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Research Article

5G Millimeter Wave Communications for High Speed Trains

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Abstract

Providing a seamless high data rate connectivity to vehicles is a prerequisite for 5G networks. Since the sub-6 GHz bands have become crowded and struggled to support high data rate communications, millimeter wave (mmWave) bands have attracted the researchers. Thus, in this paper, mmWave technology is investigated for high speed trains (HST) which is considered as one of the vertical applications of the 5G. Specifically, two candidate frequency bands, namely 28 GHz and 60 GHz, are considered. An advanced system level simulator is used to evaluate the system performance over a 2 km rail track in terms of achievable throughput (data rate) and coverage range (inter side distance) at both candidate 5G frequency bands. Moreover, the system performance is evaluated for different beamwidths and trains speeds. The results show that for Line-of-Sight (LoS) scenarios, high data rates and the seamless connectivity to HSTs can be provided even using a narrow beam (such as 12º) at both frequency bands, i.e., 1700 m and 1400 m coverage ranges with average data rates of 4.5 Gbps and 2 Gbps are achieved at the 28 GHz and the 60 GHz bands respectively. When different trains speeds are investigated, it is observed that there are slight reductions in the throughput results, which is negligible, when the train speed increases since the considered scenario is the LoS. Based on the extensive simulation results and the analysis, it is concluded that 5G mmWave communication is a viable solution to provide the reliable gigabit connectivity to the HST applications.

Keywords: 5G, Millimetre Wave Communication, V2X, High Speed Trains.

Yüksek Hızlı Trenler için 5G Milimetre Dalga Haberleşmesi

Öz

Araçlara kesintisiz yüksek veri hızı bağlantısı sağlamak, 5G ağları için bir ön koşuldur. 6 GHz altı bantlar kalabalıklaştığı ve yüksek veri hızı iletişimini desteklemekte zorlandığı için milimetre dalga (mmWave) bantları araştırmacıları cezbetmiştir. Bu nedenle, bu makalede, 5G'nin dikey uygulamalarından biri olarak kabul edilen yüksek hızlı trenler (HST) için mmWave teknolojisi araştırılmıştır. Özellikle, iki aday frekans bandı, yani 28 GHz ve 60 GHz, dikkate alınmıştır. Gelişmiş sistem seviyeli simulator kullanılarak, sistem performansı ulaşılabilir veri hacmi (veri hızı) ve kapsama alanı (baz istasyonları arası mesafe) açısından 2 km'lik bir ray hattı boyunca her iki aday 5G frekans bandı için değerlendirilir. Buna ilave olarak sistem performansı farklı hüzme genişliği ve tren hızları için de değerlendirilir. Sonuçlar, açık görüş hattı (LoS) senaryoları için, dar bir hüzme (12º gibi) kullanılsa bile her iki frekans bandında da HST'lere yüksek veri hızları ve kesintisiz bağlantı sağlanabileceğini gösterir. Yani 28 GHz frekans bandı kullanıldığında ortalama 4.5 Gbps veri hızı ve 1700 m kapsama alanı, 60 GHz frekans bandı kullanıldığında ortalama 2 Gbps veri hızı ve 1400 m kapsama alanı elde edilmiştir. Farklı tren hızları incelendiğinde, dikkate alınan senaryo LoS olduğu için tren hızı arttığında, veri hızı sonuçlarında hafif bir azalma olduğu gözlenmektedir. Kapsamlı simülasyon sonuçları ve analizlerine dayanarak, 5G mmWave haberleşmesinin HST uygulamalarına güvenilir gigabit bağlantısı sağlamak için uygun bir çözüm olduğu sonucuna varılmıştır.
Anahtar Kelimeler: 5G, Milimetre Dalga Haberleşmesi, V2X, Yüksek Hızlı Trenler.

1. Introduction

Providing broadband services to train passengers is getting very important. With the ever-growing demand for higher data rates, sub-6 GHz frequency bands are becoming saturated as the number of connected devices rises (Cisco, 2017). Millimeter wave (mmWave) bands have gained attentions as attractive alternative frequency regions due to available large bandwidths (*BW*s) at those frequencies for the mobile broadband services. Thus, the 3GPP New Radio (NR) (3GPP, 2017) proposed to use those bands for providing enhanced mobile broadband (eMBB) services to high speed trains (HST) which is considered as one of the vertical applications of 5G technology.

