Performance Evaluation of mmWave in 5G Train Communications

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***Abstract*—Seamless broadband connectivity and high data rates are a prerequisite for 5G networks, especially for connectivity to moving platforms. The H2020 5G-PICTURE project considers a complete network solution that supports operational and end-user services, for both Information and Communications Technology and vertical industries such as 5G rail. Targeting wireless access communication to High Speed Trains (HST), this paper presents an overview of both LTE-A and millimeter-Wave (mmWave) solutions. Moreover, we present a performance evaluation, considering a train, equipped with two mmWave antennas (front and rear), traveling along two 1.4km rail tracks, with several mmWave Access Points (APs) placed at the trackside. With the aid of a ray-tracing tool, to obtain realistic channels, and an IEEE 802.11ad simulator, assuming receive diversity, we investigate the impact of beamforming, frequency band (26GHz and 60GHz) and cell radius on the achievable throughput. Based on our results, the employment of beamforming considerably increases the system's throughput. Moreover, we show that even when APs on the trackside are placed 800m apart, the coverage is almost seamless. Finally, investigating the angular profile of each beam, we suggest a beamwidth of 20° to maintain connection to a distance greater than 30m from the APs, for the considered scenarios.**

***Index Terms*—millimeter wave, beamforming, trains, ray-tracing.**

I. INTRODUCTION

With the ever-growing demand for data, in a world where mobile communications underpin the running of modern society, investigation into channel characterisation and frequency bands is essential to ensure that progress can be made to meet these demands.

Sub-6GHz frequency bands are becoming more and more crowded as the number of connected devices increases [1]. Higher frequency bands, especially those in the millimeter wave (mmWave) range, are a particularly attractive alternative. In addition to allowing a considerable increase in the signal bandwidth, mmWave networks can greatly increase frequency re-use for neighbouring basestations (BSs), thus making the most of every spectral segment, in more confined network coverage. However, the high attenuation encountered at these frequencies [2] requires appropriate characterisation and consideration to achieve optimal performance, especially in time varying channels. Novel circuit design, interference mitigation techniques, adaptive beamforming, antenna directivity and spatial reuse features are some of the areas that need to be investigated to deploy 5G systems. For 5G mmWave systems, an overview of propagation and signal processing techniques are given in [3-5].

In the context of 5G research, seamless broadband internet connectivity to trains, especially at high mobility (up to 350km/h), constitutes a great challenge. High spectral efficiency and data rates (up to 100Mbps in LTE [6] and several Gbps in mmWave) are expected to support wireless access to High-Speed Trains (HST). Also, frequent handovers impose the need for harmonisation between various technologies (i.e. LTE, mmWave and optical networks) and excellent synchronization among BSs, Access Points (APs) and the core network. Thus, a complete infrastructure solution is required to support a converged transport network and flexible access.

As frequent handovers in high mobility scenarios increase signaling, and thus latency, and can adversely affect Quality of Service (QoS), the concept of Moving Extended Cell (MEC), introduced in [7] initially for mmWave frequencies, and then applied to "moving femtocells" in [8] appears as a popular solution in LTE. Thus, the notion of distributed antennas on the train (for instance two per carriage), has been introduced in [9-10]. In [6], authors introduce a combination of distributed directional (front and rear carriages) and omnidirectional (middle carriages) antennas within the concept of elongated cells, i.e. LTE femtocells in each carriage that result in the HST being connected to multiple cells simultaneously.

Beamforming has been researched in the LTE area, especially for Massive MIMO systems. In [11-12] a beamforming scheme based on vehicle location information and transmit diversity is shown to achieve satisfying transmission efficiency and provide similar performance to adaptive beamforming, with less complexity. Finally, authors in [13] propose a combination of location-aware and adaptive beamforming that maximises the achievable rate and the rate in the case of two HSTs present in the same cell.

As mentioned above, mmWave communications is widely considered as a core component of 5G networks, both in transport (FH/BH) and access. However, many argue that in high mobility vehicular environments, the Doppler spread can be too high, due to the small wavelength. Authors in [14] suggest that this is true only for omnidirectional communication, showing that in vehicular channels "the coherence time increases at least proportional to the inverse of the beamwidth" [14]. Moreover, in [15] authors prove that the beam coherence time is larger than the channel coherence time, and as a result the beam alignment overhead is considerably reduced.

Considering mmWave HST communications, beamforming is one of the most important factors to investigate, since it can provide significant data rates. There are several trade-offs that need to be considered though. For instance, the narrower the beam, the higher the transmission rate, providing however additional alignment overhead [16]. Therefore, the choice of beamforming (i.e. fixed, adaptive, location-aided, etc.) should be based on the environment feature and requirements in each case.

