A Fast Beam Alignment Scheme for Dual-band HSR Wireless Networks

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***Abstract*—To satisfy the ever increasing capacity requirements resulting from the rapid developments of the railway industry, future 5G based high-speed railway (HSR) wireless networks begin to consider using millimeter wave (mmWave) bands to expand the frequency spectrum together with the beamforming technology to guarantee the radiation range. Nevertheless, due to the high time consumption of beam alignments and the high mobility of trains, significant angle offsets will be induced during the initial access (IA) processes, which may completely invalidate the final determined beam pair. To solve this problem, in this paper we take advantage of the periodicity and regularity of trains' trajectory and propose a fast IA scheme, in which the beam training set is reduced by learning from historical beam training results and further adjusted during the IA process to compensate the angle offsets due to movements of trains. To guarantee the whole network robustness, in this study a dual-band HSR network by integrating both legacy sub-6GHz bands and mmWave bands is considered, under which the standby omnidirectional sub-6GHz link can help facilitate the IA process of the mmWave communication part. Theoretical and numerical results have shown that the proposed scheme can enhance the IA success probability and reduce the IA time consumption.**

***Index Terms*—Beam alignments; dual-band HSR wireless networks; history learning; initial access; mmWave beamforming**

I. Introduction

On future artificial intelligence (AI) based smart trains, more and more devices with advanced control and communication functions, such as real-time video surveillance cameras, will be deployed to guarantee the operational safety. Moreover, onboard passengers also have a strong desire for high-quality mobile services during long journeys, just as at home. Obviously, these applications demand more capacity from high-speed railway (HSR) wireless networks [1]. Nevertheless, the almost saturated lower frequency bands cannot shoulder this huge burden. To catch up with the rapid developments of the railway industry, future 5G based HSR wireless networks have envisioned on the use of millimeter wave (mmWave) bands that have massive available spectrum to satisfy the ever increasing capacity requirements [2], [3]. However, mmWave bands experience much higher path loss than that of lower frequency bands, unfortunately resulting in a limited coverage range. To overcome this drawback, it has been widely agreed that the directional beamforming technology, which has the ability of concentrating the energy of desired signals towards a target direction, is definitely necessary for mmWave communications to expand the signal propagation distance [4], [5].

In mmWave communications, although narrow beams formed by the beamforming technology can expand the coverage distance, it also complicates the initial access (IA) process. As a direct and effective scheme, the exhaustive search (ES) method through one-by-one tests is mostly employed to align beams between transmitters and receivers, but it may cause a large access delay [6], [7]. From the perspective of execution timing, the entire IA process consists of two phases, i.e., cell search (CS) and random access (RA) [8], [9]. In the CS phase, mmWave remote radio units (mmW-RRUs) sweep beams towards all directions so that users can discover them. Meanwhile, users go through all receiving directions to measure the signal quality of transmitting beams one by one and record the index of the best beam. In the RA phase, through the receiving direction that the best transmitting beam is detected in the CS phase, users send the index information of the best transmitting beam to mmW-RRUs. To capture this information, mmW-RRUs go through all the receiving directions. Since the number of beams in transceivers is at a large scale, the ES method will introduce excessive delay in link establishments. Especially, in HSR networks, the speed of trains is so high that the position offset during the long-lasting IA process will result in severe angle offset and invalidate the aligned beams.

In wireless communications, it is commonly known that wireless channels highly depend on the propagation environments, while the propagation environments highly depend on the physical position of users. Currently, especially in China, the major terrian of railways is the viaduct, where the scattering environment is simple and the wireless channel is approximately line-of-sight (LOS) [10]. In addition, after using the beamforming technology, with respect to LOS links, the non-LOS (NLOS) components with relatively low signal strength can be neglected [11]. As a result, the wireless channels in HSR scenarios have a strong relationship with the positions of trains. Based on this observation, we propose a fast beam alignment scheme, in which the position information of trains is used as a basis to determine the beam training set for each beam training, instead of sweeping the

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full space. Since in HSR scenarios the trajectories of trains show a strong periodicity and regularity, for a geographic position, the historical beam training results become valuable references for future beam training processes. Therefore, in the proposed scheme, for a given position, the beam training set is reduced and periodically updated based on the latest historical training results at the same position. At the very beginning of the proposed scheme, a conventional full-space beam training process is still needed, so that the best beam pair can be determined and mapped for every position. Then, at the following time, the beam search space is reduced to several beams around the best beam pair recorded in the latest beam training process. Intuitively, in relatively stable environments, at the same position the angle offset of the best beam pair recorded in two adjacent beam training processes will not be large, implying that the new updated beam training set has high probability of not missing the best beam pair. Therefore, without beam alignment failures, this iterative beam training set update process will always go on. Once a beam alignment failure happens, to guarantee the effectiveness of the following beam training processes, a full-space sweeping will be re-started to find the correct beam radiation directions under current environments. Besides, in the RA phase, based on the speed and traveling direction of trains, we propose to further adjust the beam training set so as to compensate for the angle offsets resulting from the movements of trains during the IA process. Although in this paper our focus is on the mmWave IA process, the high mobility in HSR is also challenging the beam management during data transmissions. Unlike the IA process, the beam channel information is available during data transmissions, which can be used to facilitate the beam tracking. Many existing works have studied the beam tracking during data transmissions, such as [5], [12]. In the future, we will continue the research on beam management for high-mobility scenarios.

Observing that the spot-like coverage of directional mmWave beams causes coverage blindness problem and as a result heavily degrades the whole network robustness, HSR wireless networks with high requirements on transmission reliability will not depend only on mmWave bands. In this paper, we propose to adopt the control/user-plane (C/U-plane) decoupled network architecture to enable the integration of both sub-6GHz bands and mmWave bands to guarantee the coverage and mobility performance while augmenting the capacity [13]. In this network, the control information with strict transmission reliability requirements can be carried over sub-6 GHz bands while the high-data-rate services can be carried over mmWave bands to gain more capacity. In this study, in terms of the IA process, the advantages of the dual-band network architecture are discussed. Through the omnidirectional sub-6GHz links, necessary control signaling of the IA process can be timely fed back to guide and accelerate subsequent operations.

For clarity, the main motivations and contributions of this paper can be summarized as follows.

1) To guarantee the network robustness, we apply the C/U-plane decoupled network architecture in future mmWave based HSR wireless networks where reliable and omnidirectional sub-6GHz bands are integrated to mitigate the inherent coverage blindness problem in mmWave directional communications.
2) To realize fast beam alignments in the CS phase, we propose to reduce the beam search space by learning from the latest historical beam training results. Taking the position information as index, a best beam pair look-up table at time t-1 is established to provide valuable references for the beam training set formulation at time t.
3) To overcome the angle offsets caused by the high mobility of trains during the time from CS to RA phases, we further adjust the beam training set by adding beams along the movement direction of trains.
4) To verify the effectiveness of our scheme, we derive the closed-form expressions of IA success probability and time consumption for both conventional and proposed schemes and then conduct numerical study to demonstrate that our proposed scheme can significantly enhance the IA performance for HSR scenarios.

The rest of this paper is organized as follows. Section II introduces the network architecture, analyzes the problems encountered when using conventional IA scheme in HSR wireless networks, and discusses some related works. Section III proposes the history-learning based fast IA scheme and presents the facilitated control signaling transmissions under the dual-band HSR wireless network. Section IV gives the mathematical modeling to evaluate the performance of the proposed scheme, including IA success probability and IA time consumption. Section V shows the numerical results. Finally, Section VI concludes the paper.

II. Network Architecture and Related Works

In this section, the sub-6 GHz and mmWave bands integrated network architecture is firstly presented. Then, the conventional ES based IA process is introduced, following which the beam alignment invalidation problem encountered in high-speed railway scenarios is analyzed. Finally, some related researches that aim at simplify the beam training process are discussed.

