Fast Millimeter-Wave Beam Training with Receive Beamforming

Joongheon Kim and Andreas F. Molisch

Abstract: **This paper proposes fast millimeter-wave (mm-wave) beam training protocols with receive beamforming. Both IEEE standards and the academic literature have generally considered beam training protocols involving exhaustive search over all possible beam directions for both the beamforming initiator and responder. However, this operation requires a long time (and thus overhead) when the beamwidth is quite narrow such as for mm-wave beams (1° in the worst case). To alleviate this problem, we propose two types of adaptive beam training protocols for fixed and adaptive modulation, respectively, which take into account the unique propagation characteristics of millimeter waves. For fixed modulation, the proposed protocol allows for interactive beam training, stopping the search when a local maximum of the power angular spectrum is found that is sufficient to support the chosen modulation/coding scheme. We furthermore suggest approaches to prioritize certain directions determined from the propagation geometry, long-term statistics, etc. For adaptive modulation, the proposed protocol uses iterative multi-level beam training concepts for fast link configuration that provide an exhaustive search with significantly lower complexity. Our simulation results verify that the proposed protocol performs better than traditional exhaustive search in terms of the link configuration speed for mobile wireless service applications.**

Index Terms: **Beam training, fast link configuration, interactive search, iterative search, millimeter-wave**

I. INTRODUCTION

Millimeter-wave (mm-wave) data transmission has (re-) emerged as a highly promising approach to achieving gigabit/s throughput in wireless communications links. One application lies in cable replacement for in-home entertainment systems (wireless HDMI or wireless high-definition TV (HDTV) audio/video applications) and other personal-area networks that operate indoors over short distances (less than 20 m) [1]. Mm-waves can also be used for multi-gigabit/s outdoor transmission, either as directional links for wireless backhaul, or as access technology for transmissions between base stations (BSs) and mobile stations (MSs) as a part of 5G research [2]–[6].

Due to the extremely high carrier frequencies, mm-wave signals experience high path-loss, but are also highly directional [7]. High-gain antennas are thus required to obtain reasonable signal-to-noise ratios (SNRs). For all applications where the propagation channel (both indoor and outdoor) could change, an array antenna with *adaptive* beamforming is required. Yet, determining the optimum beam direction is non-trivial. Mm-wave adaptive arrays typically can (through RF-phase shifters) only "point" the beam in different directions, so that finding the optimum direction essentially requires "sweeping" the beam through all possible directions; the sweep has to be done in steps of the beamwidth. Such an exhaustive search has been widely considered in the literature [8] and is foreseen in mm-wave standards such as IEEE 802.15.3c wireless personal area networks (WPANs) [9]–[11] and IEEE 802.11ad wireless local area networks (WLANs) [12]. Since the beamwidth for mm-waves can be as low as 1°, the overhead for the beam training is significant [13], [14].

To alleviate this problem, the current paper proposes adaptive fast beam training protocols for both fixed and adaptive modulation. For fixed modulation, this paper addresses a fast link configuration protocol between beamforming initiator (BI) and beamforming responder (BR) using (i) *interactive beam training* and (ii) *prioritized beam search space ordering*. For *interactive beam training*, the proposed protocol modifies the beam training procedure such that it immediately terminates the procedure when both BI and BR find their optimal beam directions. For this purpose, each BI and BR changes its communication mode between transmitter (Tx) and receiver (Rx) in every single operation. Then, each BI and BR can give feedback to its opposite side when it finds an "optimum" direction. We note that the optimum might be a local (not global) optimum, but this has no impact on performance if the local optimum is "good enough" for the considered modulation format. For *prioritized beam search space ordering*, we employ long-term statistics, in particular the frequency of network association request/response statistics. We know that due to the special characteristics of 60 GHz propagation (very low diffraction and through-wall transmission), certain angular ranges can be completely blocked. Ordering of directions in terms of network association request/response statistics gives an indication about such blocked regions, which consequently would not be searched with high priority. For adaptive modulation, stopping before evaluating all beam directions is not beneficial because it might miss the global optimal solution. Therefore, we propose to perform an exhaustive search by starting out with a coarse-grained search that is successively refined (multi-level beam training). We investigate the optimal numbers of *sectors* for coarse-grained training and *division orders* for fine-grained training in terms of fast operation for a given beamwidth.

The contributions of this paper are as follows: (i) For fixed modulation wireless transmission, we design an interactive

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beam training algorithm that can dramatically reduce the beam search space and thus the overhead and (ii) for adaptive modulation wireless transmission, we additionally designed iterative beam training algorithm that can also reduce overall beam training time. Simulations using standardized systems and channel models confirm the effectiveness of our approach.

The remainder of this paper is organized as follows: Section II presents the preliminaries such as the basic properties of mm-wave wireless transmission, as well as related work. For fast link configuration, Section III and Section IV explain the details of our proposed interactive and iterative beam training protocols for fixed and adaptive modulation, respectively. Section V simulates our proposed protocols in mobile wireless applications. Section VI concludes this paper and presents future research directions.

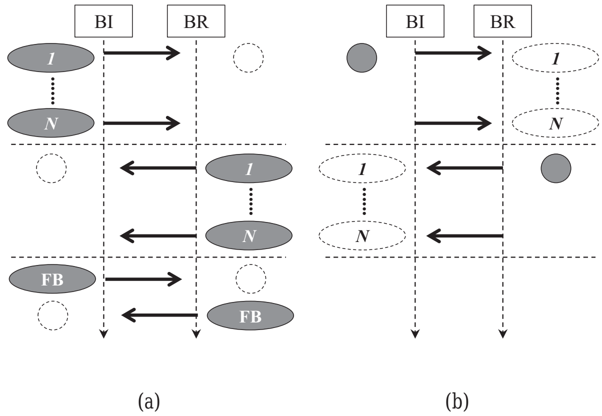


Fig. 1. A general beamforming procedure for link configuration: (a) TxBF and (b) RxBF.

II. PRELIMINARIES

A. Mm-wave Wireless Packets

According to the Friis path-loss model, the received power in free space is computed as

$$P_{\mathrm{Rx}} = \frac{G_{\mathrm{Tx}} G_{\mathrm{Rx}} c^2}{(4\pi d)^2 f_c^2} P_{\mathrm{Tx}} \tag{1}$$

where P_{Tx}, P_{Rx}, G_{Tx}, G_{Rx}, c, d, and f_c stand for the transmit power, receive power, transmit antenna gain, receive antenna gain, speed of light, distance, and carrier frequency, respectively. It can be seen that in order to compensate for the $1/f_c^2$ term, a high antenna gain is required. Many wireless propagation channel measurements have found that mm-wave channels are highly directional, i.e., if transmission occurs in a particular direction, signals are arriving at the receiver only from a few directions (and vice versa) [7], [15], [16]. This is in marked contrast to traditional microwave propagation, which is characterized by a large angular dispersion [17]. Furthermore, the small wavelength allows to create (adaptive or non-adaptive) antennas with high gain yet reasonable size: The beamwidths of current mm-wave commercial antenna solutions range from 1° to 15° [13], [14]. We note here that fully adaptive antennas that can perform digital beamforming allow very fast beam training, since they can receive a training signal at all antenna elements, and thus determine the optimum beam pattern in a single step. However, such antennas need a radio frequency (RF) chain for each antenna element, which is too costly for most consumer applications. We are thus concentrating on antenna arrays that have only a single downconversion chain, plus RF phase shifters, and thus can shift the direction of a main beam in (adjustable) increments, but can only receive with a single beampattern/direction at a time.

