2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring)

DOI: 10.1109/VTC2020-Spring48590.2020.9129457

Multi-hop relaying in mmWave band for next generation train radio

Qianrui Li

Nicolas Gresset

Multi-hop relaying in mmWave band for next generation train radio

Qianrui Li, Nicolas Gresset
Mitsubishi Electric R&D Centre Europe (MERCE)
Rennes, France
Email: {q.li,n.gresset}@fr.merce.mee.com

***Abstract*—Multi-hop relaying is a promising technology to fight against the high propagation loss, blockage and mobility sensitivity in millimeter wave band communication for high speed train. Adopting the system deployment and antenna configuration in 3GPP, based on the transmitting power configuration and instantaneous train position, we can optimize the average transmission data rate by selecting the optimal multi-hop relaying scheme. The analysis and simulation exhibit that due to antenna array directivity and path loss effect, different multi-hop relaying strategies can dominate the average transmission data rate maximization under different transmitting power regimes and distance ranges.**

I. Introduction

Recent years have witnessed the drastically increasing demand for train radio communications in order to handle safety-critical, safety-related or passenger-oriented applications. To provide a modal shift toward greener, smarter and more robust intelligent transport system, the European Union Agency for Railways, International Railway Union (UIC) and Joint Undertaking initiative Shift2rail have launched a Future Railway Mobile Communication System (FRMCS) project in which railway operators specify the requirements of a next generation train radio standard. In July 2015, a new ETSI European standardization process on next generation radio for railways was launched in ETSI Technical Committee on Railway Telecommunications (ETSI TC-RT). In the meantime, the investigation on next generation cellular communication systems is at its height and high speed train scenario has been particularly identified in 3GPP so as to target consistent passenger user experience and critical train communication reliability with very high mobility [1], [2].

In millimeter wave (mmWave) band, multiple antenna technology allows focusing the transmission towards extremely precise directions, which is a key advantage to fight against specific difficulties related to wireless communication at high speed. However, severe attenuation of signals caused by path loss and rain attenuation in mmWave band renders distinct deployment from conventional sub-6GHz train radio systems. Therefore, multi-hop relaying is a promising technology which involves using spatially dispersed nodes as well as transmission between such nodes in shorter range so as to fight against the high propagation loss, blockage and mobility sensitivity in mmWave communication [3]. With multi-hop relaying architecture, both high reception quality and robust connectivity can be assured in the face of high speed train scenario.

Multi-hop relay channel and networks have already been extensively studied in the literature [4]–[11]. Theoretical analysis on the decode-and-forward relaying and amplify-and-forward relay channel have been conducted in [4], [5]. Different optimization metrics in a multi-hop relaying network such as optimal routing path selection [6], end-to-end delay [6], [7], secrecy [8], throughput [6], [8] and fairness [9] as well as combinations of such metrics have been considered. Although some of these works [5], [7], [8] considered the linear multi-hop relay network which is relevant to the train radio, there exists very few works which take into account the realistic system configuration and deployment constraints in train radio communication systems. In [10], cooperative moving relay nodes deployed on high speed train is evaluated for sub-6GHz band LTE system. In [11], both LTE and mmWave system are considered for relaying in high speed train scenario. However, only two-hop architecture is considered.

In this work, we analyze the multi-hop relaying in mmWave band for the train radio communication system. The network deployment and antenna configuration described in 3GPP high speed train scenario for mmWave band communication are adopted. Based on the transmitting power for Remote Radio Head (RRH)/relay nodes and the geographic position of the train, the average transmission data rate from the RRH to the destination application server is maximized by selecting the optimal multi-hop relaying scheme. Simulation results reveal the transmitting power regimes and the distance ranges under which the mulit-hop relaying schemes are more beneficial.

II. System Description

A. System Model

The multi-hop communication under consideration is illustrated in Fig. 1. It is coherent with the high speed train deployment in 3GPP TR 38.913 [1], [12] which focuses on the train communication reliability with very high mobility. For this communication between the RRH and the application server, we consider that there exists multiple relay nodes located at the top of each cabin of the train. The RRH operate on the mmWave band and can communicate with any one of the relay nodes. The relay nodes are capable of receiving from the RRH and passing on the information to the adjacent relay nodes on the same mmWave band. The application server is located in the head the train and is directly wired to the relay node at the top. Therefore, for the end to end communication, messages will be delivered from RRH to a selected relay node as the receiving counterpart of the RRH, followed by multi-hop communication from such relay node to the final relay node that is connected to the application server. This transmission targets both high data rate, low latency and reliable communication since the messages can be safety-critical control information (e.g., Communication Based Train Control) and safety-related data (e.g., Closed Circuit surveillance video).

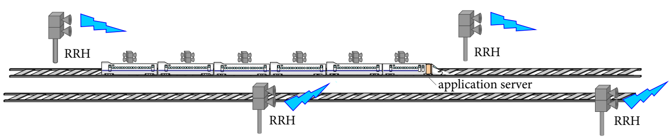

Fig. 1: Multi-hop communication from RRH to the application server in the train.

The aforementioned communication can be depicted in a simplified figure as Fig. 2.

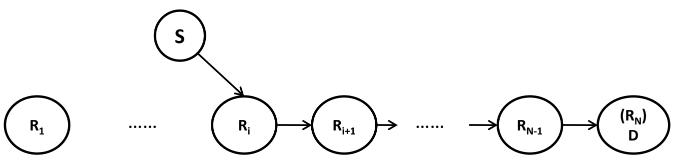

Fig. 2: Multi-hop communication system with $N-i+1$ hop transmission.