A. Network Architecture

Observing the inherent coverage blindness problem in mmWave directional communications, in this paper we apply the C/U-plane decoupled network architecture to integrate sub-6 GHz and mmWave bands so as to guarantee the coverage performance while enhancing the system capacity [13]. To improve the network deployment flexibility and baseband resource utilization, cloud radio access networks (C-RANs) are introduced in future 5G networks [14], according to which network nodes in our system are therefore deployed under the C-RAN architecture. The detailed network, from which the research of this paper is developed, is shown in Fig. 1. Two types of RRUs are linearly deployed along the rail, in which lower frequency RRUs (LF-RRUs) use omnidirectional antennas to ensure the macro coverage, while mmW-RRUs adopt directional beamforming to overcome the path loss

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in mmWave bands. All RRUs are connected to a baseband unit (BBU) pool through high-speed backhauls. To provide a dependable connection for train passengers, an access point (AP) and an mobile relay (MR) are deployed on the roofs inside and outside trains, respectively. The inside AP firstly collects the services of train passengers, which are then forwarded to roadside RRUs via MRs. In this way, the problems resulting from direct connections between onboard passengers and roadside base stations, such as the large penetration loss and group handovers, can be naturally avoided and the whole train can be viewed as a single user, i.e., the MR. Note that in this paper, the term 'user' is used in general communication scenarios, while 'MR' is dedicatedly used in the HSR communication scenario. In this network, the control information with strict transmission reliability requirements, including the signaling of IA processes, is carried over sub-6 GHz bands while the high-data-rate services are carried over mmWave bands in order to gain more capacity.

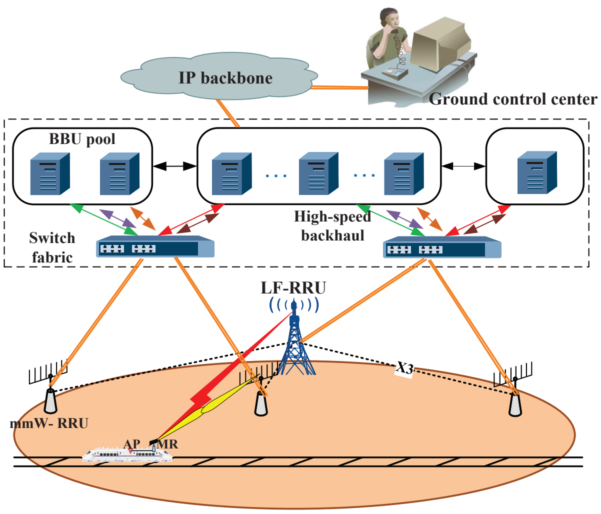

Fig. 1. Network architecture.

B. ES Based IA Process

In current mmWave systems, the entire IA process consists of two parts, the CS and RA phases. In Fig. 2, the details of the ES based IA process are illustrated. As can be seen in Fig. 2(a), in the CS phase, mmW-RRUs sweep transmitting beams towards all available downlink directions. Meanwhile, users go through all receiving directions to measure the signal quality of every beam pair and record the index of the best transmitting beam. In the following RA phase as shown in Fig.2 (b), at first users randomly select a preamble from a predefined preamble set in which the preambles are mutually orthogonal [15]. Usually, the number of orthogonal preambles determines the maximum number of users to be allowed to simultaneously access this network. By coding the recorded index of the best transmitting beam with the selected preamble, the user then sends this information through the exact receiving direction from which the best transmitting beam is detected during the previous CS phase. Meanwhile, the mmW-RRU goes through all receiving directions to capture this feedback. If the received signal qualifies, the IA process of this user will succeed. Considering that railway services with strict transmission reliability requirements have absolute priority, dedicated preambles can be pre-allocated for trains to avoid the access collisions. Besides, in mmWave systems, the preamble-coded information of the RA phase is carried by narrow beams and transmitted only to the direction where the best transmitting beam is detected in the CS phase, thereby highly decreasing the access collision probability compared with omni-directional wireless systems [8]. Based on these observations, for simplicity, the access collision is not taken into account in this study.

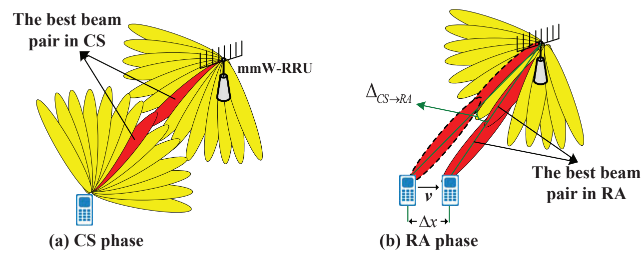

Fig. 2. The IA process: (a) CS phase. (b) RA phase

Due to the narrow beamwidth, the the number of beams at transceivers is usually at a large scale, resulting in a severe IA delay. Not only that, in high-speed railway scenarios, trains will travel a long distance during the long IA process, resulting in a significant angle offset with respect to the selected beam directions in the CS and RA phases. In other words, due to the angle offsets, the selected beam pair may have already become less optimal or even totally invalidated. In the following, we will give a simple example to unfold this problem. Suppose the HSR wireless network is linearly deployed, i.e., MRs and mmW-RRUs only need to sweep the 180^o-space, and a 3^o-beamwidth is used in both MRs and mmW-RRUs. Then, the numbers of required beam scans in the CS and RA phases are 3600 and 60, respectively, and the total number of beam scans of the entire IA process is 3660. Suppose the duration of one beam scan is 16.7us [7], then the time consumed by an IA process is approximately 61ms which corresponds to 6.1m distance offset with trains travelling under the speed of 360km/h, a typical speed in China. Since in high-speed scenarios the beam link is not that stable, it is barely exaggerated that the IA process may be triggered at anywhere within the coverage of mmW-RRUs. Intuitively, the same distance offset will lead to a smaller angle offset at the edge of mmW-RRUs than that near mmW-RRUs. By respectively setting the inter-mmW-RRU distance and the vertical distance between the rail and mmW-RRUs to 400m and 10m, the approximate angle offset corresponding to the 6.1m-distance offset falls in the region of $(0.02^o, 31.4^o)$. From this result, we can observe that when an IA process is triggered at the area near mmW-RRUs, the angle offset resulting from the large beam training delay is so significant that it can be even as large as several times of the beamwdith. In other words, the selected beams during the IA process may

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not match the current position of the train and lose the validity.

C. Related works

Recently, with regards to the long training time problem of directional mmWave communications, researchers have proposed many approaches to simplify the beam alignment process. In [6], Chen *et al* proposed a fast and reliable beam search scheme for indoor mobile scenarios, where learning algorithms are leveraged to capture the wireless propagation features in different mobility patterns. For HSR scenarios, with the attainable position and speed information of trains, many context-information based fast beam alignment schemes are also presented. In [16], Va *et al* proposed a position-based fast beam alignment scheme for HSR mmWave systems. Nevertheless, most existing works emphasize the beam training without considering the whole IA process. In this paper, we analyze all possible problems encountered in HSR scenarios during the whole IA process and provide potential solutions to these problems. Another typical problem being inevitably concerned under high-mobility scenarios is the Doppler effect. Fortunately, it was found in [16] that directional beams with dominating LOS paths will suffer only the Doppler shift which can be easily corrected using frequency offset correction techniques. By leveraging the regular movement patterns and context information of trains under HSR scenarios, a Doppler shift pre-compensation scheme is proposed in [17]. Based on the above results, with high-performance frequency offset pre-compensation technologies, HSR wireless systems, especially when using directional mmWave communications, can well handle the Doppler effect, and therefore we ignore the Doppler effect in our analysis.