B. Related Work

B.1 General Beam Training – Exhaustive Search

The general beamforming and training procedure using transmit beamforming (TxBF) is illustrated in Fig. 1(a) [8]. In Fig. 1(a), each BI and BR has N beam directions. To initiate the beam training procedure, the BI sweeps through all beam directions, transmitting one training packet in each direction. During this time, BR receives the packets with an omni-directional antenna pattern. At the end of this period, the BR can identify which beam direction of the BI resulted in the highest SNR at the BR. Subsequently, BI and BR exchange their roles and repeat the procedure, allowing the BI to determine the direction of the BR leading to the highest SNR. A last step of exchanging feedback packets allows both sides to learn their own optimal directions. A variant of this approach uses receive beamforming (RxBF) instead of TxBF as illustrated in Fig. 1(b). In Fig. 1(b), each node BI and BR has N beam directions. The BI transmits packets in omni-directional mode, while the BR scans through all directions; then BI and BR exchange roles. The two nodes then know their optimum beam directions without further exchanging of feedback packets. Due to this advantage, and because Rx beamforming is not impacted by constraints on equivalent isotropically radiated power, but only on transmitted absolute power, we henceforth consider RxBF in this paper. As explained before, the beamwidth of commercial mm-wave high-gain Cassegrain antennas is near 1°, and similar values can be achieved with adaptive antennas of realistic size. Thus, in the worst case, N should be 360 for 2D beam geometry and $360 \times 180 \approx 6.48 \times 10^4$ for a 3D beam geometry. Consequently, the beam training procedures can require a significant overhead.

B.2 Beam Training Techniques in Mm-Wave IEEE Standards

This section reviews current standardized mm-wave beam training techniques. Specifically we consider the two standards for 60 GHz wireless communications, i.e., IEEE 802.15.3c WPAN [9] and IEEE 802.11ad WLAN [12].

In the IEEE 802.11ad WLAN and IEEE 802.15.3c WPAN beamforming and training [9]–[12], the protocols use a two-stage beamforming and training operation, i.e., coarse-grained beam training (named *sector sweeping* in IEEE 802.11ad and *low-resolution (L-Re) beam training* in IEEE 802.15.3c) and fine-grained beam training (named *beam refinement* in IEEE 802.11ad and *high-resolution (H-Re) beam training* in IEEE 802.15.3c). If the protocols consider TxBF, BF and BI determine the optimum coarse-grained beam according to the exhaustive-search protocol described in Section II-B.1. In the next stage, fine-grained beam training, the same type of protocol is used to identify the best beam in each coarse-grained beam. Similar principles hold when Rx beamforming is used; however, the IEEE 802.15.3c WPAN standard does not consider RxBF. Even if both standards have their own specific beamforming and training protocols, the protocols are fundamentally based on *two-level beam training*. While this can accelerate the beamforming, it is still slow, as demonstrated in Section V.

In addition, we point out that finding the "best" direction at the Rx when the Tx is omni-transmitting (i.e., the currently used algorithms for exhaustive search, two-stage beam training, and our proposed scheme) might not be the same thing as finding the best Rx-direction when a joint Tx-Rx optimization has been done. Note that current existing mm-wave beam training protocols including IEEE 802.11ad and IEEE 802.15.3c have a similar restriction as our algorithm.

III. INTERACTIVE BEAM TRAINING FOR FIXED MODULATION

A. Interactive 2D Beam Training

A.1 Concepts

Our proposed beam training in a 2D geometry is designed based on two concepts, i.e., (i) *interactive beam training* and (ii) *prioritized sector search ordering*. Fig. 2 shows the fundamental process of the proposed two-level beam training. *Prioritized sector search ordering* orders the sectors in terms of network association statistics at first, in turn, *interactive beam training* is used for finding desired beam directions within the sorted sectors/beams.

Interactive Beam Training: An important source of inefficiency in exhaustive beam training lies in the fact that even when a BI or BR finds a good beam direction, it cannot stop because it has to search all given beam directions. Of course, in order to find the *globally optimum* direction, a complete search is necessary. However, when a fixed modulation/coding scheme is used, it is often sufficient to find a "good enough" direction that can sustain the communications with acceptable packet error rates. Thus, beam training overhead can be reduced by letting the beam search stop when both BI and BR find acceptable beam directions. This principle requires modifications in the transmission protocol.

We thus propose that the protocol proceeds as follows: As illustrated in Fig. 3, BI and BR change their communication mode between Tx and Rx after every training packet transmission. Thus, after sending a training packet in an omni-directional Tx (Omni-Tx) mode, the device, i.e., BI or BR, updates its communication mode as beamformed Rx (BF-Rx) mode to receive the training packet from the given direction of the opposite side via RxBF. When having identified a beam direction with "sufficient quality", the Rx will continue the search until it can be sure to have found a *local* optimum, i.e., determined that the SNR is worse on both sides of the "sufficiently good" direction. This is done in order to increase the robustness of the received scheme, and in light of the fact that finding the local optimum does not impose a significant increase in training overhead. If either BI or BR finds an acceptable beam direction in a BF-Rx mode, it can "piggy-back" this information on the next training

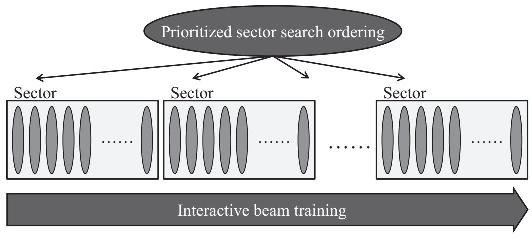


Fig. 2. A fundamental procedure of interactive beam training.

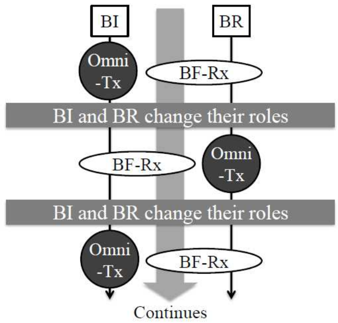


Fig. 3. A basic concept of interactive beam training.

packet. When both BI and BR have found their acceptable beam directions, this beam training procedure immediately stops.