Further that it is expected to equip the trains and tracks with sensors, cameras, LIDAR (light detection and ranging) scanners etc. in order to collect information such as position, speed, direction of movement, temperature and exchange those data between base stations (BSs) and mobile stations (MSs) for safer and better journey and passenger experience. To this end, it is estimated that massive amount of data will be generated and shared when the trains and the tracks get smarter. To successfully transmit such an amount of data to the cloud and/or data centre for processing, it is required to have very reliable, stable and high throughput links between the BS and the MS.

Although, the mmWave frequencies provide higher data rates required by the HST applications, due to the high attenuation experienced at those frequencies (Rappaport et al., 2013) it is hard to provide reliable links between the transmitter and the receiver. Thus, providing seamless eMBB services to the HST, especially at very high speeds (up to 500 km/h), would be very challenging. In this context, beamforming is one of the technologies used to combat the high propagation losses. Although, using beamforming technology provides higher data rates, there are many challenges need to be addressed. For example, using narrow beams provide higher data rates but this would require frequent alignment of the beams. Considering very high speeds of the trains there would be massive beam alignment overhead (Va, Zhang and Heath, 2015).

In order to reduce the beam alignment overhead, in (Kim and Molisch, 2013) and (Va,et al., 2016), a beam switching method which leverages train position information is considered since the train track is predetermined in contrast to vehicular routes for cars. It is stated that getting accurate location information of the train plays key role for successful deployments of the 5G networks for HST in addition to designing of suitable beams for each sector (train location). In literature, some works such as (Va, 2018 and Muns et al., 2019), studied the beam design for vehicular scenarios. However, designing suitable beams for high mobility scenarios depends on the environment, frequencies, design requirements etc. thus this topic is still under investigations.

In this work, 5G mmWave communication is investigated for HST deployment scenarios. To this end, two different candidate frequencies namely 28 GHz and 60 GHz bands are considered with different beamwidths. Using an advanced mmWave channel simulator (called NYUSIM (Sun, MacCartney Jr, and Rappaport, 2017)) and a system level simulator, the system performance is evaluated in terms of achievable throughput and the service area (i.e., coverage). The results presented in this paper would provide insight on the selection of the suitable frequency and the beams (and hence antenna array) for successful real-world deployments of the 5G network for railways, i.e., deploying such a network which provides seamless services under very high mobility scenarios.

The rest of the paper is organised as follows. Section 2 presents the material and method used in this paper. Detailed simulation results and analysis are provided in Section 3 and Section 4 concludes the paper with some recommendations.

2. Material and Method

In this section, system model and parameters used to evaluate the performance of 5G mmWave communications for HTS deployment scenarios (experiment configurations) are presented.

For simulation scenario, it is assumed that a train (MS) travels along a rail track as seen in Figure 1. A single BS was deployed in a rural environment and the simulations were performed for a 2 km distance (straight line) in order to evaluate the coverage range of the BS depending on the different frequencies, *BW*s, beamwidths and train speeds, i.e., to investigate the inter side distance between BSs when these technologies are deployed.

