Optimal Nonuniform Steady mmWave Beamforming for High-Speed Railway

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***Abstract*—Using higher frequency bands (e.g., millimeter waves) to provide higher data rate is an effective way to eliminate performance bottleneck for future wireless networks, particularly for cellular networks based high-speed railway (HSR) wireless communication systems. However, higher frequency bands suffer from significant path loss and narrow-beam coverage, which pose serious challenges in cellular networks, especially under the HSR scenario. Meanwhile, as one of the key performance indexes of ultrareliable and low-latency communications in 5G systems, network reliability should be guaranteed to provide steady reliable data transmission along the railway, especially when safety-critical railway signaling information is delivered. In this paper, we propose a novel beamforming scheme, namely, optimal nonuniform steady mmWave beamforming, to guarantee the network reliability under an interleaved redundant coverage architecture for future HSR wireless systems. Moreover, we develop a bisection-based beam boundary determination (BBBD) method to determine the service area of each predefined RF beam. Finally, we demonstrate that the proposed optimal nonuniform steady mmWave beamforming can provide steady reliable data transmissions along the railway, and the network reliability requirements can be guaranteed when the proposed BBBD method is used. We expect that our optimal nonuniform steady mmWave beamforming provides a promising solution for future HSR wireless systems.**

***Index Terms*—5th-generation (5G) networks, millimeter wave, high speed railway (HSR), ultra-reliable and low-latency communications (URLLC), interleaved redundant coverage, optimal non-uniform beamforming.**

Manuscript received August 2, 2017; revised November 5, 2017 and December 28, 2017; accepted January 17, 2018. Date of publication January 23, 2018; date of current version May 14, 2018. This work was supported in part by the Natural Science Foundation of China (NSFC) under Grant 61471303, in part by the NSFC-Guangdong Joint Foundation under Grant U1501255, and in part by EU FP7 QUICK Project under Grant PIRSES-GA-2013-612652. The work of Y. Fang was partially supported by US National Science Foundation under Grant CNS-1343356. The review of this paper was coordinated by Prof. S. He. *(Corresponding author: Xuming Fang.)*

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Digital Object Identifier 10.1109/TVT.2018.2796621

I. Introduction

As LOWER frequency bands (e.g., microwave frequency bands) tend to become more and more scarce for cellular communication systems, one of the most effective ways to alleviate the spectrum shortage at lower frequency bands while providing higher data rate for future cellular networks is to exploit higher frequency bands (e.g., millimeter waves) [1], [2]. Many countries have made recommendations on higher frequency bands. The U.S. Federal Communications Commission (FCC) has just issued new rules for wireless broadband operations (licensed: 27.5–28.35 GHz, 37–38.6 GHz, 38.6–40 GHz, and unlicensed: 64–71 GHz) to make this spectrum available for 5th generation (5G) wireless networks. In China, the Ministry of Industry and Information Technology (MIIT) has set aside the frequencies 3.3–3.6 GHz, 4.8–5.0 GHz, 24.75–27.5 GHz, and 37–42.5 GHz for the trials of 5G wireless networks [3]. Ultra-reliable and low-latency communications (URLLC) is one of the main use cases and scenarios in 5G, which supports the services requiring very low latency, and very high reliability and availability. The goal of 5G URLLC is very similar to cellular based high speed railway (HSR) wireless communication systems. In HSR wireless communication systems, not only safety-critical railway signaling information, but also various high data rate services (e.g., high definition video surveillance, passengers Internet access services, etc.) need to be guaranteed provided by train-ground data transmissions. The huge bandwidth requirement from high data rates is the strong motivation for exploiting higher frequency bands since lower frequency band (e.g., microwave) is currently very scarce [4], [5]. Thus, the higher frequency bands may be the better choice for future HSR wireless communication systems.

However, there are several issues to consider when using millimeter wave (mmWave) frequency bands in future cellular networks, such as high path loss, oxygen absorption, blockage and deafness, etc. [6], [7]. Furthermore, one of the challenges is that higher frequency signals will experience orders of magnitude more path loss than the microwave frequency signals utilized in current cellular networks. Many research works have been devoted to this issue (see [8]–[11] and the references therein). One general solution is the hybrid beamforming which employs large scaled antenna arrays to generate higher beamforming gain to overcome higher path loss. In mmWave communications, a good comprise among hardware cost, complexity, and flexibility can be achieved when hybrid beamforming architecture is applied. In this architecture, a candidate beam set, which consists of a finite number of RF beams, is predefined in the analog domain. The predefined RF beams, with equal beam width and angle interval, are used to cover the service areas. Then, the optimal beam, which is used to transmit signals at each transmission point, is selected based on the selection criterion such as capacity maximization. To facilitate the analysis in the subsequent development, the predefined RF beams set with equal beam width and angle interval is named as uniform beamforming.

Network reliability needs to be provided to guarantee the steady train-ground data transmission along the railway, especially when safety-critical railway signaling information is delivered. However, the network reliability is mostly dependent on the minimum instantaneous rate provided by the HSR wireless communication systems. Thus, under high mobility scenario such as HSR, one important issue is to guarantee network reliability by providing the steady data transmission via utilizing mmWave frequency bands. Most recent researches focusing on this issue are conducted under the assumption that the service areas are covered by uniform beamforming [12], [13]. However, this assumption may not be reasonable in an HSR scenario due to its linear network topology. It is important to point out that the transmission performance will be severely degraded and unsteady when a train moves from the cell center to the cell edge if uniform beamforming is used in mmWave communications under HSR scenarios. In other words, there is a large performance gap along the railway due to higher path loss when uniform beamforming is simply applied in mmWave communications. These characteristics lead us to deal with the challenges to guarantee the network reliability by providing steady data transmissions along the railway.