Prioritized Sector Search Ordering: To accelerate the average search speed, we prioritize the order of Rx beam directions to be searched. For this purpose, our proposed protocol also considers multi-level beam training. The proposed protocol orders the *segmented spaces* in terms of network association request/response (NAR) statistics. Notice that the term *segmented spaces* is equivalent to *sectors* in IEEE 802.11ad and *L-Re beams* in IEEE 802.15.3c. This prioritized sector search ordering is quite useful in mm-wave systems because physical obstacles can constitute very strong attenuators, thus greatly restricting the angular range from which useful signals can come in a given room (this is especially true for walls, which can be easily penetrated by microwaves, but are impervious to mm-waves, and which might not be effective reflectors for certain geometric configurations either). The regions with the largest number of NAR statistics might thus constitute the angular regions from which radiation can physically occur, or it might be a region that is preferred by users. A detailed implementation is discussed in Section III-A.2.

A.2 Detailed Designs of Algorithm Concepts

Interactive Beam Training: The piggy-backing of information on the training packet structure needs to be compliant with the existing structures. Our proposed packet has one bit Boolean information named *beam notification (BN)*. The initial value of BN is N which means that the current BI or BR does not know its sufficient beam direction. When that changes, the BN is set to Y from that time onwards. Let us assume for the following discussion that BI first finds a suitable beam direction. It then listens to the incoming training packet from BR with its optimal Rx beam and will see that the BN of the packet is the initial value, i.e., N. Recognizing that the BR has not yet found its own optimal beam direction yet, it will send out training packets in an omni-directional Tx mode, its BN field is set to Y. When the BR also finds its optimal beam direction, it will see the BN of the training packet and find that the BN is Y. Then, BR will recognize that BI already found its suitable beam direction. Now, the proposed interactive beam training operation is terminated. Therefore, as expected, our proposed procedure can be terminated when both sides find their optimal beam directions. Thus, we can avoid exhaustive search for all the given beam search directions. It is also noteworthy that the training packets transmitted with a power/spreading factor that provides sufficient SNR at the receiver even though the Tx sends them omnidirectionally; this holds true also for the currently standardized training packets.

Note that the search time of this algorithm is a random variable, strongly influenced by the direction in which the search was started. The worst-case scenario occurs when all possible directions have to be searched, i.e., the initially searched beam was close to the only admissible beam direction, but the search started into the "wrong" direction. In that case the overhead is as large as that of a conventional exhaustive search.

Note that even after the first node finds a "promising" direction, it will continue to search, in order to find a possibly better direction.

Prioritized Sector Search Ordering: Our beam training protocol is based on multi-level (i.e., two-level) beam training. Therefore, we have a given number of segmented spaces and maintain the NAR statistics for each segmented space (i.e., the summation of NAR statistics of the beams within the segmented space), and prioritize in order of aggregate number of NAR requests, where recent requests might be weighted more heavily than earlier ones. For the given N_{NAR} samples, the following equation holds:

$$N_{\mathrm{NAR}} = \sum_{i=1}^{N} f_{\mathrm{NAR}}^{\mathrm{2D}}(i) \tag{2}$$

where i stands for a beam index ($1 \leq i \leq N$), N stands for the number of beam search spaces with the given beamwidth, and $f_{\mathrm{NAR}}^{\mathrm{2D}}(i)$ stands for the NAR statistics for i-th beam ($0 \leq f_{\mathrm{NAR}}^{\mathrm{2D}}(i) \leq N_{\mathrm{NAR}}$). Then each given segmented space has NAR statistics as follows:

$$f_{\mathrm{NAR}}^{\mathrm{SS-2D}}(k) = \sum_{i=1+\frac{N}{N_{\mathrm{SS}}}(k-1)}^{\frac{N}{N_{\mathrm{SS}}}k} f_{\mathrm{NAR}}^{\mathrm{2D}}(i) \tag{3}$$

where i stands for a beam index ($1 \leq i \leq N$), k stands for a segmented space index ($1 \leq k \leq N_{\mathrm{SS}}$) where N_{SS} stands for the number of segmented spaces, and $f_{\mathrm{NAR}}^{\mathrm{SS-2D}}(k)$ stands for the NAR statistics for segmented space k ($0 \leq f_{\mathrm{NAR}}^{\mathrm{SS-2D}}(k) \leq N_{\mathrm{NAR}}$). We search the optimal Rx beam direction from the segmented space which has the highest $f_{\mathrm{NAR}}^{\mathrm{SS-2D}}(k)$ value where $1 \leq k \leq N_{\mathrm{SS}}$. Within the segmented space, the Rx beam direction search order is sequential, e.g., if we consider the segmented space k, the beam search order is from $1+(k-1)N/N_{\mathrm{SS}}$ up to N/kN_{SS}.

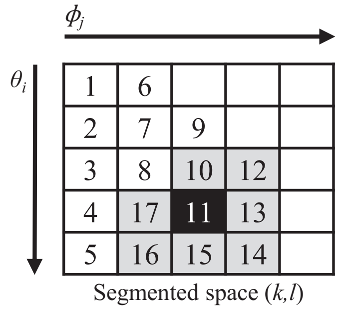


Fig. 4. An example for 3D beam search process within one segmented space. Gray and black rectangles stand for the median SNR beams and the highest SNR beam, respectively. In the figure, ϕ_j and θ_i stand for azimuth planes index j ($-180° \leq \phi_j \leq 180°$) and elevation plane index i ($-90° \leq \theta_i \leq 90°$), respectively.

B. Interactive 3D Beam Training

Even though most of beamforming and training research results are designed and implemented in a 2D scenario, a 3D geometric computation is also considerable to design more realistic beamforming and training protocols [18], [19]. The main difference to the 2D scenario is that we have to search in a 3D geometry to make sure we have a local maximum. Apart from the longer search time, the beam training mechanisms mentioned above can be reused in a straightforward way. One key difference is the search for the local optimum within the segmented space. In 2D interactive beam training, the desired beam direction can be found by a linear sequential search within every single segmented space (i.e., sector). However, this sequential search is not applicable in 3D interactive beam training due to the fact that the segmented space is formed as *plane*. The detailed operation is as follows: As presented in Fig. 4, sequential search is doing in a vertical manner (from 1 to 8) for every single column. While doing this sequential search, if we start to listen to SNR (at 8th beam in Fig. 4), then we look at the surrounding beam directions to check whether a higher-SNR beam exists or not. If yes, then we move to the beam and look at the neighbor beams, and continue this procedure. Then, finally, we are able to reach the local maximum SNR beam (i.e., 11th beam in Fig. 4).

In this section, we designed an interactive algorithm on top of a sequential search. Note that the interactive algorithm concept can also be combined with other, more efficient search algorithms (instead of the linear search), such as quadratic search, to provide a faster algorithm.

C. Discussion: Tradeoff – IFS Overheads

Our proposed scheme changes Tx and Rx modes every single training packet transmission for interactive operation. In general wireless systems, when devices change their communication modes, a time interval is defined for the mode change, i.e., inter-frame spacing (denoted as IFS). Moreover, there is another inter-frame spacing between each beam space evaluation (denoted as ifs). In general, IFS takes more time than ifs. For example, ifs is 73 ns and IFS is 0.5 μs in IEEE 802.15.3c [10], i.e., IFS is 6.85 times longer than ifs. As shown in Fig. 5(a) and Fig. 5(b), there are four and two IFS durations in the exhaustive

Table 1. IFS overhead.