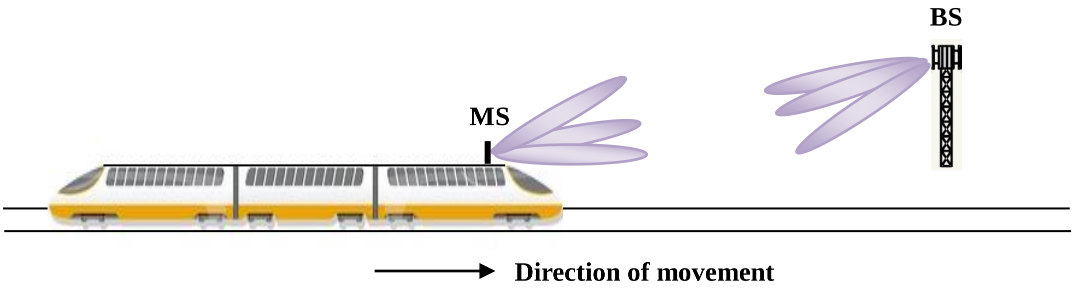

Figure 1- Simulation scenario

A state-of-the-art NYUSIM channel simulator was used to generate accurate omnidirectional and directional channel data between the BS and MS for a rural environment (Sun, MacCartney Jr, and Rappaport, 2017). NYUSIM is developed based on extensive field measurements and able to simulate a wide range of carrier frequencies range from 500 MHz to 100 GHz, and RF bandwidths from 1 MHz (continuous wave (CW)) to 800 MHz. Moreover, the NYUSIM can simulate spatially consistent channel realisations (Ju et al., 2019). Spatial consistency indicates continuous and realistic channel evolution along a trajectory in a local area unlike drop based channel models in which a static and independent channel impulse response (CIR) at a particular BS-MS separation distance is generated (i.e., there is no correlation among different channel realisations) (Ju et al., 2019). NYUSIM with spatial consistency simulates spatially correlated CIRs when a train moves in a local area (track). Thus, more realistic throughput analysis and coverage predictions are made.

For simulations, it is assumed that BS and MS modems operate at 28 GHz and 60 GHz frequency bands with bandwidths of 800 MHz and 2.16 GHz respectively. Directional transmissions at both BS and MS sides are considered. To this end, the BS and the MS are equipped with Uniform Rectangular Arrays (URAs) allowing to steer the beam with predefined azimuth and elevation half-power-beamwidths (HPBWs). For comparison, HPBWs of 12º, 20º and 32º are considered at the BS and MS (azimuth and elevation angles are set the same values). The BS and the MS antennas heights are set to 6 m and 2 m respectively and the maximum Effective Isotropic Radiated Power (EIRP) is 40 dBm. The noise figure (*NF*) is set to *NF*=7 dB. Table I presents the simulation parameters for mmWave systems operate at both 28 GHz and 60 GHz frequencies.

Table 1. Design and Analysis Parameters

Parameter	**Value**
Maximum EIRP	40 dBm
Carrier frequency (CF)	28 GHz and 60 GHz
Bandwidth	800 MHz (for 28 GHz *CF*) and 2.16 GHz (for 28 GHz and 60 GHz *CF*s)
BS antenna height	6 m
MS antenna height	2 m
Antenna azimuth HPBW at the TX and RX	12º, 20º and 32º
Antenna elevation HPBW at the TX and RX	12º, 20º and 32º
Noise figure	7 dB
MS speeds	240 km/h and 360 km/h

The equation used to generate the channel coefficients is provided by Equation (1) (Adhikary et al., 2014), where $h_{m,k}(f)$ is the channel coefficient between the m^{th} transmit antenna and the k^{th} receive antenna for the sub-carrier f, p denotes the p^{th} resolvable multipath component, α represents the amplitude of the channel gain, Φ is the phase of the multipath component, τ represents the time delay, d_T and d_R are the antenna element spacing at the transmitter and receiver, respectively, while ϕ and φ denote the azimuth angle

$$h_{m,k}(f) = \sum_p \alpha_{m,k,p} e^{j\Phi_{m,k,p}} e^{-j2\pi f \tau_{m,k,p}} e^{-j2\pi d_T m \sin(\phi_{m,k,p})} e^{-j2\pi d_R k \sin(\varphi_{m,k,p})} \quad (1)$$

of departure and angle of arrival, respectively (Adhikary et al., 2014).

In the physical (PHY) layer simulations, Orthogonal Frequency Division Multiplexing (OFDM) scheme is implemented. For each the signal-to-noise ratio (SNR) value, the packet error rate (*PER*) at the PHY layer is calculated over the transmission of 2000 information packets each with 1500 bytes in size. Then, using the Modulation and Coding Schemes (MCS) m_i defined in (IEEE 802.11ad Std., 2012), the throughput results are calculated. Nominal peak data rates for mmWave MCS index of 0 to 11 range from 693 Mbps to 6756.75 Mbps for a *BW* of 2.16 GHz and for a *BW* of 800 MHz it ranges from 256.66 Mbps to 2502.5 Mbps.

