Performance of Capacity Optimized Line-of-sight MIMO HAP-to-train Architectures

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Abstract—In this paper, the provision of high-speed broadband wireless railway services via high altitude platforms (HAPs) is studied and line-of-sight (LoS) propagation in the Ka frequency band is considered. A geometrical design method to construct full-rank capacity optimized HAP-to-train multiple-input multiple-output (MIMO) channels is applied. Then, an analysis of the sensitivity to imperfect positioning and orientation of the antenna arrays is performed with regard to the channel capacity. The results reveal relatively low sensitivity of the underlying system to displacements of antenna arrays from the optimal point. These results also depict that the orientation of the antenna arrays and the elevation angle of the platform significantly affect the channel capacity.

1. INTRODUCTION

The growing exigencies for efficient high-speed Internet access and audio, video and file transfer services in commercial train routes have prompted the development of satellite and wireless terrestrial networks [1]. Geostationary earth orbit (GEO) satellites intend to exploit line-of-sight (LoS) connections, whereas the terrestrial cellular infrastructure preserves link availability in propagation environments, where the direct communication to the satellite might not be feasible, i.e., tunnels and train stations. In recent years, the high-altitude platforms (HAPs) have also emerged [2, 3]. HAPs are quasi-stationary aerial platforms flying at a height approximately 20 km above the Earth’s surface, in the stratosphere and capable of providing ubiquitous wireless access over large coverage areas at low cost. Several frequency bands have been licensed for communications through HAPs. Among them, the Ka (28/31 GHz) [4] and V (47/48 GHz) [5] bands were licensed for broadband fixed wireless access (BFWA) services and ensure adequate bandwidth. However, their application could be extended to mobile scenarios, such as vehicular, maritime, aeronautical and railway scenarios [6].

To meet the long-term evolution for railway (LTE-R) requirements [7] imposed by the International Union of Railways (UIC) and enhance the achievable data throughput, the application of the multiple-input multiple-output (MIMO) technology seems inevitable [8]. The MIMO gain strongly depends on the channel characteristics, which are mainly determined by the antenna configuration and the richness of scattering [9]. Although the propagation at mm-wave frequencies requires a strong, dominant LoS signal for sufficient coverage, mobility effects, such as multipath, shadowing, and blockage, which are also encountered at lower frequency bands, may exist due to the local environment in the vicinity of the trains, e.g., the presence of various metallic obstacles along the train trajectory for electrical power supply. Nevertheless, the railway environment is generally characterized by sparse (insignificant) multipath [10] and the elevation angles of the HAPs with respect to the trains are high [11] which in turns imply nearly LoS (open) propagation. Conceptually, LoS propagation correspond to a rank-deficient MIMO channel matrix and low spectral efficiency due to the increased spatial correlation introduced by the linear relationship of the phases of the received signals. However, using specifically designed antenna arrays at optimal positions, a full-rank MIMO channel may be achieved [12].

In [13], geometrical design recommendations were introduced for uniform linear arrays (ULAs) and the applicability of MIMO techniques to LoS-HAP channels for BFWA along with propagation models for the Ka and V frequency bands was studied. Nevertheless, there are some technical challenges for LTE-R due to the mobility of the trains up to 500 km/h, which leads to a time-varying and non-stationary radio channel. In addition, the stratospheric winds may vary the position of the HAP, which in turns influences the stabilization of beam pointing angles to HAP motion and requires heavy and slow mechanical steering. This paper examines the viability of reliable high-data rate communications for trains through HAPs at mm-wave frequencies and assesses the capacity
performance of capacity optimized LoS-MIMO channels using the geometrical design recommendations and the maximum capacity criterion introduced in [13]. Clear sky conditions are taken into account without incorporating atmospheric fading, which leads to different channel characteristics [14]. The parameters of interest are the height and the elevation angle of the platform with respect to the train, the carrier frequency, and the antenna array configuration. The results demonstrate and discuss the sensitivity of the capacity performance to the variation of the positioning and orientation of the antenna arrays.