Currently, interleaved redundant coverage architecture is widely deployed in HSR wireless communication systems [14], [15]. In this architecture, two independent cellular networks are deployed as the hot-backup of each other with redundant and interleaved coverage topology along the railway. The signals transmitted in each network are not coordinated due to the independent network operations of the cellular networks. Inter-network interference is not considered when network planning is made. Furthermore, two independent transceivers are mounted at the top of the train, and each transceiver is deployed to receive the signals transmitted by each network independently. The two transceivers are assumed to be connected by a high-speed system bus to a central unit where received signals are processed, and the maximum one is selected as the output signal.

For future HSR wireless communication systems, directional sectors, single-stream beamforming, and adaptive multi-stream beamforming schemes based on an interleaved redundant coverage architecture are usually utilized to provide train-ground data transmissions. In directional sectorization scheme, two or three sectors are deployed in a cell to transmit signals, which is very similar to that in public mobile communication systems [16]. The performance is severely degraded and unsteady when a train travels from the cell center to cell edge. Thus, directional sectors scheme may not be suitable choice for HSR scenarios. In a single-stream beamforming scheme, the signal energy can be focused on a very small region, and beam tracking is performed to control the direction of a beam, which is helpful to improve system performance [17]. However, from the network reliability point of view, the performance still decreases gradually when a train moves towards the cell edge. In [18], single-stream beamforming is further extended to adaptive multi-stream beamforming. In this scheme, the number of active beams is adjusted adaptively with respect to the location of the train. Thus, the performance can be further improved compared with single-stream beamforming. However, the performance of adaptive multi-stream beamforming demonstrates similar trend to what single-stream beamforming does. It implies that both beamforming schemes mentioned above have limited improvement on network reliability which is mostly dependent on the minimum instantaneous rate.

In general, there are two types of beamforming technologies to provide data transmissions in HSR scenarios: beam tracking and beam switching. Beam switching is superior to beam tracking in terms of complexity and protocol overheads. Therefore, beam switching has already been widely adopted in mmWave standards, such as IEEE 802.15.3c, and IEEE 802.11 ad [19]. Generally speaking, narrower beam width will lead to significant alignment overhead, since more beam directions have to be searched, while higher data transmissions are provided due to higher directivity gain [20]. However, beam training will be significantly simplified in HSR wireless communication systems due to predictive and regular location and moving speed information provided by train control systems [21]. The overheads can also be saved if location assisted beam switching method is leveraged in HSR scenarios [12]. As a result, beam switching based method with the train location and speed information is applied to select the optimal serving beam in our study.

Based on the above background, in order to guarantee the network reliability and achieve the goal of 5G URLLC, an optimal non-uniform steady beamforming scheme for the downlink operating at mmWave is proposed in an interleaved redundant coverage architecture by providing steady data transmissions for future HSR wireless communication systems. Different from the beamforming with equal beam width and angle interval, i.e., uniform beamforming, the proposed scheme determines beam widths and beam orientations depending on their service area portions for maximizing the network reliability with power and service area constraints. In the cell center region, relatively wide RF beams are predefined to reduce beam switching times. Meanwhile, in the cell edge region, the narrow RF beams are predefined to provide relatively higher data rate due to higher directivity gain to combat higher path loss. A location assisted beam switching method is exploited to select the optimal serving beam to provide steady data transmissions along the railway. Then, a bisection based beam boundary determination (BBBD) method is suggested to determine the service area portion of each predefined RF beam. Numerical results show that the network reliability can be guaranteed and the goal of 5G URLLC can be achieved when the proposed optimal non-uniform steady mmWave beamforming is utilized with the suggested BBBD method under the predefined conditions. The steady data transmissions can be provided along the railway. It indicates that the optimal non-uniform beamforming is a better choice than uniform beamforming for future HSR wireless communication systems. It is worth mentioning that although the proposed scheme is validated under HSR scenarios, it can

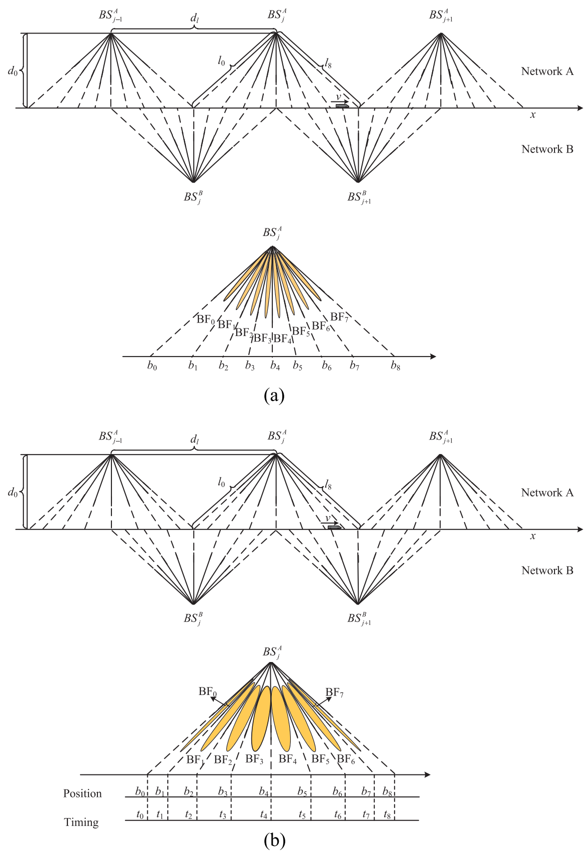

Fig. 1. System models. (a) Uniform beamforming; (b) optimal non-uniform beamforming.

also be applied to other vehicular scenarios with linear network topology.