In [17], authors compare three beamforming schemes for HST communication, denoting the importance of a solid wireless FH/BH between BSs on the ground and APs on the train. With the use of directional antennas, they propose three schemes: a) adaptive beamforming at transmitter (Tx) and receiver (Rx), b) fixed beamforming at Tx and Rx, and c) fixed beamforming at Tx and adaptive at Rx. They conclude that adaptive beamforming provides the highest SINR, with fixed beamforming achieving similar performance in most cases.

Location-aided beamforming is also considered as a solution to robust high data rate communication to HSTs since the route is predetermined in contrast to vehicular communications to cars. However, this beam training method, which exploits spatial information to focus the beam search in specific areas, thus reducing the overhead [16], results in some cases in increased noise and degraded beam alignment performance. In [16], the authors resolve this issue based on a Bayesian team decision problem.

The work presented in this paper is a result of research performed in the H2020 5G-PICTURE project. The 5G-PICTURE project aims at developing and demonstrating the integration of advanced wireless and optical network solutions in a converged FH and BH transport network infrastructure. In this context, flexible functional splits will be dynamically designated to optimize network efficiency, both in terms of resources and energy. The vision of 5G-PICTURE is a complete network solution that would support operational and end-user services, for both Information and Communications Technology and "vertical" industries. Thus, three realistic environments will be targeted: a) a 5G railway testbed located in Barcelona, b) a 5G smart city testbed in Bristol, c) a 5G stadium testbed in Bristol.

Our focus here is the 5G railway vertical, considering HSTs in sub-6GHz and mmWave frequencies, which will be one of the first 5G railway experimental testbed to demonstrate seamless service provisioning and mobility management support. Therefore, a major aspect of the above would be the wireless solutions (i.e. the Radio Access Network) for such an environment, resulting in the performance evaluation of the rail environment, in terms of throughput and coverage.

This paper introduces a throughput performance evaluation, assessing the impact of beamforming, frequency and cell radius, in a mmWave rail environment. With the aid of a ray-tracing tool, to obtain predictions of the mmWave channels, and an IEEE 802.11ad mmWave Matlab simulator, to model the system and acquire the throughput performance, we investigate the requirements to obtain high throughput and uninterrupted coverage in two rail environments (Temple Meads and Paddington stations in the UK, see Fig.1) considering an actual train traveling on a predetermined track. The results presented in this paper suggest that, in a well-designed track, seamless service, with high data rates, can be achieved with mmWave APs placed along the track every 800m. Moreover, the importance of applying beamforming is clearly shown with regards to throughput improvement. In addition, our system investigation considers both 60 and 26GHz along the two rail tracks. Finally, the angular profiles of the beams are examined, to suggest a suitable beamwidth.

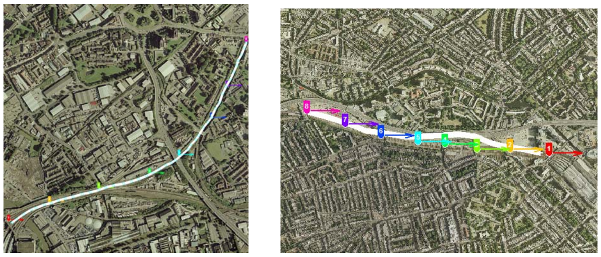

Fig. 1. (left) Temple Meads route, (right) Paddington route

II. EXPERIMENT CONFIGURATION

A ray-tracing tool was developed and upgraded in the University of Bristol to model how the signal propagates through the surrounding environment, i.e. the spatial and temporal multipath components of the propagation channel [18]. The propagation channel between each BS/AP and mobile station (MS) is modelled as the spatial convolution of polarimetric antenna patterns with spatial and temporal multipath ray components produced by the ray-tracer. All possible ray paths between the transmitter and the receiver are identified by the engine in a 3D environment. Output from the tool provides information on the amplitude, phase, time delay, azimuth and elevation AoD and AoA of each multipath component (MPC). To produce this data, the ray tracing engine incorporates multiple analytical geographic databases including terrain, buildings and foliage.