Table 2. MCS Modes and Peak Data Rates for 28 GHz and 60 GHz frequency bands

MCS index	**Modulation**	**Code rate**	**Peak data rate for 28 GHz *CF* with 800 MHz BW (Mbps)**	**Peak data rate for 28 GHz and 60 GHz *CF* with 2.16 GHz BW (Mbps)**
0	SQPSK	1/2	256.66	693
1	SQPSK	5/8	320.83	866.25
2	QPSK	1/2	513.33	1386
3	QPSK	5/8	641.66	1732.5
4	QPSK	3/4	770	2079
5	16-QAM	1/2	1026.66	2772
6	16-QAM	5/8	1283.33	3465
7	16-QAM	3/4	1540	4158
8	16-QAM	13/16	1668.33	4504.5
9	64-QAM	5/8	1925	5197.5
10	64-QAM	3/4	2310	6237
11	64-QAM	13/16	2502.5	6756.75

3. Results and Discussion

In this section, the system performance in terms of the achievable maximum throughput which is calculated using a link adaptation algorithm is evaluated considering a practical railway deployment scenario. To this end, different frequency bands (28 GHz and 60 GHz), system bandwidths (800 MHz and 2.16 GHz), beamwidths (12º, 20º, 32º) and train speeds (240 km/h, 360 km/h) were investigated to define the best system design options for the deployments of the 5G mmWave networks for HSTs.

Figure 2 shows the system performance in terms of throughput when the optimum beam switching is implemented at the BS and the MS for each MS location for 28 GHz and 60 GHz operation bands and beamwidths of 12º, 20º and 32º. In these results, it is assumed that there is an 800 MHz bandwidth available at 28 GHz band thus the nominal data rates are reduced compared to the 60 GHz band where there is a 2.16 GHz available bandwidth. It is seen from the figure that for a Line-of-Sight (LoS) scenario, both 28 GHz and 60 GHz bands provide quite good coverage when the narrow beam is implemented at the BS and the MS, i.e., 12º beamwidth provides around 1700 m and 1400 m coverage areas at 28 GHz and 60 GHz bands respectively.

As expected, lager the beamwidth lower the coverage areas due to lower antenna gains and larger angular spreads. Specifically, using larger beamwidths at 60 GHz results in significant reduction in the coverage results compared to the 28 GHz: the coverage is reduced from 1400 m to 400 m and 300 m for 60 GHz when 20º and 32º were implemented. For 28 GHz band, the 12º and 20º beams provide similar coverage results due to the maximum EIRP limit, however, the achievable maximum throughputs are different (much higher) due to the higher receive antenna gain achieved when 12º beamwidth is implemented.

It is further observed from the figure that when the system is bandwidth limited, frequency switching can be employed to get full benefits (higher throughput and coverage range) from different frequency bands. For example, for close proximity such as less than 800 m BS-MS separation, the 60 GHz band provides higher throughput after that location the 28 GHz band provides higher throughput and coverage area. Deploying dual or higher bands modems would provide seamless coverage, higher throughputs and longer inter side distances thus lower the deployment cost.