The rest of this paper is organized as follows. In Section II, the system models of both uniform beamforming and non-uniform beamforming are presented. In Section III, the problem of non-uniform beamforming is formulated as an optimization problem with power and service area constraints. Then, a BBBD method is suggested to determine the service area portion of each predefined RF beam. Numerical results and discussions are given in Section IV. Section V concludes the paper by summarizing the results and discussing some future works.

II. System Models

Consider the system models of both uniform beamforming and non-uniform beamforming operating at mmWave with the number of predefined RF beams N_b (e.g., $= 8$) in an interleaved redundant coverage architecture for HSR wireless communication systems are depicted in Fig. 1. The system model of uniform beamforming is presented in Fig. 1(a). In uniform beamforming, the RF beams set is predefined with equal beam width and angle interval for each network in an interleaved redundant coverage architecture. Only one beam is selected to transmit signals at each transmission point based on the selection criterion for each network in an interleaved redundant coverage architecture. Similarly, the system model of non-uniform beamforming is presented in Fig. 1(b). In non-uniform beamforming, N_b beams with different beam widths and angle intervals are predefined as a candidate set in the service area. Two independent transceivers are mounted at the top of the train to receive the signals transmitted by each network simultaneously and separately. The two transceivers are assumed to be connected by a high-speed system bus to a central unit where received signals are processed, and the maximum one is selected as the output signal to guarantee the steady data transmissions. The details are described in Section III. Note that, although only downlink is herein considered in this paper, the proposed optimal non-uniform steady beamforming can be extended to the uplink. The complicated transceivers could be designed and deployed on rooftops of trains due to the large size of trains.

The regular and predictive location and speed information of a train could be assumed to be provided by train control systems along the railway [22]. Therefore, location assisted beam switching method is exploited to rapidly select the optimal serving beam in this paper. That is, the serving beam is switched based on the location of a train provided by train control systems. For example, the service area of the ith predefined RF beam is within the region $[b_i, b_{i+1}]$, where b_i and b_{i+1} are the starting and ending points on the x-axis of the ith beam, respectively. t_i and t_{i+1} are the time instants corresponding to the region points b_i and b_{i+1}, respectively. Moreover, we assume that the channel estimation error can be almost well compensated by some elaborate solutions [23]–[25].

The received signal power with ith serving beam for network $k \in \mathcal{A} = \{A, B\}$ can be expressed as [26]

$$P_r^{i,k} = P_t |\boldsymbol{H}_{i,k}|^2 G_r^{i,k} G_t^{i,k} \frac{1}{d_k^{\alpha}}, \tag{1}$$

where,

- P_t is the transmit power with constraint $P_t \leq P_{total}$, and P_{total} is the total transmit power at BS;
- $\boldsymbol{H}_{i,k}$ is the small-scale fading matrix at mmWave frequency bands between a transmitter and a receiver;
- $G_r^{i,k}$ and $G_t^{i,k}$ are receiver and transmitter antenna directivity gains, respectively;
- d is the distance between a transmitter and a receiver;
- α is large-scale path loss exponent.

The small-scale fading matrix at mmWave, considering time t and the maximum Doppler shift $f_{d,max}$, can be given by [27]

$$r\boldsymbol{H}_{i,k}(t, f_{d,max}) = \frac{1}{\sqrt{L}} \sum_{l=1}^{L} g_l(t) e^{2\pi \mathrm{I} t f_{d,max} \cos(w_l)} \boldsymbol{u}_{rx}(\phi_l^{rx}) \boldsymbol{u}_{tx}^H(\phi_l^{tx}), \tag{2}$$

where,

- L is the number of paths;
- $g_l(t)$ is the complex small-scale fading gain with constraint $E\{|g_l(t)|^2\} = 1, \mathrm{I} = \sqrt{-1}$;
- $\boldsymbol{u}_{rx}(\phi_l^{rx})$ and $\boldsymbol{u}_{tx}(\phi_l^{tx})$ are the receiver and transmitter vector response functions, respectively;
- ϕ_l^{rx} and ϕ_l^{tx} are the angles of arrival and departure, respectively;
- $f_{d,max}$ is the maximum Doppler shift, and $f_{d,l} = f_{d,max} \cos(w_l)$ is the Doppler shift of lth path, w_l is the angle of arrival of the lth path relative to the direction of motion.