TABLE I. MODELLING AND ANALYSIS PARAMETERS

Parameter	Value
Carrier Frequency	26GHz & 60 GHz
Tx power (ray-tracing)	0 dBm
Tx power (simulator)	22 dBm
Tx antenna gain	0 dBi
Rx antenna gain	30 dBi
Bandwidth	2.16 GHz
Implementation loss	5 dB
Noise floor	10 dBm
AP (Tx) height	3 m
MS (Rx) height	2.5 m
Ray tracing resolution	1 m
Route length	1.4 km
Number of APs	8
Length of train	240 m
Width of train	4 m
No. of vehicles	8
Length of vehicle	30 m

Two different urban environments have been considered for this study; a 1.4 km rail route close to Temple Meads railway station in Bristol, UK, and a rail route of equivalent length leading to Paddington station in London, UK, depicted in Fig. 1. In both environments, mmWave APs are placed along the track with a separation of 2-5m between the APs along the trackside and the antenna on the train. The ray-tracing algorithm was applied on a point-to-point basis at a spatial resolution of 1m along both routes. This configuration is chosen to model a typical scenario of antennas mounted on already existent infrastructure to reduce cost and minimise interference.

Omnidirectional dipoles that illuminate a circular area around the BS were used in both scenarios for the APs. Modelling and simulations were performed at two different transmit frequencies (26GHz, 60GHz) with a transmit power to the antenna point of 22dBm. Receiver antenna sensitivity was set to -120dBm to disregard any low power rays and channel snapshots were taken every 1m throughout the entire route. The data obtained from the ray tracer was then processed by an IEEE 802.11ad Matlab system level simulator (developed in the University of Bristol [18]), where an actual train configuration was considered. We performed our simulations considering a train equipped with two antennas, one placed at the front, and one at the rear of the train, as shown in Fig. 2. We assumed that simulations start when the antenna at the rear is at point 1 and finish when it is at point 1170. All system parameters are presented in Table 1.

In the simulator, the suitable Modulation and Coding Scheme (MCS) mode (modes 1-12) was chosen by the link adaptation algorithm to maximise the throughput for the link in every scenario. Finally, statistics are generated based on the MCS modes and data throughputs of every generated point-to-point link. Any MAC overheads or TCP/IP retransmissions, which can cause additional throughput reduction, as in real implementations, are not covered in this work.

Fig. 2. Train considered traveling on the rail track

In addition, we examined how beamforming affects the throughput performance considering the application of maximum power ray selection beamforming, which is a widely adopted beamforming method at 60GHz, but not as optimal as exhaustive search, in which the beam with the maximum power is selected [4].

III. SIMULATIONS AND RESULTS

Our research focuses on how the distance between the APs, the frequency band, and the application of beamforming affects the throughput performance. Due to limited space, in this paper most results will be presented based on our simulations for the Temple Meads rail track, however a comparison between Temple Meads and Paddington will also be presented.

As mentioned in Section II, two antennas are mounted on the train (front and rear). Considering receive diversity, for all our simulations, we choose the antenna with the highest throughput.

Firstly, considering the Temple Meads route, we investigate the impact of the distance in which APs are placed as well as the employment of beamforming (we compare with no beamforming results to show the improvement). Figs. 3 and 4 depict the throughput for the route of the train on the designated track, with no beamforming considered, for distances between APs varying from 200-800m, for 60GHz and 26GHz respectively. One can observe that the throughput, when APs are placed 200m and 400m apart reaches 4.7Gbps, slightly dropping at 2.8-3 Gbps along the route. When APs are placed further apart (600m), the throughput ranges from 2-4.7Gbps, which is still a good result considering that in practice this would allow 400m radius mmWave cells. Moreover, in the case of 800m, the connection drops completely between points 800-1170, which could be optimised if APs were placed in better locations along the trackside.

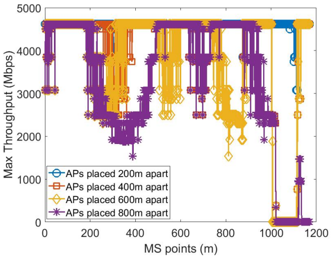

Fig. 3. Max. throughput at 60GHz for various distances between APs (no beamforming).

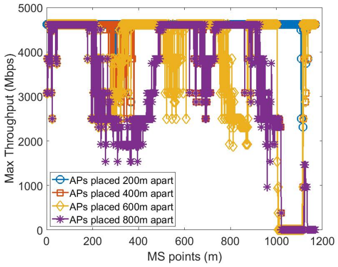

Fig. 4. Max. throughput at 26GHz for various distances between APs (no beamforming).

