and hence enable detection of more MPCs. More measurements are needed to characterize its impact on channel similarity measure due to using different bandwidth across low and high frequencies.

IV. Feasibility Study with Selected Results

In this section, we evaluate the congruence of desired beam directions between low- and high-frequency radio channels using the latter metric, where the beamforming impact is included in the analysis. We consider both measurement and ray-tracing simulation data across multiple frequency bands, e.g., sub-6 GHz, mmWave, and THz bands, and environments as summarized in Table I.

TABLE I
Ray-tracing simulation and channel measurement setups.

Data source	Point cloud ray-tracing	Channel measurement
Frequency	4 GHz and 86 GHz	28, 100, and 300 GHz
Bandwidth	/	2 GHz
Environment	Airport check-in area	Indoor corridor
Scenario	NLOS	LOS
Distance	Up to 70 m	14 m and 23 m

A. Ray-Tracing Case at Sub-6 GHz and MmWave

5G New Radio utilises a variety of frequency bands, including frequency range (FR) 1 defined in the sub-6 GHz spectrum and FR 2 defined in the mmWave spectrum. Heterogeneous sub-6 GHz/mmWave cellular networks provide a cost-effective solution for high-data-rate transmission with ubiquitous coverage, which are expected for commercial deployment in the 5G/6G era. The spatial congruence between sub-6 GHz and mmWave channels is thus first investigated based on the point cloud ray-tracing data collected in Helsinki-Vantaa airport check-in area at 4 GHz and 84 GHz. Two TX locations are selected, as well as their corresponding RX sets, resulting in 1473 and 1402 links for those different TX and RX set combinations, respectively. Here, all LOS paths between TX and RX all blocked by physical objects; in other words, only non-LOS (NLOS) links are taken into account during the simulation. Note that such scenario, with absence of LOS path, represents the pessimistic or worst case since NLOS propagation is more sensitive to the frequency changes compared LOS propagation. More details about ray-tracing configurations can be found in [13].

The beampattern of an antenna array under specific geometrical configuration is determined by inter-element spacing and number of elements. Here, we employ more practical beampattern of uniform linear array (ULA) with different element number at different frequencies instead of using ideal 3GPP beampattern. Fig. 3a shows the beampatterns of 4- and 8-element ULAs with half-wavelength inter-element spacing used at 4 GHz and 84 GHz, respectively. Beampatterns are defined for the $[-90°, 90°]$ bore-sight half plane with all-zero phasing, while the back half plane $[-180°, -90°] \vee [90°, 180°]$ is set to constant -60 dB gain. The HPBWs are $26.2°$ and $12.8°$ at these two frequencies, respectively. Here, two methods are used to estimate effective beam directions. The Method 1 (M1) selects the local maxima of beamformed PAS within a certain dynamic range, i.e., less than the threshold of 10 dB below the global maximum of PAS, which only considers the power distribution in the angular domain. The M1 is simple and intuitive, however, it may lose potential beam directions in specific cases. Some degrees of freedom of the propagation channel might be lost if, e.g., the paths are grouped in angular domain such that the filtered PAS yield only a single wide lobe with one peak. The Method

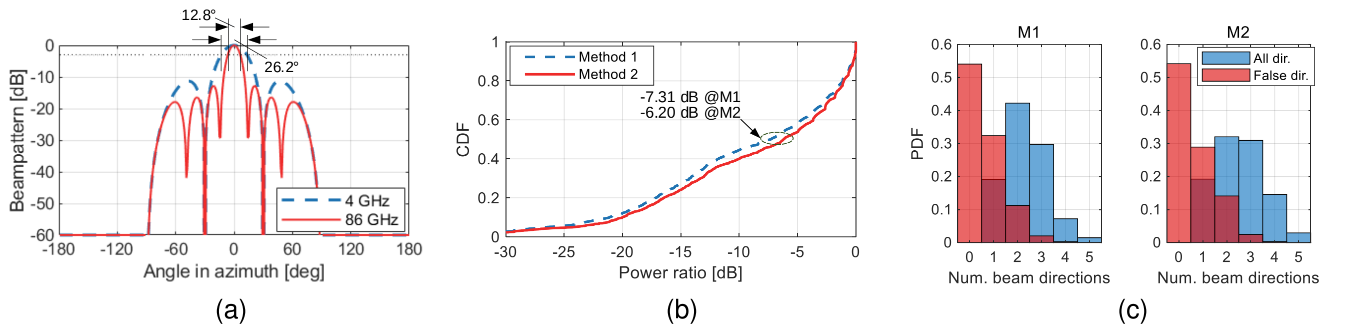


Fig. 3. (a) Practical beampatterns using for filtering propagation channels. (b) Empirical CDFs of the proposed power ratio metric using different beam direction estimation methods in [12]. (c) Empirical PDFs of the numbers of false beam directions and all proposed beam directions from low-frequency radio channel.