III. Fast IA Scheme in The Dual-band HSR wireless networks

A. The Proposed Scheme

Generally, especially in China, most rails are paved on viaducts and rural areas, where the wireless channels are mostly LOS [10]. As a result, the position information of trains becomes a key reference to determine the coarse directions of beams [18]. Nevertheless, due to the limitation of the positioning accuracy and environmental information, we cannot totally depend on the measured position information to radiate beams. Based on this observation, we propose a fast beam alignment scheme, in which the position information of trains together with the latest historical beam alignment results are both used as deterministic features to update the beam training set for each beam training. Since in HSR scenarios the trajectories of trains show a strong periodicity and/or regularity, for a position the historical beam training results become valuable references for future beam training processes. Therefore, in the proposed scheme, for a given position the beam training set is periodically updated based on the latest historical training results at the same position as shown in Fig. 3(a). At the very beginning of the proposed scheme, a full-space beam training process is still needed, so that the best beam pair can be determined and mapped for every position. Then, several beams around the recorded best beam pair are selected to form a new beam training set for the next beam training at this position. After finishing the next beam training, another best beam pair will be selected and still another several beams around this new best beam pair form another new beam training set for the following beam training. As only the latest beam training results are used as references in this scheme, not all historical beam training results are needed to be stored in the look-up table but only the latest ones, saving storage space.

Intuitively, in relatively stable environments, at the same position the angle offset of the best beam pair recorded in two adjacent beam training processes will not be large, implying that the new updated beam training set has high probability of not missing the best beam pair. Therefore, without beam alignment failures, this iterative beam training set update process will always go on. However, in outdoor scenarios, mmWave signals will suffer severe environmental impairments, such as extreme weather, which may cause significant changes in propagation channels. In such situations, the historical beam training may not match current propagation environments and the already formed new beam training sets may exclude the workable beams, resulting in beam alignment failures. To guarantee the effectiveness of the following beam training processes, once a beam alignment failure happens, a full-space sweeping will be re-initiated to find the best beam radiation directions under current environments and then repeat the above procedures.

Besides, in this scheme, the angle offset caused by the movement of trains during the CS phase is also taken into account. As shown in Fig. 3(b), in the RA phase, the beam training set of the CS phase is adjusted by adding beams along the travelling direction of trains and deleting the same number of beams in the opposite direction. The whole procedures of the proposed scheme is summarized in Fig. 3(c). Obviously, the proposed IA scheme can not only reduce the beam alignment time, but also improve the effectiveness of final selected beams by tracking the movement of trains during the IA process.

B. Facilitated Feedback in The Dual-band HSR Wireless Networks

In mmWave communications, before directional links are established, transmitters and receivers cannot communicate with each other. As a consequence, in the IA process, related control signaling needs to be broadcasted to all directions, which leads to resource wastes. For instance, in the conventional RA phase, without tunnels to get the beam training results of the CS phase, mmW-RRUs have to sweep the full space to broadcast the random access channel (RACH) opportunities, so that users can know when to transmit the RACH preamble. Instead, in the dual-band wireless network, users keep dual connectivity with the network side, including an omnidirectional link operating at sub-6GHz bands and a directional link operating at mmWave bands, where the former can help forward necessary signaling related to the directional IA process. As shown in Fig. 4, we compare the IA procedures with and without the assistance of omnidirectional links. In

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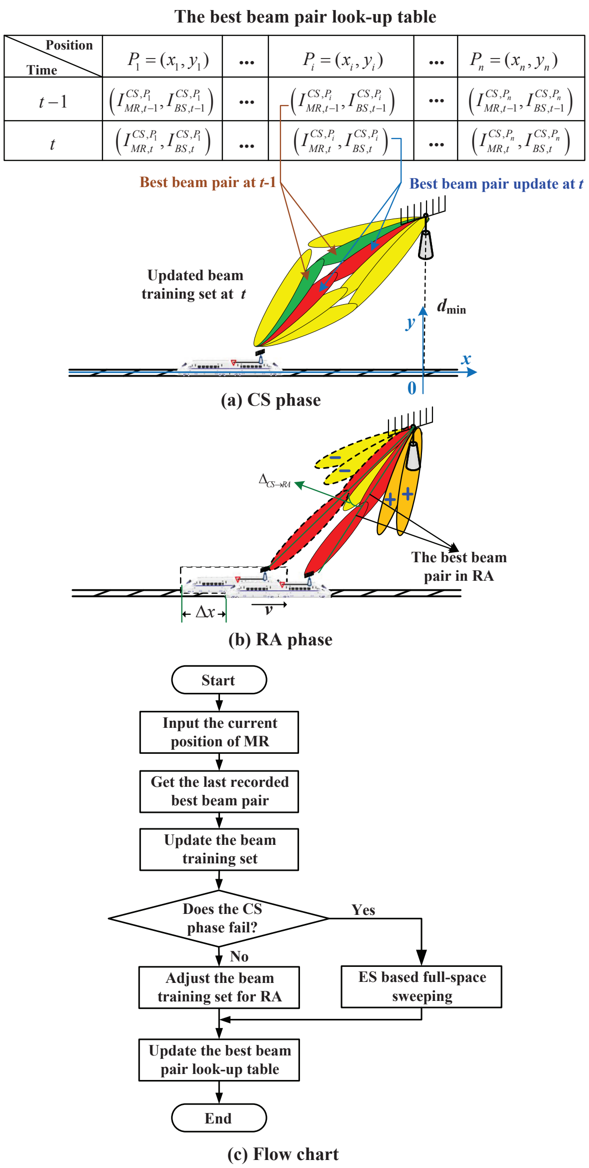

Fig. 3. The proposed fast IA scheme: (a) the CS phase, (b) the RA phase, (c) the flow chart of the proposed scheme.

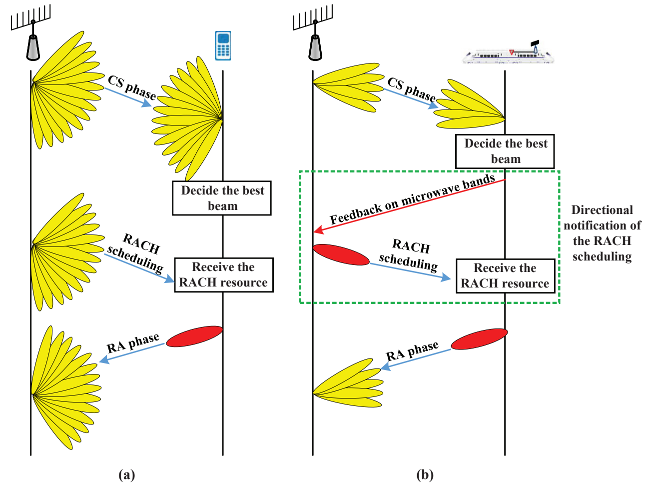

Fig. 4. The IA signaling procedures: (a) conventional method, (b) proposed scheme.

Fig. 4(b), by getting the information of the best beam in the CS phase through the omnidirectional link, mmW-RRUs can directionally send the RACH resource on the exact best direction instead of the full space as in Fig. 4(a), thereby saving more resources as well as operational time. In the proposed scheme, the position of trains is a key information, which is also carried on sub-6GHz bands. Moveover, the standby omnidirectional links enable an immediate report of the failure of directional links, and even a quick transmission fall-back to sub-6GHz bands.

IV. Mathematical Models

In this section, we adopt the IA success probability and time consumption as two metrics to evaluate the proposed scheme. For comparison, we also present the performance analysis of the conventional ES based IA scheme.

A. Theoretical Analysis for The Conventional Scheme

Firstly, we give the theoretical analysis of the IA success probability in the conventional ES based IA scheme. In line with the preceding sections, the IA success probability is determined by two events, i.e., the CS and RA performance. If and only if both CS and RA phases are successful, the whole IA process can be defined as a success. In this paper, the switched beamforming technology is applied, which means the available beam directions are fixed. Considering the linear network deployment in railway scenarios, the scan scope of beams is set to 180^o. Without loss of generality, we assume that the number of beams at the mmW-RRU and MR sides are N_{BS} and N_{MR}, respectively. Besides, we assume that at each side the transmitting and receiving beams are the same. Then, the transmitting beam codebooks (as well as receiving beam codebooks) at mmW-RRUs and MRs can be respectively expressed as

$$\begin{aligned} \Omega_{BS}^{TX=RX} &= \left\{ \theta_{BS}^1, \theta_{BS}^2, \theta_{BS}^3 \ldots, \theta_{BS}^{N_{BS}} \right\} \\ \Omega_{MR}^{TX=RX} &= \left\{ \theta_{MR}^1, \theta_{MR}^2, \theta_{MR}^3 \ldots, \theta_{MR}^{N_{MR}} \right\} \end{aligned} \tag{1}$$

where $\theta_{BS}^i = \frac{\pi(i-1)}{N_{BS}}$ and $\theta_{MR}^i = \frac{\pi(i-1)}{N_{MR}}$. Equivalently, the beamwidths of the mmW-RRU and MR are $\beta_{BS} = \frac{\pi}{N_{BS}}$ and $\beta_{BS} = \frac{\pi}{N_{MR}}$, respectively.