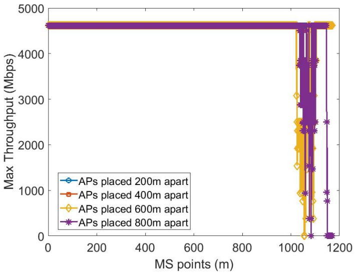

Fig. 5. Max. throughput at 60GHz for various distances between APs (with maximum ray selection beamforming).

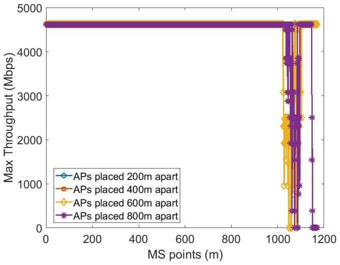

Fig. 6. Max. throughput at 26GHz for various distances between APs (with maximum ray selection beamforming).

Results for the case of employing maximum ray selection beamforming are depicted in Figs. 5 and 6. The throughput reaches 4.7Gbps and we can observe much better coverage for this case in all scenarios and especially for the 26GHz band. A narrower bandwidth configuration could be used at 26GHz, which will result in lower data rates, but greater coverage.

Furthermore, the Cumulative Distribution Functions (CDFs) of the maximum throughput for both 60GHz and 26GHz frequency bands, shown in Figs. 7-8 respectively, is investigated. In both figures we can observe that with the application of beamforming, there is less than 10% probability to achieve less than 4.7Gbps throughput, for all different distances between APs. Moreover, when no beamforming is applied, we can see a more distinctive difference in the results we get for different distances between the APs. For instance, at 60GHz, there is a 40% probability to achieve a throughput of 4.7 Gbps with an 800m distance between the APs placed along the trackside, and 60% to achieve a throughput greater than 2.4 Gbps.

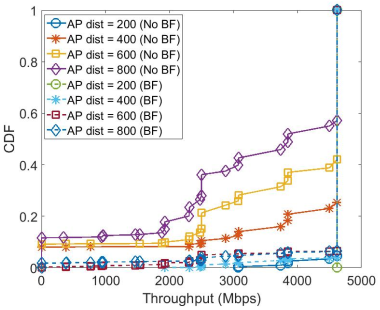

Fig. 7. CDF of Max. Throughput at 60GHz

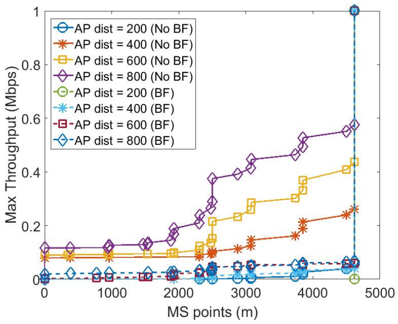

Fig. 8. CDF of Max. Throughput at 26GHz

We also observed the performance of our system at the Paddington station. Due to space limitations, only the case that the APs are placed 400m apart is presented in Fig. 9, which shows the maximum throughput achieved, by the best antenna on the train. As depicted in Fig. 9 and looking again at Fig. 3, for the case of no beamforming, results obtained from the Paddington route give lower throughput compared to the Temple Meads scenario. This is by no means unexpected, since we are comparing two different rail environments. Overall, the trend is similar for both stations.

Finally, an examination on the AoA/AoD of the rays, per MS point, was performed to conclude on the best beamwidth to be chosen for the specific scenarios modelled. This examination reveals a pattern that can be seen around every AP in the route. As seen in Fig 10, there is no substantial variation in the transmitted and received angles for the majority of the route. At distances, larger than 30m from the AP a connection can be maintained with beamwidths of 20°. A further increase to 30° allows the AP to serve the MS up to a distance of 10m without a change in the beam pattern.

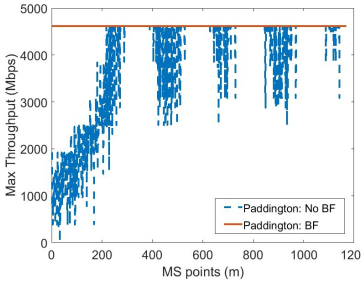

Fig. 9. London Paddington: Max. throughput for 400m distance between APs with/without beamforming (60GHz).