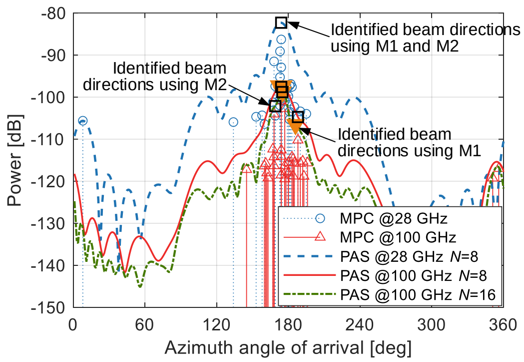
2 (M2) extends M1 by considering also propagation delays. The intention is to evaluate whether overlapping beams in nearby directions would be beneficial by approximating the correlation of beams. Details of the algorithm are given in [12]. The basic idea is to search promising beam steering angles not only on local maxima of the filtered PAS, but also on nearby beam space and to make the selection based on resulting beam correlations. We compare the cumulative distribution functions (CDFs) of the aforementioned power ratio using two methods. Fig. 3b shows slightly higher power ratio for M2 since M2 can potentially identify more beam directions. It also shows that 7.5 dB or less power loss exists in 50% of cases if beam steering at 86 GHz only follows the 4 GHz beam direction information without the aid of its own channel information. Uncertain or wrong estimation of beam directions will increase the training overhead when leveraging out-of-band spatial information. The number of false directions is less than or equal to 1 in most of the cases (>80%) as shown in Fig. 3c. This suggests that spatial channel similarity between sub-6 GHz and mmWave bands, which exists almost 24 times frequency difference, can be exploited to realize coarse estimation of mmWave beam directions without noticeable accuracy decrease even in NLOS scenario.

B. Measured Channel Case at MmWave and THz

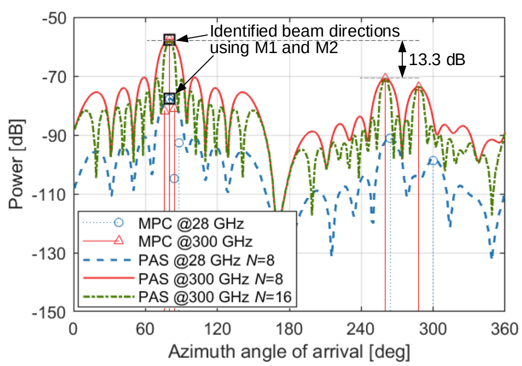
Radio communication operating at THz band is an area of active research for 6G. To show the usability of our proposed metric, we evaluate the channel similarity between mmWave and THz channels based on multi-band channel sounding data. The channel sounder reported in [14] is used for directional channel measurements with horn antenna rotating in 360° azimuth plane. Measurement campaigns were conducted in indoor corridor at 28, 100, and 300 GHz with the same bandwidths of 2 GHz. Only one TX-RX pair was selected for each frequency combination as frequency and beam sweeping become highly time-consuming. For 28 GHz and 100 GHz measurements, the omnidirectional antennas were used on TX side; and the horn antennas with the same HPBWs of 40° were used on RX side with the rotation steps of 1.5° and 1° at 28 GHz and 100 GHz, respectively. For 28 GHz and 300 GHz measurements, the same horn antennas with the HPBW of 8° and gain at 25 dBi were rotated in step of 4° on both TX and RX sides at 300 GHz; and at 28 GHz, bi-conical antenna with 0 dBi gain and horn antenna with the HPBW of 8° and gain at 20 dBi were used on TX and RX sides, respectively.

Figs. 4a and 4b show the mmWave and THz beam direction estimation results based on the power delay angular profiles. Note that the measured power difference between 28 GHz and 100 GHz (or 300 GHz) is caused by physics of wave propagation and horn antenna gains at different frequencies, while it will not impact the channel similarity measure using our proposed metric. We assume that receivers are equipped with 8- and 16-element ULAs at 100/300 GHz, and with solely 8-element ULAs at 28 GHz. For 28 GHz and 100 GHz case with the same ULAs, the power losses are 1.55 dB and 0.77 dB when using M1 and M2 to estimate beam directions, respectively, while with larger ULA at 100 GHz, the power losses are 1.69 dB and 1.87 dB. Using much larger antenna array along with narrower beampattern at high frequency, lower degree of multi-band channel similarity can be observed due to more power loss. In this regard, less side information can be extracted from low-frequency channel for high-frequency beam search considering practical beampattern difference. There is no power loss for 28 GHz and 300 GHz case since received signals are more concentrated along LOS direction and less MPCs can be detected with frequency increasing. The numbers of false directions are 0 for all measurement-based cases. The M2 can estimate more possible beam directions for the channel existing dense diffuse MPCs in ever resolvable angle bin; however, it will result in uncertain direction estimation especially for the radio channel filtered by narrower beampattern, leading to higher power loss (yet still within reasonable limits). Hence, it is likely to improve the spatial congruence of radio channels by first distinguishing diffuse and discrete components, where only discrete MPCs associated with the cluster centroids are used for beam direction estimation.