$$
\begin{aligned}
&P_r^{i,k}(t,v,\theta_b^{i,k}) \\
&= \frac{(2\pi-(2\pi-\theta_b^{i,k})z)P_t}{\theta_b^{i,k}d_k^{\alpha}}\Big|\frac{1}{\sqrt{L}}\sum_{l=1}^{L}g_l(t)e^{2\pi \mathrm{I}t\cos(w_l)vf_c/c}\boldsymbol{u}_{rx}(\phi_l^{rx})\boldsymbol{u}_{tx}^H(\phi_l^{tx})\Big|^2 \\
&= \frac{(2\pi-(2\pi-\theta_b^{i,k})z)P_t}{\theta_b^{i,k}Ld_k^{\alpha}}\Big|\sum_{l=1}^{L}g_l(t)e^{2\pi \mathrm{I}t\cos(w_l)vf_c/c}\boldsymbol{u}_{rx}(\phi_l^{rx})\boldsymbol{u}_{tx}^H(\phi_l^{tx})\Big|^2 \\
&= \frac{(2\pi-(2\pi-\theta_b^{i,k})z)P_t}{\theta_b^{i,k}Ld_k^{\alpha}}\sum_{l=1}^{L}\Big|g_l(t)\Big|^2\Big|e^{2\pi \mathrm{I}t\cos(w_l)vf_c/c}\Big|^2\Big|\boldsymbol{u}_{rx}(\phi_l^{rx})\boldsymbol{u}_{tx}^H(\phi_l^{tx})\Big|^2 \\
&= \frac{(2\pi-(2\pi-\theta_b^{i,k})z)P_t}{\theta_b^{i,k}Ld_k^{\alpha}}\sum_{l=1}^{L}e^{-4\pi\Im[vtf_c\cos(w_l)/c]}\Big|g_l(t)\Big|^2\Big|\boldsymbol{u}_{rx}(\phi_l^{rx})\boldsymbol{u}_{tx}^H(\phi_l^{tx})\Big|^2,
\end{aligned} \tag{6}
$$

The maximum Doppler shift can be expressed as

$$f_{d,max} = vf_c/c, \tag{3}$$

where v is the moving speed of the train, c is the speed of light, and f_c is carrier frequency.

Substituting (3) into (2), the small-scale fading matrix can be rewritten as

$$
\begin{aligned}
&r\boldsymbol{H}_{i,k}(t,v) \\
&= \frac{1}{\sqrt{L}}\sum_{l=1}^{L}g_l(t)e^{2\pi \mathrm{I}t\cos(w_l)vf_c/c}\boldsymbol{u}_{rx}(\phi_l^{rx})\boldsymbol{u}_{tx}^H(\phi_l^{tx}).
\end{aligned} \tag{4}
$$

For tractability of the analysis, we approximate the actual antenna patterns by a sectored antenna model, where it is assumed that the antenna directivity gain is uniform within the main lobe and is a smaller constant in side lobes. In this context, the antenna directivity gain of uniform linear arrays (ULA) can be expressed as [20]

$$
G(\theta_b) = \begin{cases} \frac{2\pi-(2\pi-\theta_b)z}{\theta_b}, & \text{in the main lobe;} \\ z, & \text{in side lobes,} \end{cases} \tag{5}
$$

where θ_b is the beam width in radian and z is the average gain of side lobes that $0 \le z < 1$.

Substituting (4), (5) into (1), the received signal power with ith serving beam for network k can be rewritten as (6) shown at the top of this page, where $\Im[\cdot]$ denotes the imaginary part of the complex number. To simplify the analysis, we set $G_r^{i,k} = 1$, since omnidirectional radiation pattern is assumed at receiver in the proposed optimal non-uniform steady mmWave beamforming scheme.

III. Optimal Non-Uniform Steady mmWave Beamforming

As one of the Key Performance Indexes (KPIs), network reliability should be guaranteed by providing steady data transmissions along the railway, especially when safety-critical railway signaling information is delivered. Moreover, the network reliability mostly depends on the minimum instantaneous rate provided by the HSR wireless communication systems. However, the transmission performance will be severely degraded with uniform beamforming when a train moves from the cell center to the cell edge. The data rate is relatively high around cell center, while it becomes relatively low at cell edge. Therefore, data rate fluctuation will occur with uniform beamforming and influence the steady data transmissions. In this section, we focus on optimizing beam width and orientation of each predefined RF beam to balance the data rate to achieve steady and reliable data transmissions along the railway.

A. Problem Formulation

To overcome the limitations of uniform beamforming in HSR scenarios, a novel optimal non-uniform steady mmWave beamforming scheme is proposed. In the proposed scheme, RF beams with different beam widths and angle intervals are predefined as a candidate set with power and service area constraints. Then, the optimal serving beam, which is used to transmit signals at each transmission point, is selected based on the location assisted beam switching criterion.

For the optimal non-uniform steady beamforming, a finite number of RF beams are predefined to cover the service areas. Only one beam is selected to transmit signals at each transmission point. Interference and synchronization are not considered, which are assumed to be resolved by network planning in an interleaved redundant coverage architecture. The received signal-to-noise ratio (SNR) with the ith serving beam for network k can be expressed as

$$
\begin{aligned}
SNR^{i,k}(t,v,\theta_b^{i,k}) &= \frac{P_r^{i,k}(t,v,\theta_b^{i,k})}{N_0B} = \frac{(2\pi-(2\pi-\theta_b^{i,k})z)P_t}{N_0B\theta_b^{i,k}Ld_k^{\alpha}} \\
&\sum_{l=1}^{L}e^{-4\pi\Im[vtf_c\cos(w_l)/c]}\Big|g_l(t)\Big|^2\Big|\boldsymbol{u}_{rx}(\phi_l^{rx})\boldsymbol{u}_{tx}^H(\phi_l^{tx})\Big|^2,
\end{aligned} \tag{7}
$$

where B is the bandwidth, and N_0 is the noise power spectrum density.