The remainder of the paper is organized as follows. Section 2 describes the HAP-to-train LoS-MIMO system scenario, while Section 3 defines the channel capacity and the maximum capacity criterion. Section 4 provides results. Finally, conclusions are drawn in Section 5.

2. CHANNEL MODEL SCENARIO

The system model employed throughout this paper considers $n_T$ transmit and $n_R$ receive antenna elements installed on a HAP and the top of a train, respectively. All antennas are omni-directional and are numbered as $1 \leq p \leq q \leq n_T$ and $1 \leq l \leq m \leq n_R$, respectively. The spacing between HAP and train antenna elements is denoted $\delta_T$ and $\delta_R$, respectively and angles $\theta_T$ and $\theta_R$ represent the orientation of the HAP and train antenna arrays, respectively. The heights of HAP and train antenna arrays are $h_T \approx 20 \text{ km}$ and $h_R \approx 3 \text{ m} \ll h_T$, respectively. In addition, the elevation angle of the HAP with respect to the train is denoted $\beta_T$ and dynamically changes with the movement of the train and/or the HAP. A minimum elevation angle of $\beta_{T,\min} = 30^\circ$ and a maximum elevation angle of $\beta_{T,\max} = 60^\circ$ are considered, which correspond to a $R_{\max} = h_T / \tan \beta_{T,\min} \approx 34.6 \text{ km}$ and $R_{\min} = h_T / \tan \beta_{T,\max} \approx 11.5 \text{ km}$ radius, respectively, and $d_{\min} = h_T / \sin \beta_{T,\min} \approx 40 \text{ km}$ and $d_{\max} = h_T / \sin \beta_{T,\max} \approx 23.1 \text{ km}$ LoS distance, respectively. Moreover, the carrier frequency and signal bandwidth are 28 GHz (downlink) and 25 MHz, respectively. It is assumed that there are $N$ trains within the coverage area at a given time, which may be on the directly adjacent track and may travel toward or away from each other. These trains simultaneously transmit uncorrelated signals within the same frequency band. The maximum speed of the trains is considered to be 300 km/h. Therefore, a multiple HAP constellation should be used for sufficient coverage. Single-carrier quaternary phase-shift keying (QPSK) transmission is assumed based on the IEEE 802.16 standard for broadband fixed wireless access [15]. Fig. 1 depicts the geometrical characteristics of a HAP-to-train LoS-MIMO communication system with $n_T = n_R = 2$ antenna elements and defines the Cartesian coordinate system.

![Geometrical model for HAP-to-train LoS-MIMO channels.](image)

3. THE MAXIMUM CHANNEL CAPACITY CRITERION

Assuming that the channel is known to the receiver (train) and unknown to the transmitter (HAP), the available MIMO capacity can be obtained from [16]

$$C(t) = \log_2 \det \left( I_{n_R} + \left( \frac{SNR}{n_T} \right) H(t) H^H(t) \right) \text{ bps/Hz},$$

where $H(t) = [h_{ij}(t)]_{n_R \times n_T}$ is the $n_R \times n_T$ channel matrix containing the free-space LoS responses between all array elements, $h_{ij} = e^{-j2\pi d(i,j)/\lambda}$ is the complex response between a transmit element $i$, and a receive element $j$, $d(i,j)$ is the LoS distance between the two elements, $\lambda$ is the carrier
wavelength, $\mathbf{I}_n$ is the identity matrix of size $n_R$, $SNR$ corresponds to the average signal-to-noise ratio at the input of the receiver, $(\cdot)^H$ denotes the complex conjugate transpose operator, and $\text{det}(\cdot)$ denotes the matrix determinant. Note that the LoS distances between the antenna elements can be obtained using the geometrical model in Fig. 1 [13]. Besides, the maximum capacity of a $2 \times 2$ HAP-to-train LoS-MIMO channel can be reached, providing that antenna inter-element distance at both ends, the carrier wavelength, the height and elevation angle of the HAP, and the antenna array orientation fulfill the following criterion [13]:

$$\delta_T \delta_R = (2v + 1) \frac{\lambda h_T}{2 \sin \beta_T \sin \theta_T \sin \theta_R},$$

where $v \in \mathbb{Z}$.