Considering the sensitivity to frequency changes when electromagnetic waves interact with an object comparable in size to its wavelength, multipath effect will reduced the degree of spatial congruence of beamformed channels. Thus, we can find that power loss is much lower in LOS component dominated scenario by comparing with the ray-tracing simulation results in NLOS scenario. In this context, the scheme of leveraging out-of-band spatial information for mmWave/THz beam search performs better in the scenario with dominant (e.g. LOS) and well-separated paths. More multi-band channel sounding data



(a)



(b)

Fig. 4. Comparison of spatial channel similarity for (a) 28 GHz vs. 100 GHz and (b) 28 GHz vs. 300 GHz using different beam patterns. Note that higher-gain horn antenna was used in 300 GHz measurements, resulting in much higher RX power compared with the result at 28 GHz.

in typical environments is still needed for further statistical analysis.

V. Future Challenges Associated with Exploiting Channel Similarity

The feasibility of out-of-band spatial information aided mmWave/THz beam seach strongly depends on the spatial congruence with a focus on the channel direction information estimated from low- and high-frequency radio channels. Such information involves the beamforming impact when different antenna geometries and beamforming schemes are used in different frequency bands. The higher degree of spatial channel similarity quantified by our proposed metric, i.e., less power loss and number of false directions, the more accurate beam direction information can be provided from out-of-band channel and the lower training overhead is needed compared with solely using in-band channel information for beam search.

However, to progress the implementation of out-of-band information aided mmWave/THz beam search strategy, many challenges still remain in exploiting channel similarity. They are two-fold: first, increasing the accuracy of channel similarity measure to avoid over- or under-estimation; then, translating low-frequency spatial channel information to high frequency according to channel similarity.

Beamforming Impact: All the evidence from measurement and simulation results shows that the level of spatial channel similarity is sensitive to the antenna beampattern with respect to radio channels. The results reported in [13] also prove that the beamwidth difference between two frequencies has even stronger impact on channel similarity than the frequency gap. Its impact becomes more obvious for the channel with adjacent significant MPCs (see Fig. 2b) and dense MPCs (see Fig. 4a). Thus, improved method is required to ensure the accuracy of beam direction estimation results, leading to more accurate channel similarity measure. Meanwhile, out-of-band information just initialize the beam search at the upper frequency. Beam sweeping within narrow angular range around the potential beam directions, which are extracted from low-band channel, is still needed when using different antenna configurations in low and high frequency bands. In this regard, optimal antenna design is required to ensure high level of channel similarity observed by different antenna systems, while providing sufficient beamforming gain under a restriction on the antenna size.

Channel mobility and blockages: Our proposed metric is performed to compare the potential beam directions between low- and high-frequency static channels. However, link establishment in higher band becomes even more challenging with user and scatterer mobility [15], as well as the presence of blockages. In real-world communication systems, beam pointing angles may change if low- and high-frequency systems observe slightly different channels, and in turn low-frequency channel direction information cannot be translated directly for high-frequency beam search. A clear relationship of the multi-band channel similarity with the evolution of time and location has to be established, which helps track the variation of the physical directions of dominant paths between two frequency bands. From extensive dynamic channel measurements in various environments, such multi-band similarity characterization can be developed for accurate translation of channel direction information, and consequently to improve the availability of out-of-band information aided high-frequency beam search in dynamic and complicated environments.

Transmission schemes: The significant power loss due to using out-of-band spatial information is normally introduced in the cases with multiple potential beam directions. However, mmWave/THz channels become more specular and sparse when beamforming is employed at both link ends [1], where the signals are limited to very small angular range and most received power can be collected with simple beamshape. It is expected that the power loss and number of false directions can be reduced when the desired number of beam directions is selected in advance. These correspond to the single-beam and multi-beam cases. For example, much higher level of spatial congruence can be observed if only the strongest channel direction (e.g., LOS) is taken into account. In this way, more useful and accurate out-of-band information can be provided to aid mmWave/THz beam search with the improvement of multi-band spatial channel similarity. Hence, we need to investigate how many dominant beams of interest that should be included in the analysis of spatial congruence.

VI. Conclusion

The concept of using out-of-band spatial information for high-frequency beam search has attracted considerable interest over the past decade. This idea relies on exploiting spatial channel similarity between low- and high-frequency bands. Some recent works have started to promote frequency-dependent channel characterization from centimetric to THz bands with visual comparison and statistical analysis of the concerned channel parameters, yet lacking a standard metric to measure the degree of multi-band spatial congruence. In this article, we discuss the feasibility of such beam search scheme by investigating the spatial similarity of expected radio channels based on the propagation data collected from ray-tracing simulations and channel measurements. In contrast to propagation channel, the impact of practical antenna configuration and beamforming scheme is considered in radio channel observed by different devices. Both ray-tracing and channel measurement results show high level of spatial similarity across sub-6 GHz, mmWave, and THz channels. It means that such beam search strategy is feasible in LOS scenario and even in NLOS scenario if using well-designed antenna patterns in specific frequency bands. Open challenges still remain to gain insights into multi-band spatial channel similarity with a focus on the extraction and translation of out-of-band spatial information to aid mmWave/THz beam search.

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