N	BF mode	$k/N=0.94$	$k/N=0.95$	$k/N=0.96$	$k/N=0.97$	$k/N=0.98$	$k/N=0.99$
90	TxBF	0.9498	0.9599	0.9700	0.9801	0.9902	1.0003
90	RxBF	0.9606	0.9708	0.9810	0.9913	1.0015	1.0117
180	TxBF	0.9553	0.9655	0.9756	0.9858	0.9959	1.0061
180	RxBF	0.9607	0.9709	0.9812	0.9914	1.0016	1.0118
360	TxBF	0.9581	0.9683	0.9784	0.9886	0.9988	1.0090
360	RxBF	0.9608	0.9710	0.9812	0.9914	1.0017	1.0119

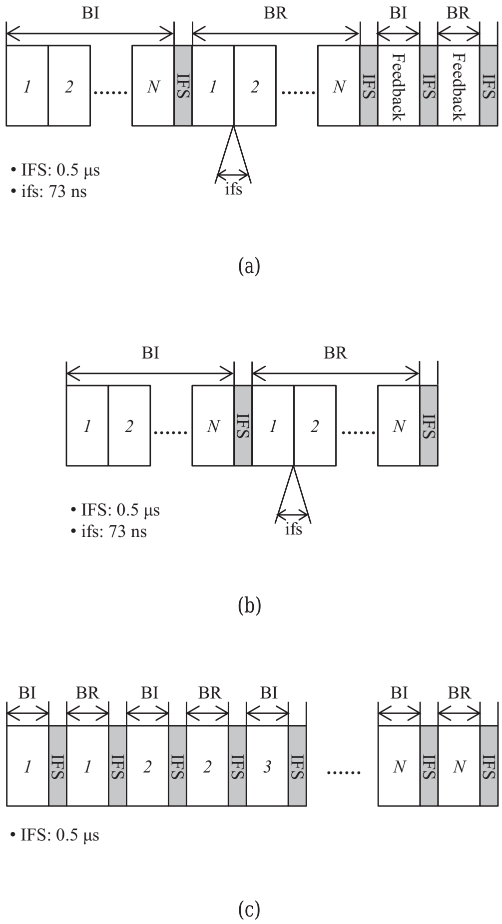


Fig. 5. IFS durations: (a) IFS for the exhaustive search using TxBF, (b) IFS for the exhaustive search using RxBF, and (c) IFS for the proposed procedure.

beam training procedure using TxBF and RxBF when each device changes its communication mode. In addition, $2\times(N-1)$ ifs durations in the exhaustive beam training procedure using both TxBF and RxBF. However, the proposed protocol requires much more IFS durations which can lead to time-overheads as shown in Fig. 5(c). To observe the impact of IFS durations, the time-overheads are computed and simulated.

As a reference control frame structure in this paper, the control frame defined in the 60 GHz IEEE 802.15.3c standard is used. In IEEE 802.15.3c, *common mode signaling (CMS)* is used for synchronization/beacon frame transmission including beamforming/training procedure (see Section 12.1.12 in [10]) and the frame structure is as illustrated in Fig. 6 [10]. In Fig. 6, the CMS frame consists of CMS physical layer (PHY) payload (42 octets and 47.8 Mbps, thus, required time to transmit this part is 12.09 μs), CMS frame header (33 octets and 27.8 Mbps, i.e., required time to transmit this part is 5.52 μs), and CMS PHY preamble (3.26 μs is required). Among them, the CMS frame header consists of Reed-Solomon (RS) parity bits (16 octets), header check sequence (2 octets), medium access control (MAC) header (10 octets), and PHY header (5 octet). More details are in [10]. Notice that the forward error correction scheme for CMS is RS coding and the coding rate is 239/255, i.e., $RS(255,239)$.

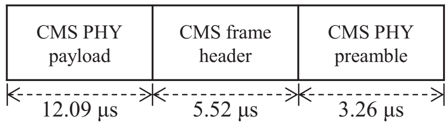


Fig. 6. CMS frame structure.

Finally, as can be seen in Fig. 6, the required time to transmit one training packet is

$$t_{\text{pkt}} = 12.09\mu\text{s} + 5.52\mu\text{s} + 3.26\mu\text{s} = 20.87\mu\text{s}. \quad (4)$$

The results of IFS overhead simulations are as presented in Table 1 where k and N stand for the search order of optimal beam direction and the total number of beam directions, respectively. For example, if the optimal beam direction of a device is the 36th beam direction and N is set to 360, then $k/N = 36/360 = 0.1$. The computed values in Table 1 stand for $T_{\text{interactive}}/T_{\text{exhaustive}}$ where $T_{\text{interactive}}$ and $T_{\text{exhaustive}}$ are the operation times for the proposed interactive beam training and the general (exhaustive) beam training, respectively. Thus, if this is bigger than 1, our proposed protocol is slower than the general procedure because of IFS overheads. The simulation is performed for three different search space sizes, i.e., $N = 90, 180, 360$. Note that there are no segmented spaces in this simulation. As we can observe in Table 1, the performance is almost the same even if the size of the search spaces are varying. If approximately $k < (98/100)\,N$, our proposed protocol is faster than the traditional ones. Otherwise, the performance of the proposed protocol is worse due to the IFS overheads. Therefore, it is true that the impact of IFS overheads is realized with approximately 2%, i.e., we cannot observe the IFS overhead impacts, in general.

In conclusion, if the NAR statistics for all Rx beams are uniformly distributed (i.e., there are no preferred beam directions),

$$E\left[T_{\text{interactive}}\right] = \frac{2\cdot(t_{\text{pkt}}+t_{\text{IFS}})}{(\delta_{\text{BR}}^{\max}+1)\cdot(\delta_{\text{BI}}^{\max}+1)}\times \sum_{\delta_{\text{BR}}=0}^{\delta_{\text{BR}}^{\max}}\sum_{\delta_{\text{BI}}=0}^{\delta_{\text{BI}}^{\max}} \max\left[\frac{\left\|\left(-\pi+\frac{2\pi}{\delta_{\text{BI}}^{\max}}\delta_{\text{BI}}\right)-s\right\|_{\mathcal{S_B}}^{\min}}{\theta}, \frac{\left\|\left(-\pi+\frac{2\pi}{\delta_{\text{BR}}^{\max}}\delta_{\text{BR}}\right)-s\right\|_{\mathcal{S_B}}^{\min}}{\theta}\right] \quad (5)$$

Table 2. Numerical analysis of training speed (θ: Beamwidth).

	$\theta=1°$	$\theta=4°$	$\theta=7°$	$\theta=10°$
$\frac{E[T_{\text{exhaustive}}]}{E[T_{\text{interactive}}]}$	10.511	10.519	10.527	10.534
$\frac{E[T_{\text{multi-level}}]}{E[T_{\text{interactive}}]}$	1.433	1.791	2.149	2.506

we can achieve faster beam training results with the probability of around 98% than the traditional exhaustive searches. By exploiting beam prioritization, we can achieve an even higher overall reduction of the training time.