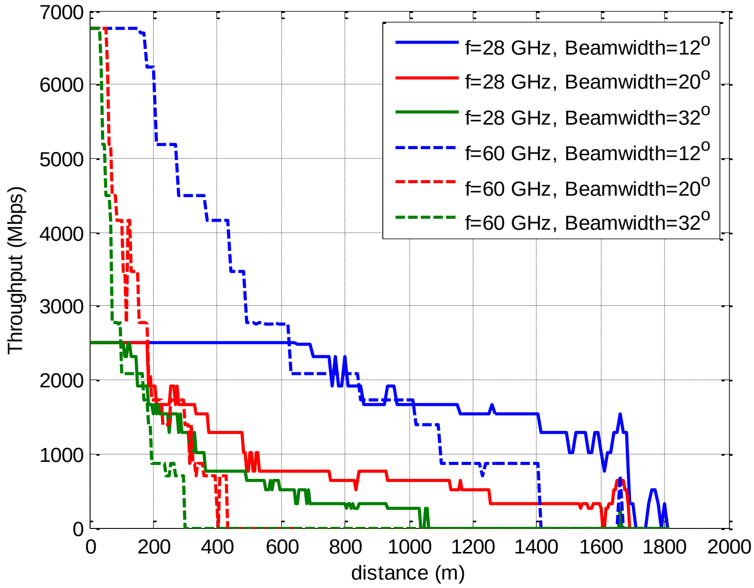

Figure 2- Throughput versus distance: BW=800 MHz for 28 GHz band and BW=2.16 GHz for 60 GHz band

In Figure 3, the same simulations were performed assuming that there is a 2.16 GHz available bandwidth at 28 GHz band. It is seen that the 28 GHz band provides at least 2 Gbps and average 4.5 Gbps data rates over 1700 m of the track while the 60 GHz band provides minimum1 Gbps and average 2Gbps over 1400 m distance. It is shown that seamless gigabit connectivity even with a very narrow beamwidth (12º) is achieved over such long distances. Since the LoS scenario is considered in this work, it is observed that the quality of the links (throughput results) are insensitive to the beamwidths. Thus, these results suggest that for LoS locations of the track, narrow beams can be selected to boost the coverage and the maximum data rate (throughput). These results state that it is possible to provide Gbps data rate connections to the HSTs by using the 5G mmWave communications. Therefore, it is viable to deploy mmWave networks for HSTs applications.

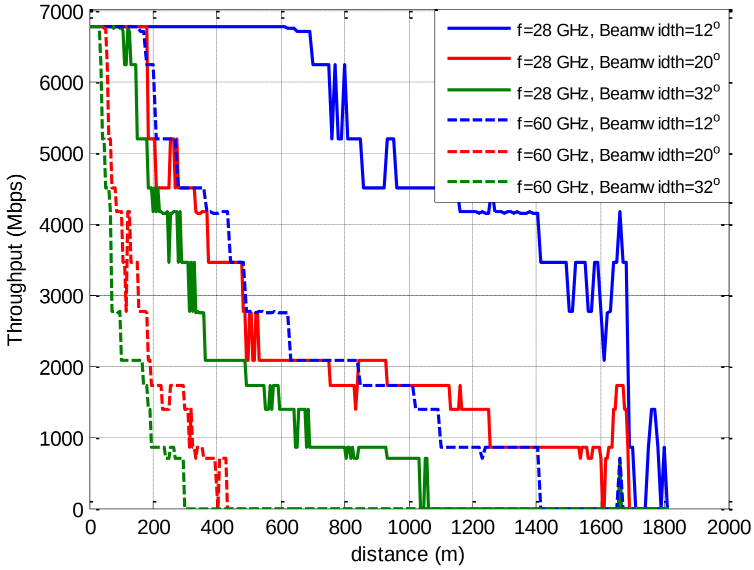

Figure 3- Throughput versus distance: BW=2.16 GHz for both 28 GHz and 60 GHz bands

In the following figures, the effect of the train speed on the system performance is investigated. Figure 4and Figure 5 show the Cumulative Distribution Function (CDF) graphs of the achievable throughput depending on the train speed and the beamwidth for 28 GHz (assuming 2.16 GHz bandwidth) and 60 GHz bands respectively. In both figures we can observe that increasing the train speed slightly reduce the system performance, i.e., reductions in the throughput results are obviously negligible. It is also seen that when the narrow beams are implemented the throughput results are more sensitive to the trains speed. This is a result of the misalignment due to rapid displacements of the train the selected positions of the beams would be suboptimal.

When compared to the 28 GHz and the 60 GHz bands, the 28 GHz band is less sensitive to the higher train speed than the 60 GHz. However, as long as there is a LoS link between the BS and the MS then the misalignment (suboptimal beam switching) does not degrade the system performance (throughput results) much. Since the reliability of the mmWave communication links for high speed scenarios is concerned in term of real-world deployment, these results suggest that mmWave communications can be quite robust for LoS scenarios (considering that most of the HST tracks have LoS scenarios).