In our proposed scheme, two independent transceivers are mounted at the top of a train to receive the signals transmitted by each network simultaneously and separately, and the two transceivers are assumed to be connected by a high-speed transmission bus to a central unit where received signals are processed. The maximum one is selected as the output signal.

Thus, the system received SNR can be expressed as

$$SNR^i(t,v,\theta_b^i) = \max\left\{SNR^{i,k}(t,v,\theta_b^{i,k}), k\in\mathcal{A}=\{A,B\}\right\} = \frac{(2\pi-(2\pi-\theta_b^i)z)P_t}{N_0B\theta_b^i Ld^\alpha} \sum_{l=1}^{L} e^{-4\pi\Im[vtf_c\cos(w_l)/c]}\left|g_l(t)\right|^2\left|\boldsymbol{u}_{rx}(\phi_l^{rx})\boldsymbol{u}_{tx}^H(\phi_l^{tx})\right|^2. \quad (8)$$

Then, the instantaneous rate can be expressed by using the Shannon capacity formula (for study purpose)

$$R^i(t,v,\theta_b^i) = B\log_2(1+SNR^i(t,v,\theta_b^i)) = B\log_2\Big(1+\frac{(2\pi-(2\pi-\theta_b^i)z)P_t}{N_0B\theta_b^i Ld^\alpha} \sum_{l=1}^{L} e^{-4\pi\Im[vtf_c\cos(w_l)/c]}\left|g_l(t)\right|^2\left|\boldsymbol{u}_{rx}(\phi_l^{rx})\boldsymbol{u}_{tx}^H(\phi_l^{tx})\right|^2\Big). \quad (9)$$

In order to measure the performance of the proposed optimal non-uniform steady beamforming, the average rate function $D^i(v,\theta_b^i)$ is defined as the average data rate transmitted using the ith beam within the region $[b_i, b_{i+1}]$. Given beam width θ_b^i with the ith serving beam, the average rate function $D^i(v,\theta_b^i)$ can be expressed as

$$D^i(v,\theta_b^i) = \frac{\int_{\frac{b_i}{v}}^{\frac{b_{i+1}}{v}} R^i(t,v,\theta_b^i)dt}{\frac{b_{i+1}}{v}-\frac{b_i}{v}}, \quad (10)$$

where θ_b^i is the beam width of the ith beam.

When the optimal non-uniform steady beamforming is used in HSR scenarios, how to split the service area of each predefined RF beam to minimize the performance gap between adjacent beams to balance the data rate is an important issue, especially for safety-critical railway signaling information. Network reliability can be guaranteed by providing steady data transmissions if the data rate balance is achieved.

The problem can be formulated as an optimization problem with the objective function expressed as

$$\min_{\theta_b^i} \sum_{i=1}^{N_b-1}\left|\frac{D^i(v,\theta_b^i)}{D^{i-1}(v,\theta_b^{i-1})}-1\right|\Big/ N_b$$

$$\text{s.t.} \quad \sum\theta_b^i \le 2\arctan\left(\frac{b_{N_b}-b_0}{2d_0}\right), \quad \theta_b^i>0, \quad P_t\le P_{total}, \quad P_t>0, \quad (11)$$

where the constraints of problem (11) are for the total power consumed at BS and the service areas of the candidate beam set, respectively.

B. Bisection Based Beam Boundary Determination (BBBD)

To solve the problem (11), a BBBD method is developed. The essential idea is to find the boundary points of the beam that satisfy the objective function in (11) by the bisection method. Repeat the procedure until all the boundary points of N_b predefined RF beams are determined. The detailed steps are given in Algorithm 1.

Algorithm 1: BBBD method.

Input: P_{total}, d_0, l_0;
Initialization:
  $b_{min}=b_0, b_{max}=b_{N_b}, \Upsilon=\{b_0,b_{N_b}\}$,
  $M=size(\Upsilon), \varepsilon>0$;
Determine the boundary points of each beam service area: Set $\Omega=\{s_0,s_1,\cdots,s_j,\cdots,s_{M-2}\}$;
  $\overline{\Upsilon}=\Upsilon+\Omega=\{b_0,s_0,b_1,s_1,\cdots,s_j,b_i,\cdots,s_{M-2},b_{M-1}\}$;
  for each $m\in\overline{\Upsilon}$ **do**
    if $M\le N_b+1$ **then**
      Find the value of s_j for
      $\left|\frac{\int_{b_m/v}^{b_{m+1}/v} R^m(t,v,\theta_b^m)dt}{\int_{b_{m-1}/v}^{b_m/v} R^{m-1}(t,v,\theta_b^{m-1})dt}-1\right|<\varepsilon$,
      $m=1,2,\cdots,2M-3$;
      Update $\Upsilon\leftarrow\overline{\Upsilon}$, $M=size(\Upsilon)$;
    else
      Break;
    end if
  end for
Output: Υ.

In the proposed method, the inputs are the total power at BS and service areas' parameters. The service areas' parameters are used to determine the portions of the candidate beams set. During the initialization phase, $\Upsilon=\{b_0,b_{N_b}\}$ denotes the initial boundary points set of beams, b_0 and b_{N_b} are the cell coverage boundary points, and ε denotes the solution accuracy of the proposed method.