D. Analysis

To analyze the expected link setup speed of the proposed protocol (i.e., $E\left[T_{\text{interactive}}\right]$), suppose that BI and BR start the training from the angles θ_{BI} and θ_{BR} where $-180° \le \theta_{\text{BI}} \le 180°$ and $-180° \le \theta_{\text{BR}} \le 180°$. For simplicity, we only consider forward search, thus, the training will stop when BI and BR meet the nearest global/local optimum direction in forward search directions. $\mathcal{S_B}$ means the set of global/local optima (e.g., $\mathcal{S_B} = \{-152°, -122°, 0°, 102°, 128°, 140°\}$ and $|\mathcal{S_B}| = 6$ in the 60 GHz mm-wave IEEE 802.15.3c CM1.3 channel model as simulated in Fig. 11, s is an element of $\mathcal{S_B}$ which is located in the forward search as seen from the current angle of arrival (AoA). According to the fact that forward search is used, e.g., if current direction is $130°$, only $140°$ can be s in the IEEE 802.15.3c CM1.3 channel model.

$\|x-s\|_{\mathcal{S_B}}^{\min}$ stands for the AoA distance between x and the nearest s. Then, the time that BI finds its global/local optimum direction (denoted as t_{BI}^*) is as follows:

$$t_{\text{BI}}^* = (t_{\text{pkt}}+t_{\text{IFS}})\cdot\left(\frac{\|\theta_{\text{BI}}-s\|_{\mathcal{S_B}}^{\min}}{\theta}\right) \quad (6)$$

where θ stands for beamwidth. Similarly, the time that BR finds its global/local optimum direction (denoted as t_{BR}^*) is as follows:

$$t_{\text{BR}}^* = (t_{\text{pkt}}+t_{\text{IFS}})\cdot\left(\frac{\|\theta_{\text{BR}}-s\|_{\mathcal{S_B}}^{\min}}{\theta}\right) \quad (7)$$

and our algorithm stops when both find their "good enough" global/local optima, i.e.,

$$2\times\max\left\{t_{\text{BI}}^*, t_{\text{BR}}^*\right\}. \quad (8)$$

To deal with any possible cases with any arbitrary θ_{BI} and θ_{BR}, the two parameters are defined as follows:

$$\theta_{\text{BI}} = -\pi + \frac{2\pi}{\delta_{\text{BI}}^{\max}}\cdot\delta_{\text{BI}}; \quad (9)$$

$$\theta_{\text{BR}} = -\pi + \frac{2\pi}{\delta_{\text{BR}}^{\max}}\cdot\delta_{\text{BR}} \quad (10)$$

where $\delta_{\text{BI}}^{\max}$ and $\delta_{\text{BR}}^{\max}$ mean the sampling sizes for the evaluation on BI and BR, δ_{BI} and δ_{BR} are indices for the sampling where $0\le\delta_{\text{BI}}\le\delta_{\text{BI}}^{\max}$ and $0\le\delta_{\text{BR}}\le\delta_{\text{BR}}^{\max}$.

Finally, the expected link setup speed of the proposed protocol (i.e., $E\left[T_{\text{interactive}}\right]$) can be computed by (5). We also assume that the NAR statistics for sectors are uniformly distributed.

The expected link setup speeds of the traditional exhaustive protocol with RxBF (see Section II-B.1) and multi-level protocol with RxBF (see Section II-B.2), i.e., $E\left[T_{\text{exhaustive}}\right]$ and $E\left[T_{\text{multi-level}}\right]$, can be computed as follows:

$$E\left[T_{\text{exhaustive}}\right] = 2\left[\left\lceil\frac{2\pi}{\theta}\right\rceil\cdot t_{\text{pkt}} + t_{\text{IFS}} + \left(\left\lceil\frac{2\pi}{\theta}\right\rceil - 1\right)\cdot t_{\text{ifs}}\right]; \quad (11)$$

$$E\left[T_{\text{multi-level}}\right] = 2\left[\left(\left\lceil\frac{2\pi}{\theta_s}\right\rceil + \left\lceil\frac{\theta_s}{\theta}\right\rceil\right)\cdot t_{\text{pkt}} + t_{\text{IFS}} + \left(\left\lceil\frac{2\pi}{\theta_s}\right\rceil + \left\lceil\frac{\theta_s}{\theta}\right\rceil - 2\right)\cdot t_{\text{ifs}}\right] \quad (12)$$

where $\lceil x\rceil$ stands for the function which is the smallest integer not less than x where $0°\le\theta\le 360°$, θ stands for the mm-wave beamwidth, and θ_s stands for the width of each sector. As shown in Table 2, the proposed protocol is $10.511-10.534$ times faster than brute-force search and $1.433-2.506$ times faster than multi-level beam training with 8 sectors.

IV. ITERATIVE BEAM TRAINING FOR ADAPTIVE MODULATION

For adaptive modulation, we have to find the global optimum so that we can choose the highest-rate modulation and coding scheme supported by the channel. Thus, we have to find a way to get the optimal Rx beam directions for BI and BR while observing all beam directions. Yet, we still wish to reduce the overhead compared to the exhaustive search described in Section II.

In this section, we maintain the basic structure of multi-level beam training, i.e., (i) coarse-grained beam training (L-Re/sector sweeping) and (ii) fine-grained beam training (exhaustive search within the computed optimal L-Re/sector) as presented in Fig. 7(a). In order to reduce the operation time of the protocol, we suggest *iterative subspace partitioning* with given *division order* instead of exhaustive search, as illustrated in Fig. 7(b).

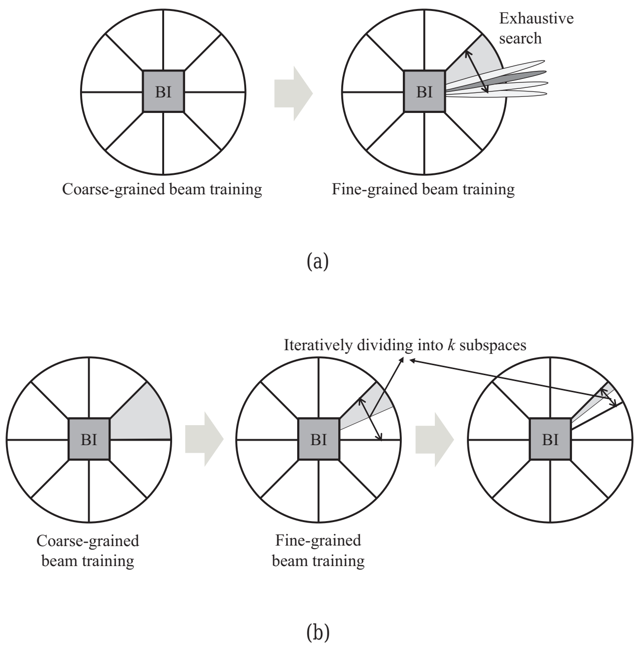


Fig. 7. Fundamental concepts of iterative subpace partitioning: (a) Traditional multi-level beam training and (b) iterative subspace partitioning.