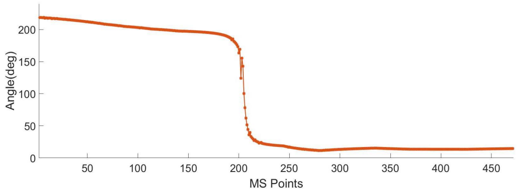

Fig. 10. AoA/AoD profile in AP vicinity (Temple Meads-60GHz)

IV. CONCLUSIONS

In this paper, based on our research for the vertical rail of the H2020 5G-PICTURE project, we presented simulation results on the performance of a mmWave network in a rail environment at 26GHz and 60GHz. Considering an actual train, mounted with two antennas (front, rear) traveling along a train track (Temple Meads and Paddington), and several mmWave APs placed at the trackside, we have shown that seamless connectivity can be achieved even when APs on the trackside are placed 800m apart. Additionally, the application of maximum ray selection beamforming has considerably improved the throughput performance. The maximum achievable throughput was simulated at around 4.7 Gbps. Finally, based on our analysis, a 20° beamwidth is sufficient to provide coverage for most of the MS points in the vicinity of an AP.

ACKNOWLEDGMENT

The authors would like to thank Dr. D. Kong for his help using the ray-tracing tool, and Dr. N. F. Abdullah and Dr. A. Goulianos for their help with the IEEE 802.11ad Matlab system level simulator. The research leading to these results has received funding from the European Commission H2020 programme under grant agreement n762057 (H2020 5G-PICTURE project) and the CDT in Communications (University of Bristol).

REFERENCES

[1] Cisco, “CISCO Visual Networking Index: Forecast and Methodology: 2016–2021”, *White Paper*, June 2017.

[2] T.S. Rappaport et al., “Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!”, *IEEE Access*, vol. 1, May 2013.

[3] T.S. Rappaport et al., “Overview of Millimeter Wave Communications for Fifth-Generation (5G) Wireless Networks-With a Focus on propagation Models”, *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, Dec 2017.

[4] S. Lutty, D. Sen, “Beamforming for Millimeter Wave Communications: An Inclusive Survey”, *IEEE Commun. Surveys Tut.,* vol. 18, no. 2, 2nd quarter 2016.

[5] R.W.Heath Jr. et al, “An Overview of Signal Processing techniques for Millimeter Wave MIMO Systems”, *IEEE J. Sel. Topics Signal Process.*, vol.10, no.3, April 2016.

[6] A. Parichehreh et al., “Seamless LTE connectivity in high-speed trains”, Journal on *Wireless Communications and Mobile Computing*, vol. 16, no. 12, Aug. 2016.

[7] N. Pleros et al., “A 60GHz radio-over-fiber network architecture for seamless communication with high mobility”, *J. Lightw. Technol.,* vol. 17, no. 12, May 2009.

[8] O.B. Karimi, J. Liu, C. Wing, “Seamless wireless connectivity for multimedia services in high speed trains”, *IEEE J. Sel. Areas Commun*, vol. 30, no. 4, May 2012.

[9] L. Tian, et al., “Seamless dual-link handover scheme in broadband wireless communication systems for high speed rail”, *IEEE J. Sel. Areas Commun*, vol. 30, no. 4, April 2012.

[10] C. Yang, et al., “An on-vehicle dual-antenna handover scheme for high-speed railway distributed antenna system”, *Conference on WCNMC*, Chengdu, 2010.

[11] X. Chen, et al., “Massive MIMO Beamforming with Transmit Diversity for High Mobility Wireless Communications”, *IEEE Access*, vol. 5, Oct. 2017.

[12] X. Chen, J. Lu, P. Fan, “Massive MIMO Beam-forming for High Speed Train Communication: Directivity vs Beamwidth”, available Online: arXiv:1702.02121.

[13] X. Chen, et al., “Directivity-Beamwidth Tradeoff of Massive MIMO Uplink Beamforming for High Speed Train Communication”, *IEEE Access*, vol. 5, April 2017.

[14] V. Va, R.W. Heath Jr., “Basic Relationship between Channel Coherence Time and Beamwidth in Vehicular Channels”, *IEEE VTC*, Boston, Sept. 2015.

[15] V. Va, J. Choi, R.W. Heath Jr., “The Impact of Beamwidth on Temporal Channel Variation in Vehicular Channels and its Implications”, *IEEE Trans. Veh. Technol.*, vol. 66, no. 6, June 2017.

[16] F. Maschietti, D. Gesbert, P. de Kerret, H. Wymeersch, “Robust Location-Aided Beam Alignment in Millimeter Wave Massive MIMO”, available Online: arXiv:1705.01002

[17] J. Kim, et al., “A Study on Millimeter-Wave Beamforming for High-Speed Train Communication”, *Inf. and Commun. Techn. Conv. Conf.*, Jeju, Oct. 2015.

[18] N.F. Abdullah, A. Doufexi, A. Nix, “Effect of beamforming on mmWave Systems in various Realistic Environments”, IEEE VTC, Sydney, June 2017.