By using this method, the boundary points of each RF beam are determined. Let Ω denote the candidate boundary point set. s_j is the possible boundary point, where $j=0,1,\cdots,M-2$. $\overline{\Upsilon}$ is the union of sets Υ and Ω. The elements of sets Υ and Ω are staggered and interleaved with each other. Brute-force search is used to determine the boundary points. It is worth mentioning that the suggested BBBD method is a simple and efficient way to determine the beam boundary points. Meanwhile, there are sparse user distribution and static network deployment in the HSR scenario. The beam boundary points will be computed in an off-line way, and the results will be available for a long time. Thus, the method complexity will not be necessarily considered and the suggested BBBD method will be suitable for HSR wireless communication systems.

In order to measure the performance stability by analyzing the data rate fluctuation, a new metric, termed stationary function, is defined as follows

$$\sigma = E\left[\frac{\max\left[R^i(t,v,\theta_b^i)\right]-\min\left[R^i(t,v,\theta_b^i)\right]}{D^i(v,\theta_b^i)}\right], \quad (12)$$

where the physical meaning of the stationary function σ is the expectation of the ratio between data rate gap and the average rate function. The data rate gap is the difference between the largest and smallest instantaneous rates. The larger value of stationary function means the severer data rate fluctuation, which will result in unsteady performance. On the contrary, the performance will be steady if the value of stationary function is small.

The outage probability metric is introduced to measure the probability of link failure of a network connection, which can be expressed as

$$P_{outage} = P\big[SNR^i(t, v, \theta_b^i) < \gamma_{th}\big], \tag{13}$$

which represents the probability that the instantaneous SNR is lower than the given threshold γ_{th}. The network connection link will be dropped when the instantaneous SNR is lower than γ_{th}.

Substituting (8) into (13), the outage probability can be rewritten as (14) [28], (14) shown at the bottom of this page, where $\eta = \frac{N_0 B \theta_b^i L d^\alpha \gamma_{th}}{(2\pi-(2\pi-\theta_b^i)z)P_t}$. Note that the impacts of both beam width θ_b^i and the path loss d^α on outage probability increase exponentially with the number of paths L. The impact of moving speed v on outage probability depends son the product of small-scale fading of each path l. Furthermore, the impact of path loss can be combated by adjusting the beam width.

IV. Numerical Results and Discussions

In this section, numerical analysis is conducted to evaluate the proposed scheme described in the previous section. Then, some future studies are discussed.

A. Numerical Results

To evaluate our proposed scheme, we now conduct numerical analysis. We assume that a train moves from the cell center to cell edge for network A under an interleaved redundant coverage architecture in our study. Without loss of generality, we set the number of predefined RF beams N_b to be 8 as an example, and the train moves from b_4 to b_8 on the x-axis, as depicted in Fig. 1. Solution accuracy ε is set to 0.01. Propagation parameters at the 28 GHz mmWave frequency bands are used in our study [29]. The other detailed values of parameters are listed in Table I [10], [29].

The instantaneous rates of the uniform beamforming and the optimal non-uniform steady beamforming with different number of predefined RF beams N_b and moving speed v are shown in Fig. 2. The instantaneous rate curves are like U-shape because an interleaved redundant coverage architecture is deployed in HSR scenarios. Taking $N_b = 16$ and $v = 360$ km/h as another example, the instantaneous rate drops from 6.7 Gbps to 1.8 Gbps with the uniform beamforming when a train moves far away from the BS, while the instantaneous rate drops from 5.3 Gbps to 3.3 Gbps with the optimal non-uniform steady beamforming. It is obvious that a larger performance gap occurs when using uniform beamforming. The optimal non-uniform beamforming could provide more steady data transmission than the uniform beamforming. Moreover, the transmission performance gap becomes smaller and smaller with the optimal non-uniform beamforming as N_b increases. Thus, it will be helpful to guarantee the network reliability and stability.

TABLE I
Parameter Settings

Parameters	Values
Carrier frequency	28 GHz
Bandwidth	500 MHz
Total BS transmit power	30 dBm
Inter-BS distance	1.5 km
Distance from BS to the track	30 m
Path loss exponent	2
The side lobe gain	0.1
Noise figure	7 dB
Thermal noise	−174 dBm/Hz

The beam width comparisons for the uniform beamforming and the optimal non-uniform steady beamforming with different N_b and v are shown as in Fig. 3. For the optimal non-uniform beamforming, the wide RF beams are predefined in the cell center region to reduce the beam switching times, while narrow RF beams are predefined to provide higher antenna directivity gain to overcome higher path loss in the cell edge region. Contrary to the uniform beamforming, the advantages of the optimal non-uniform beamforming become more and more obvious as N_b increases. For example, $N_b = 16$ and $v = 360$ km/h, the beam width ratio of non-uniform beamforming and uniform beamforming is 0.46 when the beam index $BI = 9$, and the ratio is 0.02 when $BI = 15$.