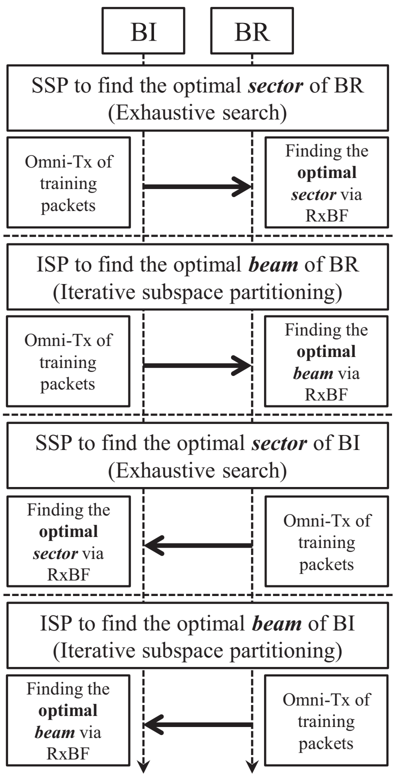


Fig. 8. A procedure of iterative beam training.

Therefore, our objective is finding (i) *optimal number of segmented spaces (i.e., sectors)* for coarse-grained beam training and (ii) *optimal division order* that can minimize the number of evaluated search spaces in iterative subspace partitioning.

A. Iterative 2D Beam Training

For the sector sweeping phase (SSP), the omni-directional spaces of BI and BR are divided into $\mathcal{N}^{2D}_{\text{sector}}$ number of segmented spaces (i.e., sectors) at first. The proposed protocol finds the optimum sectors according to the exhaustive search procedure described in Section II. For the next phase (i.e., iterative subspace partitioning (ISP)), BI transmits training packets in an omni-directional Tx mode, again. At the same time, BR breaks down the optimum sector which were found in SSP into φ subspaces where φ stands for the division order ($\varphi \geq 2$). Then we have to evaluate each subspace. Thus, we receive φ number of training packets from the BI for each subspace partitioning. This procedure is repeated until the subspace becomes smaller than the beam width θ (termination condition). Now, BR finds its optimal beam direction. Then BI and BR exchange roles, and the optimum subspace at the BI is found. This procedure is illustrated in Fig. 8. Note that SSP could be interpreted to be just one further step in the ISP. However, in order to retain the backward compatibility to the procedure described in the IEEE standards, we identify them here as two separate stages in the beamforming process.

Let us now analyze the total number of training packets that need to be transmitted by the BI (an equivalent number has to be transmitted by the BR). In the first phase, the BI transmits $\mathcal{N}^{2D}_{\varphi}$ training packets. In addition, during each iteration step of the beam refinement, φ training packets are required. Let $\mathcal{N}^{2D}_{\varphi}$ be the number of iteration steps, i.e., the minimum positive integer that satisfies

$$\frac{\alpha}{\mathcal{N}^{2D}_{\text{sector}}} \cdot \left(\frac{1}{\varphi}\right)^{\mathcal{N}^{2D}_{\varphi}} \leq \theta \tag{13}$$

where $\alpha = 360$. To get the $\mathcal{N}^{2D}_{\varphi}$ from (13), take the logarithm (base: φ) on the left-hand side and right-hand side of (13), then following (14) is eventually obtained:

$$\mathcal{N}^{2D}_{\varphi} = \left\lceil \log_{\varphi}\left(\frac{\alpha/\mathcal{N}^{2D}_{\text{sector}}}{\theta}\right)\right\rceil \tag{14}$$

where $\lceil x \rceil$ stands for the function which is the smallest integer not less than x where $0° \leq \theta \leq 360°$. Thus, in our two-level beam training, we have to evaluate $\mathcal{N}^{2D}_{\text{sector}}$ number of coarse-grained beams at first, and iteratively we have to break-down $\mathcal{N}^{2D}_{\varphi}$ times. In each breaking down, we have to evaluate φ search spaces. Therefore,

$$\mathcal{N}^{2D}_{\text{sector}} + \varphi \cdot \left\lceil \log_{\varphi}\left(\frac{\alpha/\mathcal{N}^{2D}_{\text{sector}}}{\theta}\right)\right\rceil \tag{15}$$

number of training packet transmissions are required. After the confirmation of the optimum beam direction of BR, BI and BR swap their roles and find the optimum beam direction of BI. Then, the proposed protocol is terminated.

The proposed scheme has three parameters as follows:

- $\mathcal{N}^{2D}_{\text{sector}}$: The number of sectors, a positive integer;
- φ: A division order, an integer where $\varphi \geq 2$;
- θ: A beamwidth, a real number where $1 \leq \theta \leq 10$.

Among them, θ is given and our main optimization framework finds the optimal $\mathcal{N}^{2D}_{\text{sector}}$ and φ to minimize the number of training packet transmission, i.e., minimize (15).

Data:
- Beamwidth θ where $1 \leq \theta \leq 10$

Result:
- Optimum number of sectors: $\overline{\mathcal{N}}^{2D}_{\text{sector}}$
- Optimum division order: $\overline{\varphi}$

Initialization;
- Optimum number of sectors: $\overline{\mathcal{N}}^{2D}_{\text{sector}} \leftarrow \alpha$ where α is the value more than 360 (max value of $\mathcal{N}^{2D}_{\text{sector}}$), e.g., 400
- Optimum division order: $\overline{\varphi} \leftarrow \beta$ where β is the value more than 360 (max value of φ), e.g., 400
- Minimum (optimum) number of search spaces: $\overline{\mathcal{N}}_{\text{search}} \leftarrow \gamma$ where γ is extremely high value, e.g., 10^{10}
- Number of search spaces: $\mathcal{N}_{\text{search}}$
- Central angle of sector: ϑ

```
For the given beamwidth θ where 1 ≤ θ ≤ 10,
while N^2D_sector ∈ {1, 2, ··· , 360} do
    while φ ∈ {2, 3, ··· , 360} do
        if φ ≤ (360/N^2D_sector)/θ then
            N_search ← N^2D_sector;
            ϑ ← 360/N^2D_sector;
            flag ← true;
            while flag == true do
                if ϑ < θ then
                    // Multiplying 2 for both BI and BR
                    N_search ← N_search × 2;
                    // Escaping from this loop
                    flag ← false;
                else
                    // Iterative subspace partitioning
                    ϑ ← ϑ/φ;
                    // Evaluating partitioned subspaces
                    N_search ← N_search + φ;
                end
            end
            if N̄_search > N_search then
                N̄_search ← N_search;
                N̄^2D_sector ← N^2D_sector;
                φ̄ ← φ;
            end
        end
    end
end
```

Fig. 9. Pseudo-code to find $\mathcal{N}^{2D}_{\text{sector}}$ and φ.

B. Pseudo-Code and Computational Complexity

The pseudo-code to find optimal number of sectors and optimal division order in the proposed iterative beam training for a 2D scenario is as represented in Fig. 9. The protocol for a 3D case is equivalent to Fig. 8 and the Fig. 9 with some straightforward modifications of the parameters. In addition, the computational complexities are $O\left(N^2\right)$ for both 2D and 3D scenarios (polynomial-time computation).