Without loss of generality, during the beam training, we choose the beam pair with the highest received signal quality as the best candidate. By respectively denoting the angle-of-departure (AOD) at mmW-RRUs and the angle-of-arrival (AOA) at MRs as $\phi_{BS,CS}^{es}$ and $\varphi_{MR,CS}^{es}$, the transmitting beam should radiate towards

$$\theta_{BS,\max}^{es,CS} = \underset{\theta_{BS}^i \in \Omega_{BS}^{TX=RX}}{\arg\min} \left(\left| \theta_{BS}^i - \phi_{BS,CS}^{es} \right| \right) \tag{2}$$

Similarly, MRs should receive at the direction of

$$\theta_{MR,\max}^{es,CS} = \underset{\theta_{MR}^i \in \Omega_{MR}^{TX=RX}}{\arg\min} \left(\left| \theta_{MR}^i - \phi_{MR,CS}^{es} \right| \right) \tag{3}$$

Based on [19], the directional gain of antenna arrays can be approximately modeled as a function of the beamwidth β and

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the angle difference $\Delta\theta$ between the main lobe and the real orientation, i.e.,

$$G(\beta, \Delta\theta)\,[dB] = 10\lg\left(\frac{\pi}{\beta}e^{-\eta\left(\frac{\Delta\theta}{\beta}\right)^2}\right) \quad (4)$$

where $\eta = 4\log 2$.

In the CS phase, only when the received signal quality is beyond a predefined threshold Γ can MRs successfully discover an available mmW-RRU. Therefore, the CS success probability can be expressed as

$$\begin{aligned} P_{su}^{es,CS}(d) &= \Pr\Big(P_{t,BS} + G\left(\beta_{BS}, \Delta\theta_{BS}^{es,CS}\right) \\ &+ G\left(\beta_{MR}, \Delta\theta_{MR}^{es,CS}\right) - PL(d) - \xi - N_0 > \Gamma\Big) \\ &= \Pr\Big(P_{t,BS} + G\left(\beta_{BS}, \Delta\theta_{BS}^{es,CS}\right) \\ &+ G\left(\beta_{MR}, \Delta\theta_{MR}^{es,CS}\right) - PL(d) - \Gamma - N_0 > \xi\Big) \\ &= \Phi\left(\frac{P_{t,BS} + G\left(\beta_{BS}, \Delta\theta_{BS}^{es,CS}\right) + G\left(\beta_{MR}, \Delta\theta_{MR}^{es,CS}\right) - PL(d) - N_0 - \Gamma}{\sigma_\xi}\right) \end{aligned} \quad (5)$$

where $\Phi(x) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{x} e^{-\frac{t^2}{2}}dt$. $P_{t,BS}$ denotes the transmit power of mmW-RRUs. For clarity, we use $\Delta\theta_{BS}^{es,CS} = \theta_{BS,\max}^{es,CS} - \phi_{BS,CS}^{es}$ and $\Delta\theta_{MR}^{es,CS} = \theta_{MR,\max}^{es,CS} - \phi_{MR,CS}^{es}$ to facilitate the expression. In this paper, the free space path loss model is used, i.e., $PL(d) = 32.4 + 20\lg f_c\,(GHz) + 20\lg\sqrt{d_{\min}^2 + d^2}\,(m)$ [20]. ξ represents the Gaussian distributed shadow fading with mean zero and variance σ_ξ^2. N_0 is the noise power. To simplify the theoretical analysis of this paper, we only consider the two dominant propagation fading factors, i.e., the path loss and shadowing fading, just as in [4].

During the period from CS to RA, high-speed trains may travel a considerable distance, causing angle offsets to the selected beam directions in the previous CS phase. By denoting the angle offset as $\Delta_{CS\to RA}^{es}$, the actual AOD of MRs and AOA of mmW-RRUs in the RA phase become $\phi_{MR,RA}^{es} = \phi_{MR,CS}^{es} + \Delta_{CS\to RA}^{es}$ and $\phi_{BS,RA}^{es} = \phi_{BS,CS}^{es} + \Delta_{CS\to RA}^{es}$. Based on our previous work [5], the angle offset can be modeled as

$$\Delta_{CS\to RA}^{es} = arc\tan\left(\frac{d + \Delta x_{es}}{d_{\min}}\right) - arc\tan\left(\frac{d}{d_{\min}}\right) \quad (6)$$

where Δx_{es} is the distance offset as shown in Fig. 2. To simplify the expressions, we use $L_{CS,BS}^{TX}$ and $L_{CS,MR}^{RX}$ to represent the number of beam scans at mmW-RRUs and MRs in the CS phase, respectively. Then, under the conventional ES method, we can get $L_{CS,BS}^{es,TX} = N_{BS}$ and $L_{CS,MR}^{es,RX} = N_{MR}$. Suppose the order of beam scans is fixed as from the left to the right both at mmW-RRU and MRs. In the conventional ES based IA scheme, the final selected beam pair is decided by testing all available beam pairs. Then, the distance offset from CS to RA is determined by the interval between the time of finding the best direction and the last sweeped beam. Denoting the time consumption of a beam scan, the speed of MRs and the index of the best direction as τ, v and $I_{\theta_{BS,\max}^{es,CS}}$, respectively, the distance offset can be expressed as

$$\Delta x_{es} = v\left(L_{CS,BS}^{es,TX} - I_{\theta_{BS,\max}^{es,CS}}\right)L_{CS,MR}^{es,RX}\tau. \quad (7)$$

In the RA phase, through the receiving direction from which the best transmitting beam is detected in the CS phase, MRs send the recorded index of the best transmitting beam. Meanwhile, mmW-RRUs go through all receiving directions, so that they will not miss this information. Consequently, the best receiving direction of mmW-RRUs is

$$\theta_{BS,\max}^{es,RA} = \underset{\theta_{BS}^{i} \in \Omega_{BS}^{TX=RX}}{\arg\min}\left(\left|\theta_{BS}^{i} - \phi_{BS,RA}^{es}\right|\right). \quad (8)$$

Similarly, the RA success probability can be expressed as (9) at the bottom of this page. To simplify the expressions, we use $\Delta\theta_{BS}^{es,RA} = \theta_{BS,\max}^{es,RA} - \phi_{BS,RA}^{es}$ in (9). By combining the above results, we can get the entire IA success probability of the conventional ES method as

$$\gamma_{es}(d) = P_{su}^{es,CS}(d) \cdot P_{su}^{es,RA}(d). \quad (10)$$

It is obvious that the IA success probability strongly depends on the distance between MRs and mmW-RRUs. The farther they are away with each other, the lower the IA performance will be. In fact, when MRs enter a new mmW-RRU and need an IA process, they have the longest distance to mmW-RRUs and therefore the lowest IA performance. Nevertheless, due to the instability of directional beams, outage and loss of synchronization will happen more frequently. In other words, the IA process may happen anywhere. As aforementioned, in the area near mmW-RRUs, due to the movements of trains during the period from CS to RA, the consequent angle offsets may totally invalidate the final selected beam pair. This problem needs to be carefully addressed before applying the mmWave communication technology into HSR wireless networks.