The average rate comparisons with different N_b and v are shown in Fig. 4. It is shown that the average rate of the

$$\begin{aligned}
P_{outage} &= P\big[SNR^i(t, v, \theta_b^i) < \gamma_{th}\big] \\
&= P\left[\frac{(2\pi-(2\pi-\theta_b^i)z)P_t}{N_0 B \theta_b^i L d^\alpha} \sum_{l=1}^{L} e^{-4\pi \Im[v t f_c \cos(w_l)/c]} \left|g_l(t)\right|^2 \left|\boldsymbol{u}_{rx}(\phi_l^{rx}) \boldsymbol{u}_{tx}^H(\phi_l^{tx})\right|^2 < \gamma_{th}\right] \\
&= P\left[\sum_{l=1}^{L} e^{-4\pi \Im[v t f_c \cos(w_l)/c]} \left|g_l(t)\right|^2 \left|\boldsymbol{u}_{rx}(\phi_l^{rx}) \boldsymbol{u}_{tx}^H(\phi_l^{tx})\right|^2 < \frac{N_0 B \theta_b^i L d^\alpha \gamma_{th}}{(2\pi-(2\pi-\theta_b^i)z)P_t}\right] \\
&= P\left[\sum_{l=1}^{L} e^{-4\pi \Im[v t f_c \cos(w_l)/c]} \left|g_l(t)\right|^2 \left|\boldsymbol{u}_{rx}(\phi_l^{rx}) \boldsymbol{u}_{tx}^H(\phi_l^{tx})\right|^2 < \eta\right] \\
&\approx \frac{\eta^L}{L! \prod_{l=1}^{L} e^{-4\pi \Im[v t f_c \cos(w_l)/c]} \left|\boldsymbol{u}_{rx}(\phi_l^{rx}) \boldsymbol{u}_{tx}^H(\phi_l^{tx})\right|^2},
\end{aligned} \tag{14}$$

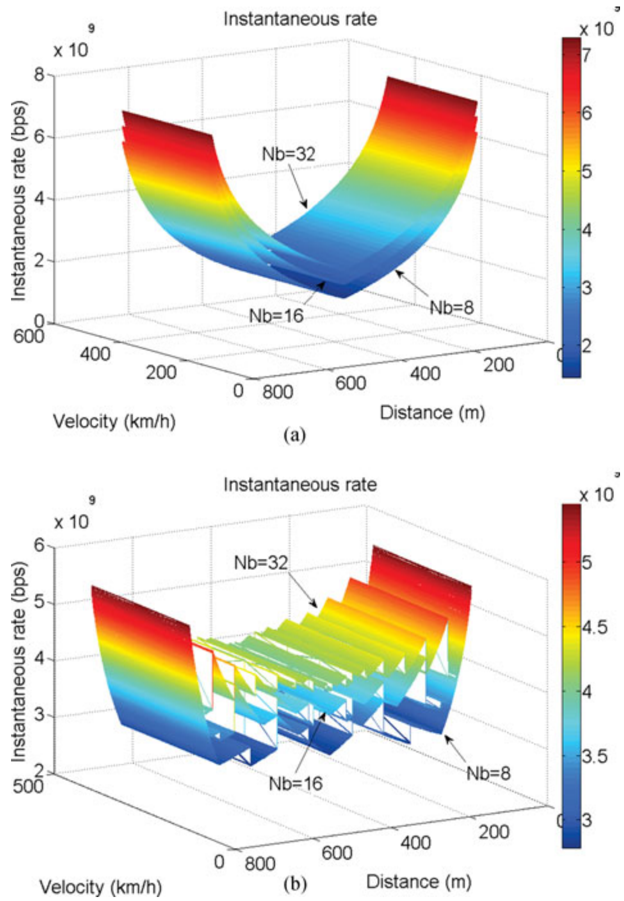

Fig. 2. Instantaneous data rates with different N_b and v. (a) Uniform beamforming; (b) optimal non-uniform beamforming.

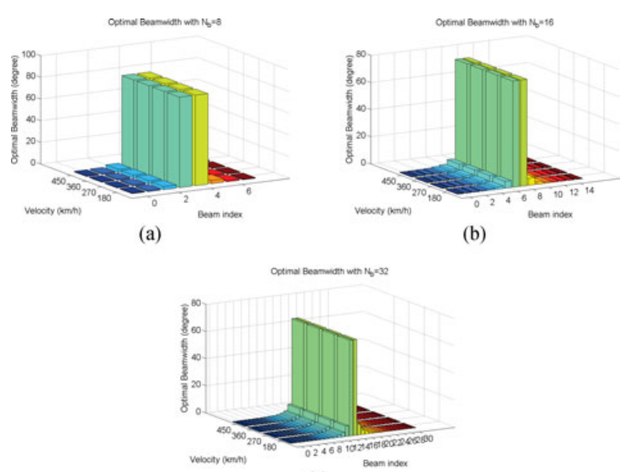

Fig. 3. Optimal beam width with different N_b and v. (a) Number of predefined RF beams $N_b = 8$; (b) number of predefined RF beams $N_b = 16$; (c) number of predefined RF beams $N_b = 32$.

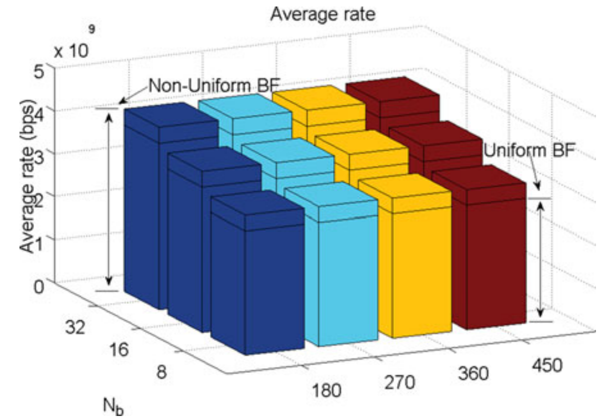

Fig. 4. Average rate with different N_b and v.