V. PERFORMANCE EVALUATION

This section evaluates the performance of proposed protocols in terms of the wireless link configuration speed because our objective is *fast* beam configuration.

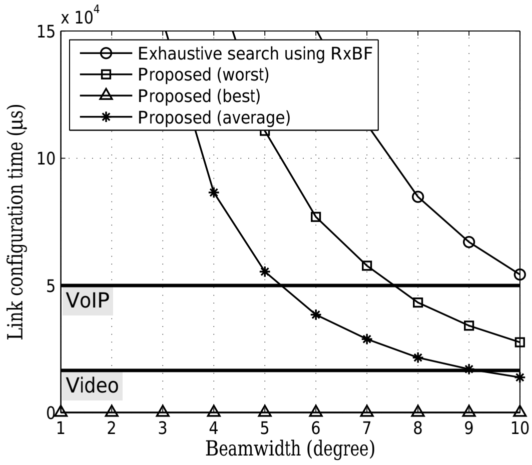


Fig. 10. Simulation results for mobile wireless services.

A. Interactive Beam Training for Fixed Modulation

This section presents the simulation results in terms of the fastness of beam training in mobile wireless service applications.

For the performance evaluation of mobile wireless services, our considered scenario includes one access point (AP) as a BI and one device as a BR in a room. In this setting, BI and BR are located at the top corner and ground, respectively. Here, BI uses only $1/8$ of the beam directions (i.e., only Southeast down-side directions are available) and BR uses $1/2$ (i.e., only upper-side directions are available) of the beam directions among all possible sphere beam directions. Thus, we consider that the given network has 8 segmented spaces with a $\pi/2 = 90^\circ$ central angles value.

Then the link establishment time comparison between the proposed protocol and the exhaustive search using RxBF is simulated as presented in Fig. 10. The simulation is performed with various beamwidths, i.e., from 1° to 10° (x-axis). As shown in Fig. 10, if the proposed protocol finds the optimal beam directions for the first beam directions every time (i.e., the best case), the link establishment only takes 64.11 μs that is significantly less than for the exhaustive search with RxBF. Even if the proposed protocol finds the optimal beam directions for the last tested beam directions for the segmented spaces with positive NAR statistics (i.e., the worst case and the segmented spaces which have no NAR statistics are ignored), the link establishment time is almost half of the link establishment time of exhaustive search with RxBF (due to the fact that it does not due unnecessary searches in segments that do not have positive NAR values). Therefore, the performance is almost twice better than the widely used RxBF based exhaustive search operation in terms of link establishment time.

As summarized in [20], if seamless mobile services are required, the following latency requirements should be met:
- Video services: 1.66×10^4 μs;
- Voice over IP (VoIP) services: 5×10^4 μs.

Then, as can be seen in Fig. 10 and Table 3, it is obvious that the currently existing exhaustive search using RxBF cannot support seamless mobile video and VoIP services at all. However,

Table 3. Link establishment time comparison (unit: μs).

Beamwidth	Exhaustive search	Proposed search with highest performance	Proposed search with lowest performance	Proposed search with average performance
$1°$	3.01×10^6	6.41×10^1	2.77×10^6	1.38×10^6
$2°$	7.52×10^5	6.41×10^1	6.92×10^5	3.46×10^5
$3°$	3.34×10^5	6.41×10^1	3.08×10^5	1.54×10^5
$4°$	1.88×10^5	6.41×10^1	1.73×10^5	8.66×10^4
$5°$	1.20×10^5	6.41×10^1	1.11×10^5	5.54×10^4
$6°$	8.36×10^4	6.41×10^1	7.69×10^4	3.85×10^4
$7°$	6.28×10^4	6.41×10^1	5.78×10^4	2.89×10^4
$8°$	4.70×10^4	6.41×10^1	4.33×10^4	2.17×10^4
$9°$	3.72×10^4	6.41×10^1	3.42×10^4	1.71×10^4
$10°$	3.01×10^4	6.41×10^1	2.77×10^4	1.39×10^4

if our proposed protocol can find optimal Rx beam directions in the first search space (i.e., the best case), then all kinds of seamless mobile services can be supported even if there is no prioritized segmentation. Even in the worst case, at least seamless mobile VoIP services can be supportable if the beamwidth is equal to or larger than $8°$; in the average case, seamless mobile VoIP services can be supportable when the beamwidth is equal to or larger than $6°$ (without search space prioritization). In addition, seamless mobile video services can be also achieved if the beamwidth is equal to or wider than $9°$ in the average case.

As an example, we investigate the performance in a channel model that is adopted from IEEE 802.15.3c [21]. Among the various IEEE 802.15.3c TSV channel model scenarios, we considered channel model CM1.3, i.e., a line-of-sight (LOS) scenario (at a 5 m distance, which leads to an LOS-component attenuation of 82 dB) and a residential environment. For this channel model, the angular power spectrum (APS) is shown in Fig. 11(a). From this we derive the distribution of the SNR over the AoA with omni-directional transmitter and receiver in Fig. 11(b). As can be seen, the receiver is able to get an appreciable SNR around 6 times based on the CM1 channel model because of the multi-path components by reflection. Note that the SNR in $0°$ is the global optimum. The other SNR representations are local maxima.

Let th_d and th_v be the threshold SNR for decodability of the MAC header and the threshold SNR for the successful actual data transmission (video signal decoding), respectively. As presented in Section III-C, the training packet is CMS and CMS uses modulation/coding scheme level 0 (MCS0) [10]. As presented in [22], th_d is 2.9 dB if our desired bit-error-rate (BER) performance is 10^{-4}. For th_v, the minimum bounds of SNR for decoding the most significant bits (MSB) and the least significant bits (LSB) of video signals with BER performance 10^{-4} are 7 dB and 10.5 dB, respectively, in IEEE 802.15.3c as verified in [23]. Note that in the scalable coded video, the base layer is encoded as MSBs, while additional layers exist. If the wireless channel bandwidth is enough to transmit all the scalable video layers, we can transmit the scalable video coding layers up to LSB (i.e., all layers are able to be transmitted). Moreover, let G_s and G_b be the antenna gain of a sector antenna (i.e., coarse-grained beam) and the gain of the adaptive array that is used for the transmission over final beams (fine-grained beam, i.e., used for actual data transmission), respectively. G_s and G_b are set to 10 dB and 23 dB, respectively [21].

Table 4. Optimal number of sectors and optimal division orders in interactive 2D beam training.