Based on the result of the IA success probability, we next analyze the IA time consumption. Denote the numbers of beam scans at mmW-RRUs and MRs of the RA phase as $M_{RA,BS}^{RX}$ and $M_{RA,MR}^{TX}$, respectively. Then, under the conventional ES based IA scheme, we can get $L_{CS,BS}^{es,TX} = N_{BS}$, $L_{CS,MR}^{es,RX} = N_{MR}$, $M_{RA,MR}^{es,TX} = 1$ and $M_{RA,BS}^{es,RX} = N_{BS}$. We use T to represent a complete transmission frame duration including both the IA and data delivery parts. Generally, if an user fails in an IA process, it will wait for the next IA opportunity. Besides, in the conventional scheme, mmW-RRUs broadcast the RACH scheduling information by sweeping the whole space. Therefore, the total IA time consumption of the conventional ES based IA scheme is

$$\begin{aligned} D_{es}(d) &= \left[L_{CS,BS}^{es,TX} \cdot (L_{CS,MR}^{es,RX} + 1) + M_{RA,BS}^{es,RX}\right]\tau \\ &+ (S_{es}(d) - 1)\,T \end{aligned} \quad (11)$$

$$\begin{aligned} P_{su}^{es,RA}(d) &= \Pr\left(P_{t,MR} + G\left(\beta_{MR}, \Delta\theta_{MR}^{es,CS} + \Delta_{CS\to RA}^{es}\right) + G\left(\beta_{BS}, \Delta\theta_{BS}^{es,RA}\right) - PL(d) - \xi - N_0 > \Gamma\right) \\ &= \Phi\left(\frac{P_{t,MR} + G\left(\beta_{MR}, \Delta\theta_{MR}^{es,CS} + \Delta_{CS\to RA}^{es}\right) + G\left(\beta_{BS}, \Delta\theta_{BS}^{es,RA}\right) - PL(d) - N_0 - \Gamma}{\sigma_\xi}\right) \end{aligned} \quad (9)$$

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where $S_{es}(d)$ represents the total number of IA attempts which follows the geometric distribution as [21]

$$P\left(S_{es}(d)=S\right)=\left(1-\gamma_{es}(d)\right)^{S-1}\gamma_{es}(d) \tag{12}$$

and has an average $E\left[S_{es}(d)\right]=\frac{1}{\gamma_{es}(d)}$. Consequently, the average IA time consumption to successfully access an mmW-RRU can be given as

$$E\left[D_{es}(d)\right]=\left[L_{CS,BS}^{es,TX}\cdot\left(L_{CS,MR}^{es,RX}+1\right)+M_{RA,BS}^{es,RX}\right]\tau + \left(\frac{1}{\gamma_{es}(d)}-1\right)T. \tag{13}$$

B. Theoretical Analysis for The Proposed Scheme

Similarly, in this subsection, we will first analyze the IA success probability of the proposed scheme, and then formulate the IA time consumption. In the proposed IA scheme, to reduce the beam training time and complexity, mmW-RRUs and MRs reduce the beam search space into several beams based on the historical beam training result. In the CS phase, suppose at time $t-1$ the finally selected best transmitting beam by mmW-RRUs is at angle $\theta_{BS,t-1}^{pro,CS}$ with the index $I_{BS,t-1}^{pro,CS}$ and the finally selected best receiving beam by the MR is at angle $\theta_{MR,t-1}^{pro,CS}$ with the index $I_{MR,t-1}^{pro,CS}$. As aforementioned, considering the positioning errors and environmental conditions, the previous beam training results cannot completely match the current wireless channel. Without loss of generality, we express the AOD of mmW-RRUs and AOA of MRs at time $t-1$ as $\phi_{BS,t-1}^{pro,CS}$ and $\phi_{MR,t-1}^{pro,CS}$. Then, at time t, because of the possible environmental impact, the AOA and AOD respectively become

$$\phi_{BS,t}^{pro,CS}=\phi_{BS,t-1}^{pro,CS}+\Delta_{BS} \tag{14}$$

and

$$\phi_{MR,t}^{pro,CS}=\phi_{MR,t-1}^{pro,CS}+\Delta_{MR} \tag{15}$$

where Δ_{BS} and Δ_{MR} respectively denote the angle offsets at mmW-RRUs and MRs from time $t-1$ to t. Without loss of generality, we assume that Δ_{BS} and Δ_{MR} follow zero-mean Gaussian distributions with variance of σ_{BS}^2 and σ_{MR}^2, respectively, i.e., $\phi_{BS,t}^{pro,CS}\sim N\left(\phi_{BS,t-1}^{pro,CS},\sigma_{BS}^2\right)$ and $\phi_{MR,t}^{pro,CS}\sim N\left(\phi_{MR,t-1}^{pro,CS},\sigma_{MR}^2\right)$.

In the proposed scheme, to reduce the beam training set without degrading its effectiveness, we propose that the beam training sets of mmW-RRUs and MRs at time t are reduced to the X_{BS}^{CS} and X_{MR}^{CS} beams symmetrically surrounding the selected best beams at time $t-1$, $\theta_{BS,t-1}^{pro,CS}$ and $\theta_{MR,t-1}^{pro,CS}$, respectively. For simplicity, we set X_{BS}^{CS} and X_{MR}^{CS} to odd numbers. Then, at time t, the beam training set of mmW-RRU denoted by $\Lambda_{BS,t}^{pro,CS}$ and the beam training set of MRs denoted by $\Lambda_{MR,t}^{pro,CS}$ can be respectively expressed as

$$\Lambda_{BS,t}^{pro,CS}=\left\{\theta_{BS}^{I_{BS,t-1}^{pro,CS}-\frac{X_{BS}^{CS}-1}{2}},\ldots\theta_{BS}^{I_{BS,t-1}^{pro,CS}-1},\right. \left.\theta_{BS}^{I_{BS,t-1}^{pro,CS}},\theta_{BS}^{I_{BS,t-1}^{pro,CS}+1},\ldots,\theta_{BS}^{I_{BS,t-1}^{pro,CS}+\frac{X_{BS}^{CS}-1}{2}}\right\} \tag{16}$$

and

$$\Lambda_{MR,t}^{pro,CS}=\left\{\theta_{MR}^{I_{MR,t-1}^{pro}-\frac{X_{MR}^{CS}-1}{2}},\ldots\theta_{MR}^{I_{MR,t-1}^{pro,CS}-1},\right. \left.\theta_{MR}^{I_{MR,t-1}^{pro,CS}},\theta_{MR}^{I_{MR,t-1}^{pro,CS}+1},\ldots,\theta_{MR}^{I_{MR,t-1}^{pro,CS}+\frac{X_{MR}^{CS}-1}{2}}\right\}. \tag{17}$$

It should be noted that to simplify the expression of beam training sets in (16) and (17), we use the indices of angles to represent beams according to the definition in (1). Therefore, the central beams in (16) and (17) satisfy $\theta_{BS}^{I_{BS,t-1}^{pro,CS}}=\theta_{BS,t-1}^{pro,CS}$ and $\theta_{MR}^{I_{MR,t-1}^{pro,CS}}=\theta_{MR,t-1}^{pro,CS}$, respectively.

Similarly, in the proposed scheme, the beam pair that achieves the highest received signal quality will be selected as the best candidate. Based on the antenna gain expression in (4), it is obvious that the beam that has the smallest angle difference from the real angle of time t will output the highest-quality signals. Therefore, the best transmitting and receiving beams at time t can be respectively given as

$$\left[\theta_{BS,t}^{pro,CS},I_{BS,t}^{pro,CS}\right]=\underset{\theta_{BS}^{i}\in\Lambda_{BS,t}^{pro,CS}}{\arg\min}\left(\left|\theta_{BS}^{i}-\phi_{BS,t}^{pro,CS}\right|\right) \tag{18}$$

and

$$\left[\theta_{MR,t}^{pro,CS},I_{MR,t}^{pro,CS}\right]=\underset{\theta_{BS}^{i}\in\Lambda_{MR,t}^{pro,CS}}{\arg\min}\left(\left|\theta_{BS}^{i}-\phi_{MR,t}^{pro,CS}\right|\right). \tag{19}$$

In the CS phase of the proposed IA scheme, the beam training sets at both mmW-RRUs and MRs are reduced based on the historical training results of the same position. Nevertheless, although the selected training beams surrounds the most possible target direction determined by the previous training result, under large positioning errors or severe environmental impact this scheme still suffers the risk of performance degradation without full-space sweeping. In the worst case, if the real AOA or AOD are out of the scope of the selected beam training set, the entire IA process will definitely fail. Furthermore, even though the selected beam training set can cover the MR, the IA process will still fail if the received signal quality is under the threshold. Consequently, in the proposed scheme, the success probability of the CS phase is determined by two independent factors, namely the accuracy of selected beam training sets and the received signal quality, which can be formulated as (20) at the bottom of next page, where $\Delta\theta_{BS,t}^{pro,CS}=\theta_{BS,t}^{pro,CS}-\phi_{BS,t}^{pro,CS}$ and $\Delta\theta_{MR,t}^{pro,CS}=\theta_{MR,t}^{pro,CS}-\phi_{MR,t}^{pro,CS}$.