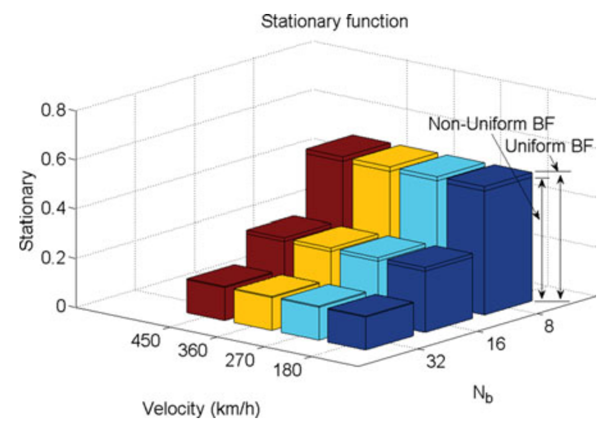

Fig. 5. Stationary function with different N_b and v.

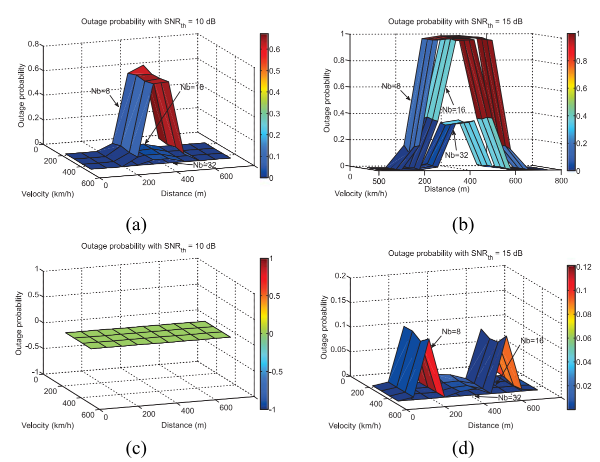

Fig. 6. Outage probability with different γ_{th} and v. (a) SNR threshold $\gamma_{th} = 10$ dB with the uniform beamforming; (b) SNR threshold $\gamma_{th} = 15$ dB with the uniform beamforming; (c) SNR threshold $\gamma_{th} = 10$ dB with the optimal non-uniform beamforming; (d) SNR threshold $\gamma_{th} = 15$ dB with the optimal non-uniform beamforming.

optimal non-uniform beamforming is always better than that of the uniform beamforming at arbitrary N_b.

The stationary function comparisons are shown in Fig. 5. We can see that the stability of the optimal non-uniform beamforming is always better than that of the uniform beamforming at arbitrary N_b. As a result, the network reliability and stability can be guaranteed by providing the steady data transmission with optimal non-uniform beamforming along the railway. However, it is worth mentioning that the stationary gap between the uniform beamforming and the non-uniform beamforming is smaller and smaller as N_b increases.

The outage probability comparisons with different SNR threshold γ_{th} and v are shown in Fig. 6. Taking $\gamma_{th} = 10$ dB as an example, there is almost no connection link failure with the optimal non-uniform beamforming at arbitrary N_b, seen in

Fig. 6(c). In other words, the outage probability of optimal non-uniform beamforming is zero with $\gamma_{th} = 10$ dB at arbitrary N_b. Meanwhile, the maximum outage probability of the uniform beamforming is 67% as $N_b = 8$ and $v = 360$ km/h.

B. Discussions

The numerical results in the previous section demonstrate that the network reliability and stability will be guaranteed by providing steady data transmission along the railway if the optimal non-uniform beamforming is utilized for HSR wireless communication systems. From the reliability and stability points of view, the number of predefined RF beams N_b would be as larger as possible to achieve the better steady data transmission. However, the upper bound of N_b is limited by hardware process capability, cost, and algorithm performance. In recent published literatures, $N_b = 64$ could be already supported in mmWave communications [30]. We believe that the more number of predefined RF beams would be soon supported with the improvement of hardware processing capability, cost, and algorithm.

Note that the two independent transceivers mounted at the top of a train can be co-located or distributed deployment. The co-located deployment is applied to simplify the analysis in the proposed scheme. In the co-located deployment, the space and cost are saved, the power supply will also be provided conveniently. However, the scalability and flexibility are limited, and the maintenance may be complicated in the co-located deployment. In the distributed deployment, the situation is just the reverse.

With our proposed optimal non-uniform beamforming, the network reliability will be guaranteed. However, how to design the optimal non-uniform beamforming architecture will be a challenge, which is our future work.

Although the proposed scheme is validated only under HSR scenarios, it can also be applied to other vehicular scenarios with linear network topology. However, different from HSR scenarios, multiple beams may be selected if there are multiple vehicles in the serving area. In our future work, we will conduct more extended study for the proposed non-uniform beamforming under general network settings. Moreover, social attributes among vehicles can be considered in vehicular scenarios to alleviate traffic load [31], [32], which is also an interesting topic for our future work.

V. CONCLUSION

For HSR wireless communication systems, network reliability and stability are important design issues and should be addressed carefully when higher data rate services are provided, especially when safety-critical railway signaling information is delivered. In this work, we propose a novel optimal non-uniform steady beamforming for downlink at mmWave frequency bands in HSR scenarios and design an effective algorithm to determine the service area portion of each predefined RF beam. Our extensive studies show that our optimal non-uniform beamforming can effectively guarantee the network reliability and stability while providing steady data transmissions.

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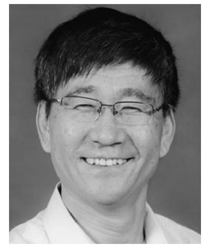

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