4. RESULTS

Although the route of the trains is definite and fixed and the path predictable, there is usually a need for high capacity over an area, rather than to a fixed point. Moreover, in practical situations, the parameters $\beta_T$, $\theta_T$, and $\theta_R$ in (2) may be difficult to be determined with sufficient accuracy. Hence, a compromise is required, under more realistic deployment and propagation conditions or imperfectly positioned arrays. In this section, the sensitivity of the performance to the orientation and positioning of the arrays in practical high-speed railway scenarios is discussed and evaluated.

Using (2) and considering that $v = 0$, $h_T = 20$ km, $\beta_T = 45^\circ$, and $\theta_T = \theta_R = 90^\circ$, the required product between $\delta_T$ and $\delta_R$ for the 28 GHz frequency band is approximately $151.5 \frac{\text{m}^2}{\text{Hz}}$. By assuming that the HAP antenna inter-element spacing is equal to $\delta_T = 30 \text{ m}$, the corresponding train spacing is set $\delta_R = 5.05 \text{ m}$.

Figure 2 examines the sensitivity of the performance to train antenna array shifting from the optimal point. Since multiple HAP constellations are required for sufficient coverage, the evaluation takes place in a location range (displacement range referring to the optimal initial point) from 0 to 20,000 m. This is assumed to be equivalent to the whole trajectory, i.e., the distance from the mid sub-platform-point (SPP) between two HAPs, i.e., the midpoint directly below the two HAPs, to the closest SPP of another HAP. In particular, Fig. 2 demonstrates the variation of the capacity with different antenna array displacements and shows the influence of up to 20,000 m shifting along $x$- and $y$-axis for SNR = 20 dB. One observes that the capacity is relatively insensitive to these displacements from the optimum point. For a maximum shifting of 20,000 m, the capacity is only 3.3% and 2.2% lower than the maximum capacity, respectively.

![Figure 2: The normalized capacity obtained using the optimized HAP-to-train LoS-MIMO architecture as a function of the train antenna array shifting from the optimal point.](image)

Figure 3 demonstrates the channel capacity for different orientation of the HAP antenna array. The capacity is evaluated for SNR = 20 dB and $0 < \theta_T \leq 90^\circ$. According to Fig. 3, decreasing $\theta_T$ from $90^\circ$ to $45^\circ$ has an insignificant effect on the capacity, while a further decrease in $\theta_T$ drastically decreases the capacity. Hence, the results show a large sensitivity (in terms of capacity) to the orientation of the arrays. From (2), it is clear that the same results apply for $0 < \theta_R \leq 90^\circ$ and $0 < \beta_T \leq 90^\circ$.

![Figure 3: The normalized capacity obtained using the optimized HAP-to-train LoS-MIMO architecture for different orientation of the HAP antenna array.](image)
5. CONCLUSION

As the demand for uninterrupted quality broadband wireless services in the area of passenger transport in railways and high-data rate communications to multiple moving trains grow, the railroad scenario seems a promising and commercially attractive field for HAP-based systems. In this paper, a method to achieve orthogonality between spatially multiplexed signals has been employed to construct a full-rank HAP-to-train LoS-MIMO channel matrix at Ka frequency bands. Providing that the system parameters are carefully selected, the results have demonstrated the sensitivity of the capacity performance to the positioning and orientation of the arrays. These results imply that a thorough investigation of the design of any practical HAP-to-train LoS-MIMO system is required mainly in terms of the orientation of the antenna arrays and the elevation angle of the platform.

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