Next, we will analyze the success probability for the RA in the proposed scheme. In high-speed railway scenarios, during the interval from CS to RA, trains may have traveled long distances. To compensate the corresponding caused angle offsets, we propose to adjust the beam search space by adding ΔX_{RA} beams towards the same direction of trains' movements while deleting ΔX_{RA} beams at the opposite direction. Then, the beam training set of the RA phase becomes

$$\Lambda_{BS,t}^{pro,RA}=\left\{\theta_{BS}^{I_{BS,t}^{pro,CS}-\frac{X_{BS}^{CS}-1}{2}+\Delta X_{RA}},\ldots\theta_{BS}^{I_{BS,t}^{pro,CS}-1},\right. \left.\theta_{BS}^{I_{BS,t}^{pro,CS}},\theta_{BS}^{I_{BS,t}^{pro,CS}+1},\ldots,\theta_{BS}^{I_{BS,t}^{pro,CS}+\frac{X_{BS}^{CS}-1}{2}+\Delta X_{RA}}\right\} \tag{21}$$

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Since in the proposed scheme the beam search space is significantly downsized, the interval from CS to RA is also highly reduced, thereby mitigating the angle offset problem. Similar to (6), the angle offset can be expressed as

$$\Delta_{CS \to RA}^{pro} \approx \frac{\Delta x_{pro} \cdot d_{\min}}{d^2 + d_{\min}^2} \tag{22}$$

where Δx_{pro} represents the distance traveled by trains during the interval from CS to RA and can be calculated as

$$\Delta x_{pro} = v \left(I_{BS,t-1}^{pro,CS} + \frac{X_{BS}^{CS} - 1}{2} - I_{BS,t}^{pro,CS} \right) X_{MR}^{CS} \tau. \tag{23}$$

Consequently, the AOA at mmW-RRUs becomes

$$\phi_{BS,t}^{pro,RA} = \phi_{BS,t}^{pro,CS} + \Delta_{CS \to RA}^{pro} \tag{24}$$

By going through all the receiving directions contained in the beam training set, mmW-RRUs will select the best receiving beam with the angle of

$$[\theta_{BS,t}^{pro,RA}, I_{BS,t}^{pro,RA}] = \underset{\theta_{BS}^{i} \in \Lambda_{BS,t}^{pro,RA}}{\arg\min} \left(\left| \theta_{BS}^{i} - \phi_{BS,t}^{pro,RA} \right| \right) \tag{25}$$

Similarly, the success probability at the RA phase is also determined by two independent events, i.e., the event that the new receiving beam set can cover MRs after their movements from CS to RA and the event that the received signal quality is beyond the threshold. Therefore, the RA success probability of the proposed scheme can be calculated as (26) at the bottom of this page, where $\Delta\theta_{BS,t}^{pro,RA} = \theta_{BS,t}^{pro,RA} - \phi_{BS,t}^{pro,RA}$.

Based on the above results, with the proposed scheme, the success probability of the entire IA process can be obtained as

$$\gamma_{pro}(d) = P_{su}^{pro,CS}(d) \cdot P_{su}^{pro,RA}(d). \tag{27}$$

In addition, under the dual-band network architecture, the RACH scheduling information can be directionally sent to the best direction which is fed back through the omnidirectional sub-6GHz link. Using τ_{fb} to denote the time consumption of the feedback process on omnidirectional links, the total IA time consumption of the proposed scheme can be thereby expressed as

$$\begin{aligned} E[D_{pro}(d)] = &\left(X_{BS}^{CS} \cdot X_{MR}^{CS} + X_{BS}^{CS} + 1 \right) \tau \\ &+ \tau_{fb} + \left(\tfrac{1}{\gamma_{pro}(d)} - 1 \right) T. \end{aligned} \tag{28}$$

V. Numerical Results

In this section, based on the formulated theoretical models in Section V, we conduct numerical simulations to demonstrate the IA performance improvements for our proposed scheme. The parameter values are set as listed in Table I [22], [23]. Observing that IA processes may happen anywhere within the coverage of mmW-RRUs due to the instability of beam links, we investigate the performance of both conventional and proposed schemes at all positions of mmW-RRUs. In Fig. 5(a) and (b), the CS and RA success probabilities of two schemes are shown, respectively. As shown in Fig. 5(a), although some side beams are removed to reduce the beam search space, the proposed scheme can still reach the same CS performance as the conventional one. When it comes to the RA phase, the situation is quite different. As can be seen in Fig. 5(b), due to the long beam training time, when the MR is in the area near mmW-RRUs where the beam training is very sensitive to angle offsets, the conventional scheme has a poor RA performance with almost as low as zero success probability. On the contrary, in the proposed scheme,

$$\begin{aligned} P_{su}^{pro,CS}(t,d) = &\Pr\left(\theta_{BS}^{I_{BS,t}^{pro,CS} - \frac{X_{BS}^{CS}-1}{2}} < \phi_{BS,t}^{pro,CS} < \theta_{BS}^{I_{BS,t}^{pro,CS} + \frac{X_{BS}^{CS}-1}{2}} \right) \cdot \Pr\left(\theta_{MR}^{I_{MR,t}^{pro,CS} - \frac{X_{MR}^{CS}-1}{2}} < \phi_{MR,t}^{pro,CS} < \theta_{MR}^{I_{MR,t}^{pro,CS} + \frac{X_{MR}^{CS}-1}{2}} \right) \\ &\times \Pr\left(P_{t,BS} + G\left(\beta_{BS}, \Delta\theta_{BS,t}^{pro,CS}\right) + G\left(\beta_{MR}, \Delta\theta_{MR,t}^{pro,CS}\right) - PL(d) - \xi - N_0 > \Gamma \right) \\ = &\left(\Phi\left(\frac{\theta_{BS}^{I_{BS,t}^{pro,CS} + \frac{X_{BS}^{CS}-1}{2}} - \phi_{BS,t-1}^{pro,CS}}{\sigma_{BS}} \right) - \Phi\left(\frac{\theta_{BS}^{I_{BS,t}^{pro,CS} - \frac{X_{BS}^{CS}-1}{2}} - \phi_{BS,t-1}^{pro,CS}}{\sigma_{BS}} \right) \right) \\ &\times \left(\Phi\left(\frac{\theta_{MR}^{I_{MR,t}^{pro,CS} + \frac{X_{MR}^{CS}-1}{2}} - \phi_{MR,t-1}^{pro,CS}}{\sigma_{MR}} \right) - \Phi\left(\frac{\theta_{MR}^{I_{MR,t}^{pro,CS} - \frac{X_{MR}^{CS}-1}{2}} - \phi_{MR,t-1}^{pro,CS}}{\sigma_{MR}} \right) \right) \\ &\times \Phi\left(\frac{P_{t,BS} + G\left(\beta_{BS}, \Delta\theta_{BS,t}^{pro,CS}\right) + G\left(\beta_{MR}, \Delta\theta_{MR,t}^{pro,CS}\right) - PL(d) - N_0 - \Gamma}{\sigma_{\xi}} \right) \end{aligned} \tag{20}$$