# of sectors: $\mathcal{N}^{\rm 2D}_{\rm sector}$	Division order φ	Statistics (out of 9001)	Statistics (%)
2	2	1637	18.19
2	3	4036	44.84
3	2	1041	11.57
3	3	1575	17.50
4	2	0	0
4	3	712	7.91

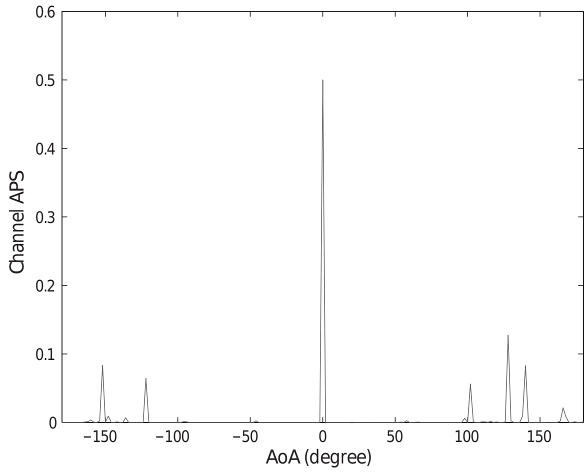
Based on Fig. 11(b), if both transmitter and receiver have omni-directional beam patterns, the training packets are not able to be decoded because the maximum SNR (AoA: $0°$) is lower than 7 dB. However, due to the fact that the maximum SNR with G_s is larger than th_d, the training packets of our coarse-grained beam training can be decoded. Depending on the distance, only the globally optimum AoA, or several of the local maxima, can be decoded. Moreover, for actual video data transmission, the transmitted video signals are able to be decoded if following equation holds:

$$\{\text{max SNR (AoA: } 0°\text{) in Fig. 11(b)}\} + 2G_b \geq th_v. \quad (16)$$

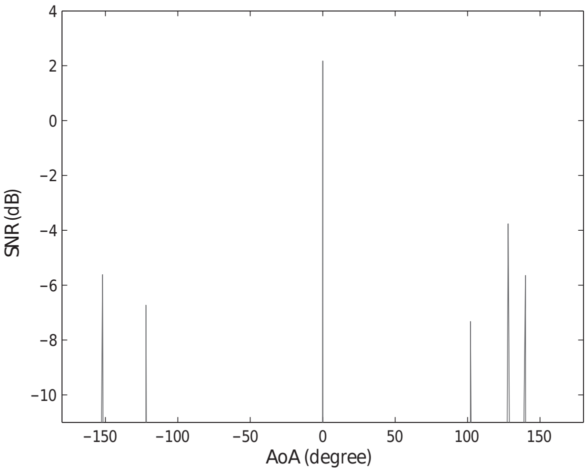
Then, it is true that all MSB and LSB information with all given 10^{-4} BER performance are satisfying this equation. Therefore, all video signals are able to be decoded as well. It is noteworthy that decodability of the packet header implies that video packets can always be decoded (due to the fact that the antenna gain during video transmission is much higher than the sector antenna gain). On the other hand, there can be situations where a video decoding would be possible but the connection cannot be set up since the transmitter and receiver cannot find suitable sectors. This is a weak point in the 802 protocols whose resolution would be important for future applications, but which likely cannot be alleviated without impact on backward compatibility.

B. Iterative Beam Training for Adaptive Modulation

With the given beamwidths, i.e., from $1°$ to $10°$ with $0.001°$ step size (i.e., totally 9001 sample evaluation), the optimal numbers of sectors and optimal division orders are simulated for a



(a)



(b)

Fig. 11. 60 GHz channel realization: (a) Channel APS and (b) SNR distribution (omni-Tx and omni-Rx).

2D scenario. The simulation results with 9001 samples are presented in Table 4. As presented in this table, the possible numbers of sectors are 2, 3, and 4 and the possible division orders are 2 and 3. The other values are not optimal in terms of operation time (i.e., number of search spaces).

In Table 5, our proposed protocol is faster than the exhaustive search using RxBF for all evaluated 9001 samples. In addition, our link configuration speeds for all evaluated samples are less than $1.66 \times 10^4 \mu s$ and $5 \times 10^4 \mu s$, i.e., the requirements for seamless video and VoIP services, respectively. This means that our protocol can set up the wireless link within the delay bounds of video and VoIP services as summarized in [20]. Thus, even if the wireless link is disconnected while it serves video or VoIP streams, we can establish the link before the disconnection of the session.

Table 5. Iterative 2D beam training performance (unit: μs).

Beamwidth	Iterative beam training	Exhaustive search
$1°$	1.42×10^3	1.5×10^4
$2°$	1.26×10^3	7.52×10^3
$3°$	1.17×10^3	5.01×10^3
$4°$	1.09×10^3	3.76×10^3
$5°$	1.01×10^3	3.01×10^3
$6°$	1.01×10^3	2.51×10^3
$7°$	9.23×10^2	2.18×10^3
$8°$	9.23×10^2	1.88×10^3
$9°$	9.23×10^2	1.67×10^3
$10°$	9.23×10^2	1.51×10^3

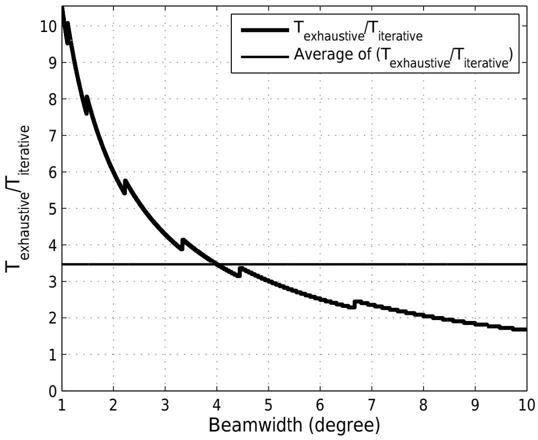


Fig. 12. $T_{\text{exhaustive}}/T_{\text{iterative}}$.

In Fig. 12, link configuration time comparison, i.e., the link configuration time of exhaustive search with RxBF over the link configuration time of iterative subspace partitioning, is plotted. For the given beamwidths, the link configuration time of iterative search is always faster than the one of exhaustive search. In the best case, iterative search is approximately 10 times faster than exhaustive search when the beamwidth is near $1°$. In the average case, iterative search is around 3.46 times faster than exhaustive search.

VI. CONCLUSIONS AND FUTURE WORK

This paper investigated fast 2D and 3D interactive beam training protocols for narrow-beam mm-wave wireless systems. In traditional beam training systems, exhaustive search is widely used, however, this protocol definitely takes a lot of beam training time in narrow-beam mm-wave wireless applications. For fixed modulation, our proposed protocols are designed based on interactive beam training and prioritized search space ordering for both 2D and 3D cases. The performance of our protocols are verified by simulation in terms of mm-wave wireless link configuration speed in standardized propagation channel models. For adaptive modulation, multi-level beam training protocols are proposed which have two steps, i.e., L-Re/sector sweeping and iterative subspace partitioning. For each step, we find the optimal number of sectors and division orders to minimize the operation speed. These protocols can serve as relevant improvements for the existing mm-wave IEEE standards, i.e., IEEE 802.15.3c or IEEE 802.11ad. Importantly, all the suggested procedures can be adapted into the standards with minimum changes, i.e., introduction of one new bit in the MAC header.

As a future research direction, we will verify our two fast beam training protocols with real-world measurement data in (i) 28 GHz and 38 GHz mm-wave 5G cellular systems and (ii) 60 GHz indoor WLAN.

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