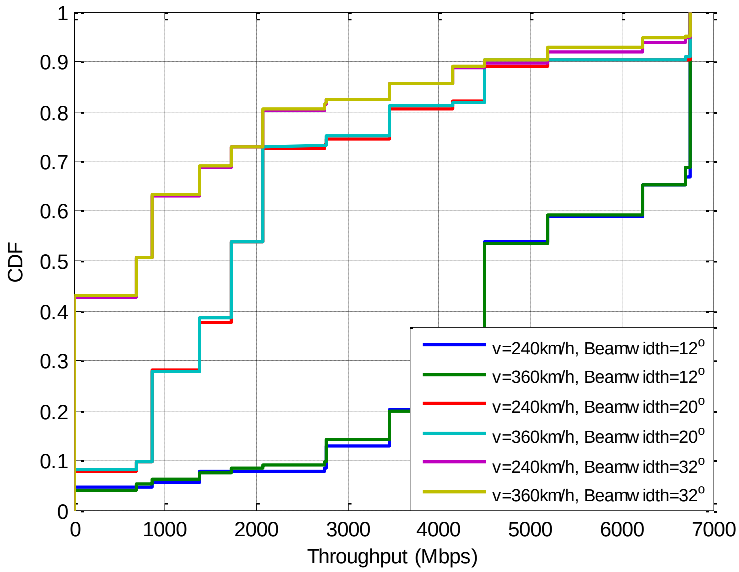

Figure 4- Throughput versus distance at different train speeds (v): BW=2.16 GHz, f=28 GHz

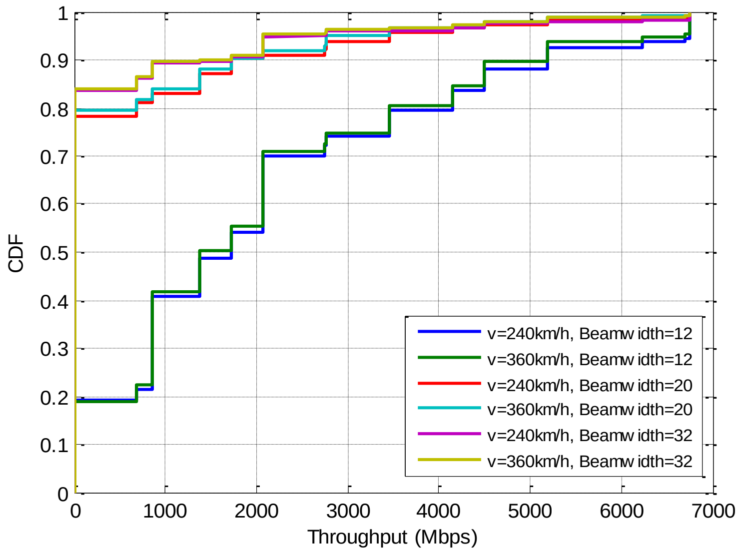

Figure 5- Throughput versus distance at different train speeds (v): BW=2.16 GHz, f=60 GHz

4. Conclusions and Recommendations

In this paper, the 5G mmWave communications for the deployments of the HTS scenarios was investigated. To this end, an advanced system level simulator was used to evaluate the system performance in terms of achievable throughput and coverage range (inter side distance) at both candidate 5G frequency bands of 28 GHz and 60 GHz. The results showed that for LoS scenarios seamless gigabit connectivity to HSTs can be achieved even using narrow beams (such as 12º). When compared to the 28 GHz and the 60 GHz bands, it was shown that 1700 m and 1400 m coverage ranges with the average data rates of 4.5 Gbps and 2 Gbps were achieved with a beamwidth of 12º respectively. When larger beams are implemented, there are considerable decreases in the coverage and the throughput results. Additionally, the system performance was investigated at both 28 Ghz and 60 GHz frequency bands for different train speeds considering different beamwidths of 12º, 20º and 32º. It was observed that there are slight reductions in the throughput results when the train speed increases since the considered scenario is LoS. Finally, based on extensive simulation results and analysis, it is concluded that 5G mmWave communication is a viable solution to provide reliable gigabit connectivity to the HST applications.

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