$$\begin{aligned} P_{su}^{pro,RA}(t,d) = &\Pr\left(\theta_{BS}^{I_{BS,t}^{pro,CS} - \frac{X_{BS}^{CS}-1}{2} + \Delta X_{RA}} < \phi_{BS,t}^{pro,CS} + \Delta_{CS \to RA}^{pro} < \theta_{BS}^{I_{BS,t}^{pro,CS} + \frac{X_{BS}^{CS}-1}{2} + \Delta X_{RA}} \right) \\ &\times \Pr\left(P_{t,MR} + G\left(\beta_{MR}, \Delta\theta_{MR,t}^{pro,CS} + \Delta_{CS \to RA}^{pro}\right) + G\left(\beta_{BS}, \Delta\theta_{BS,t}^{pro,RA}\right) - PL(d) - \xi - N_0 > \Gamma \right) \\ = &\left(\Phi\left(\frac{\theta_{BS}^{I_{BS,t}^{pro,CS} + \frac{X_{BS}^{CS}-1}{2} + \Delta X_{RA}} - \phi_{BS,t}^{pro,CS} - \Delta_{CS \to RA}^{pro}}{\sigma_{BS}} \right) - \Phi\left(\frac{\theta_{BS}^{I_{BS,t}^{pro,CS} - \frac{X_{BS}^{CS}-1}{2} + \Delta X_{RA}} - \phi_{BS,t}^{pro,CS} - \Delta_{CS \to RA}^{pro}}{\sigma_{BS}} \right) \right) \\ &\times \Phi\left(\frac{P_{t,MR} + G\left(\beta_{MR}, \Delta\theta_{MR,t}^{pro,CS} + \Delta_{CS \to RA}^{pro}\right) + G\left(\beta_{BS}, \Delta\theta_{BS,t}^{pro,RA}\right) - PL(d) - N_0 - \Gamma}{\sigma_{\xi}} \right) \end{aligned} \tag{26}$$

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the beam search space is significantly reduced, mitigating the angle offset problem caused by the movements of trains from CS to RA. Therefore, in the angle-offset-sensitive areas, the proposed scheme can still offer higher RA performance. While in the area far from mmW-RRUs, the two schemes perform the same, which is consistent with our intuition. As aforemention, in addition to angle offsets, the received signal quality also contributes significantly to the IA performance. As shown in both Fig. 5(a) and (b), at points beyond 200m, due to the large path loss and therefore low signal quality, on the whole the CS and RA success probabilities drop sharply. In addition to propagation fading, the antenna gain, which is sensitive to the angle differences between the real orientation and the main lobe direction as in (4), is another factor that greatly affects the received signal quality in mmWave communications. In our study, the switched beamforming technology with fixed beam radiation patterns is used, and therefore within a given distance, trains and mmW-RRUs may always select the same beam pairs, causing variations for the antenna gain within this distance. For clarity, in Fig. 5(c), we show the changes of the sum of the transmitting and receiving antenna gain according to the movements of trains within an mmW-RRU. As a result, as shown in Fig. 5(a) and (b), at the edge areas of mmW-RRUs, due to the antenna gain fluctuations, the success probability curves are not smooth, and this phenomenon can also be found in the subsequent results.

TABLE I
PARAMETER SETTINGS

Parameters	Values
A beam scan duration	16.7us [7]
Bandwidth	1GHz
Beam training period	100ms
d_{min}	10m
MmW-RRU frequency band	32GHz
MmW-RRU transmit power	30dBm
Noise power	-174dBm/Hz
SNR threshold	10dB
Time of sub-6GHz feedback	1ms
Variance of shadowing	6dB
$\sigma_{MR} = \sigma_{BS}$	1^o

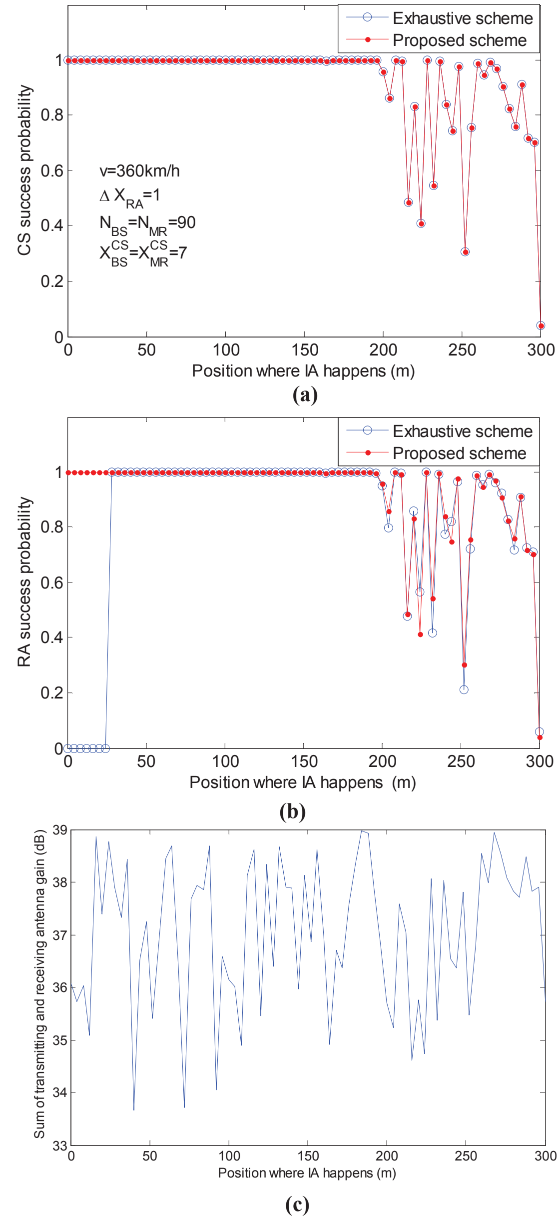

Fig. 5. Performance comparisons: (a) CS phase, (b) RA phase, (c) antenna gain.

In Fig. 6, the success probability of the entire IA process under different velocity settings, which is actually the product of the two success probabilities of the CS and RA phases, is depicted. From an overall point of view, the IA success probability has the same trend of that of the RA phase. In the area near mmW-RRUs where the IA process is more sensitive to angle offsets, the proposed scheme achieves much higher performance than the conventional scheme. For the area far away from mmW-RRUs, the whole performance is pulled down by the low received signal quality. Moreover, by comparing the results in Fig. 6(a) and (b), under the same time duration, the higher the MR velocity, the larger the angle offset is, and hence in the angle offset sensitive areas near mmW-RRUs the conventional scheme under a lower MR velocity shows higher performance than that under a higher one. Nevertheless, even under a lower MR velocity, the conventional scheme still fails at the area closer to mmW-RRUs. Due to the reduced time consumptions, under different MR velocity settings, the proposed IA scheme can always succeed at the angle offset area and therefore outperform the conventional scheme.

In Fig. 7, the relationship between the size of reserved beam search space for the proposed scheme and the IA success probability is illustrated. Due to the high possible inaccuracy in positioning systems and environmental impact, the recorded best beam pair in the historical latest beam training process may have some offsets with respect to the real wireless channel at the current time. Therefore, in the proposed scheme, the beam search space is reduced to the several beams around the best beam pair recorded in the latest historical beam training process, instead of directly using this recorded best beam pair. In addition, during the period from CS to RA, the movements of MRs will also cause a considerable angle offset, especially in the area near mmW-RRUs. As shown in

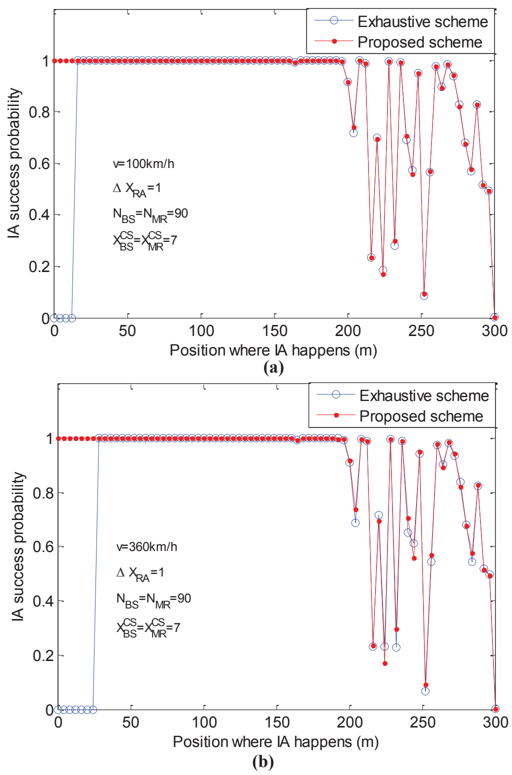

Fig. 6. Comparisons of IA success probability: (a) MR velocity=100km/h, (b) MR velocity=360km/h.

Fig. 7, the IA succuss probability at three different positions is illustrated. Compared with the case at position 20m, the angle offset at position 40m is lower, thereby leading to higher IA success probability. While at position 120m, the high path loss pulls down the received signal quality as well as the IA performance. As for the effect of the size of the reserved beam search space, from an overall point of view, the IA success probability gradually goes to 1 with the increase of the size of the reserved beam search space. That is because the more beams are reserved, the higher the probability that the beam training set can cover MRs will be.

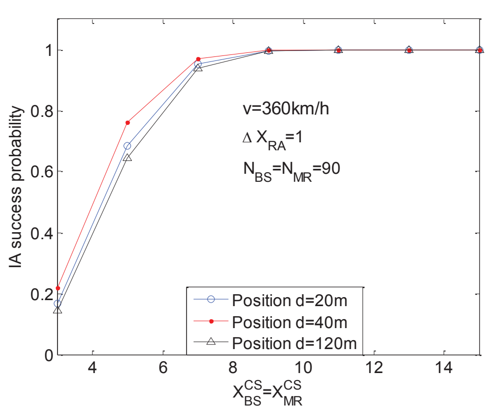

Fig. 7. IA success probability VS the size of reserved beam search space.

As discussed in the above, the angle offset resulting from the movement of trains during the period from CS and RA will also degrade the whole IA performance. To solve this problem, in the proposed scheme, based on the speed and traveling direction of trains, the beam training set of the RA phase is adjusted by adding beams along the traveling direction and deleting beams of the opposite direction. In Fig. 8, the IA performance under different beam-number adjustments in the RA phase is presented. As can be seen in Fig. 8, under the current parameter settings, one-beam adjustment can almost cover the angle offsets caused by the movements of trains during the period from CS to RA. On the contrary, two-beam adjustment increases the risk of missing MRs, thereby having a slightly lower IA performance.

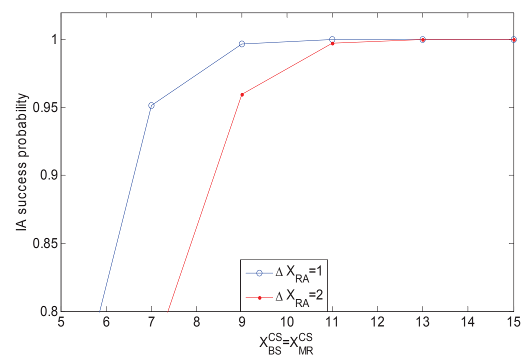

Fig. 8. IA success probability VS adjusted beams in the RA phase.

Finally, the average time consumption for different IA schemes is compared in Fig. 9 with different beamwidth settings. Since in the proposed scheme the beam search space in both CS and RA phases is significantly reduced, the time consumption is greatly reduced from an overall point of view. In Fig. 9(a), the beamwidth is wider than that in Fig. 9(b). At the cell edge, owing to the narrower beamwidth and thereby higher antenna gain, the case in Fig. 9(b) has higher IA success probability and achieves lower average IA time consumption. Based on these results, we can find that to guarantee the IA efficiency at the cell edge where the IA process happens most frequently, the suitable inter-mmW-RRU distances for the cases in Fig. 9(a) and (b) should be about 150m and 200m, respectively. Besides, as discussed in Section III.B, in the dual-band network architecture, through the omnidirectional link the selected best beam in the CS phase can be timely fed back to mmW-RRUs, thereby realizing directional notification of the RACH resource and saving more time. In this simulation, the time consumption of the feedback on the omnidirectional sub-6GHz link is set to 1ms, one subframe duration of LTE. In Fig. 9(a) and (b), the numbers of beam scans in the mmW-RRU side are $N_BS = 90$ and $N_BS = 180$, that is, the time consumption of the RACH resource notification for the two cases are respectively $90 \times 16.7 \approx 1.5ms$ and $180 \times 16.7 \approx 3ms$, both longer than 1ms. As a conclusion, the broadcast capability of omnidirectional sub-6GHz links in the dual-band network architecture can facilitate the operations of directional mmWave links and save more time.

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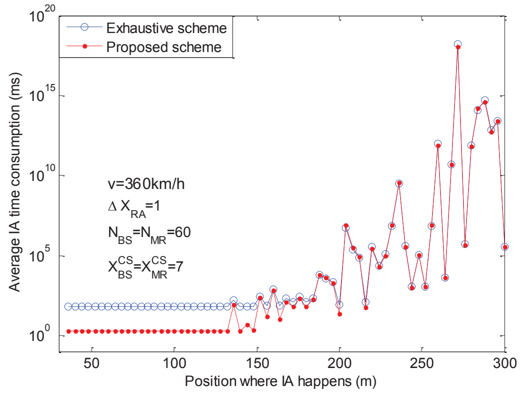
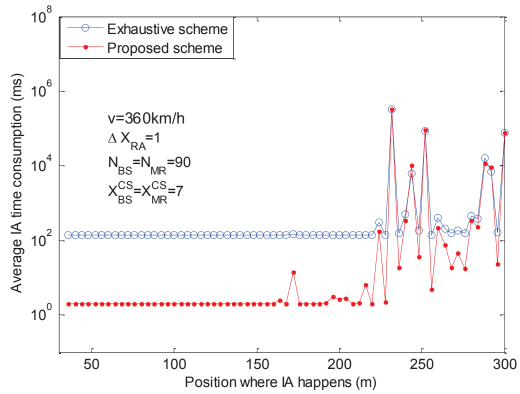


(a)



(b)

Fig. 9. Comparisons of average IA time consumption.

VI. Conclusions

To catch up with the rapid developments of the railway industry, the railway wireless networks need to evolve to the future 5G based HSR wireless networks, which have a great potential in exploring bandwidth-rich mmWave bands to meet the ever-increasing capacity requirements. To overcome the severe path loss of mmWave bands, beamforming is widely viewed as the necessary technology of future mmWave communications to guarantee the radiation range. Nevertheless, the spot-like narrow coverage of beams complicates the initial access (IA) processes. In this paper, by taking advantage of the periodicity and regularity of trains' trajectory in HSR scenarios, we propose a fast IA scheme through learning from historical beam training results. To reduce the IA time consumption, according to the position information, the beam search space during the CS phase is reduced to several beams around the best beam pair recorded in the latest beam training process. To compensate the angle offset during the period from CS to RA, the proposed scheme also adjusts the beam training set by adding beams along the train's traveling direction while deleting beams along the opposite direction. Besides, to enhance the network robustness, the C/U-plane decoupled network architecture is applied to integrate both sub-6 GHz and mmWave bands to guarantee the coverage performance while enhancing the capacity. In the dual-band network architecture, necessary control signaling during the IA process can be timely fed back via the more reliable omnidirectional links, thereby further accelerating the whole process and saving time. Theoretical and numerical results have shown that the proposed scheme can significantly increase the IA success probability and reduce the average IA time consumption.

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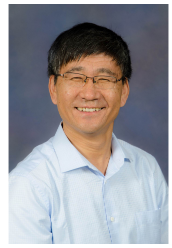

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