The multi-hop system operates on a Time Division Multiple Access (TDMA) transmission mode where the source to destination transmission is split into $N-i+1$ single hop transmission: 1 hop from the source RRH to the first selected relay node and $N-i$ hops between relay nodes. N is the total number of relay nodes in the system and i is the index of the first selected relay. There is only one pair of transmitting and receiving nodes during each hop, which prevents interference at the receiver. Since the relays are placed at the top of each train cabin in an equal distance manner, the transmissions between any two adjacent relay nodes are assumed to suffer from the same propagation attenuation and thus transmission characteristics are exactly the same. We assume that the total transmit duration is T_{tot}. Let $T_{\text{SR}_i}, T_{\text{RR}}$ denote the transmission time from the source S to the first selected relay node R_i and the transmission time from one relay node to the next relay, respectively. We can have the following relations

$$T_{\text{tot}} = T_{\text{SR}_i} + (N-i)T_{\text{RR}}. \tag{1}$$

Let $C_{\text{SR}_i}, C_{\text{RR}}$ denote the achievable transmission rate from source RRH to the first selected relay node R_i and the achievable transmission rate between two relay nodes. Let C_{SD} denote the average achievable transmission rate from source RRH to the destination application server. Due to the TDMA transmission mode, the total transmitted information W_{tot} during each hop transmission should be coherent

$$W_{\text{tot}} = C_{\text{SR}_i} \cdot T_{\text{SR}_i} = C_{\text{RR}} \cdot T_{\text{RR}} = C_{\text{SD}} \cdot T_{\text{tot}}. \tag{2}$$

According to (1) and (2), the data rate $C_{\text{SD}}, C_{\text{SR}_i}, C_{\text{RR}}$ satisfy

$$\frac{1}{C_{\text{SD}}} = \frac{1}{C_{\text{SR}_i}} + \frac{N-i}{C_{\text{RR}}}. \tag{3}$$

B. Antenna and Path Loss Model

We assume that both RRH and relays are equipped with Uniform Linear Array (ULA), analysis for other antenna array structure such as Uniform Plenary Array (UPA) can be conducted in similar manner. The ULA is consist of identical directional antenna element and thus can create an unidirectional array field pattern. At the RRH side, the array is downtilt with 90°, i.e., the array is perpendicular with the railway track and the antenna aperture is aligned with the same direction along the railway track as in Fig. 1. At the relay node side, there will be two back-to-back arrays with 90° and 270° downtilt, which facilitates the transmission to the adjacent relays nodes on both left and right. For the sake of simplicity, we adopt the same assumption in [1] such that anolog beamforming is precluded at both RRH and relay nodes. However, if considering antennas with dynamic analog beams, the weight coefficients for antenna elements combination are defined by the beam vectors. The arrays field pattern for one port after analog beamforming can be calculated with formula $(8.1-4,5)$ in [13].

According to [12], the antenna element radiation pattern for both RRH and relay nodes in local sphere coordinate system reads

$$\begin{aligned}
A(\theta,\phi) &= -\min\{-\lfloor A_{\text{E,V}}(\theta) + A_{\text{E,H}}(\phi)\rfloor, A_m\} \\
A_{\text{E,V}}(\theta) &= -\min\left[12\left(\frac{\theta-90^\circ}{\theta_{3\text{dB}}}\right)^2, SLA_v\right] \\
A_{\text{E,H}}(\phi) &= -\min\left[12\left(\frac{\phi}{\phi_{3\text{dB}}}\right)^2, A_m\right],
\end{aligned}$$

where $\theta_{3\text{dB}} = 65^\circ, SLA_v = 30\text{dB}, \phi_{3\text{dB}} = 65^\circ, A_m = 30\text{dB}$. The maximum directional gain of an antenna element is $G_{\text{E,max}} = 8\text{dBi}$.

Consider the ULA has N_t antenna element with equal spacing of $\frac{\lambda}{2}$, the normalized array factor is

$$\text{AF}(\theta) = \frac{\sin\left(\frac{N_t \pi \cos\theta}{2}\right)}{N_t \sin\left(\frac{\pi\cos\theta}{2}\right)}.$$

Therefore, the array directive gain $G(\theta,\phi)$ for a given direction (θ,ϕ) in local sphere coordinate system can be denoted as

$$G(\theta,\phi) = \text{AF}(\theta)\cdot\left(A(\theta,\phi) + G_{\text{E,max}}\right).$$

Regarding the path loss model, according to [12], the distance between RRH and the railway track is 5m, both the RRH and the relays have the height of 2.5m. Given this deployment with equal height RRH and relay nodes, we adopt a path loss model (in dB) which is the same as V2V links in highway [14]

$$P_{\text{PL}}(d) = 32.4 + 20\log 10(d) + 20\log 10(f_c), \quad (4)$$

where d is the distance between the transmit and the receive nodes in meters, f_c is the carrier frequency in GHz.

III. Optimal Relay selection for the Multi-hop Relaying System

A. Receive Signal Strength calculation

Assume that the distance between two adjacent relay nodes is L, let the distance along the railway track between the RRH and the first relay node be x, therefore the distance along the railway track between the RRH and the ith relay can be denoted as $d_{x,i} = x + (i-1)L$. As is shown in Fig.3, since the distance between the RRH and the railway track is d_s and both the RRH and the relays have the height of h, the distance between RRH and the ith relay is $d_{\text{SR}_i} = \sqrt{d_s^2 + (x+(i-1)L)^2}$.

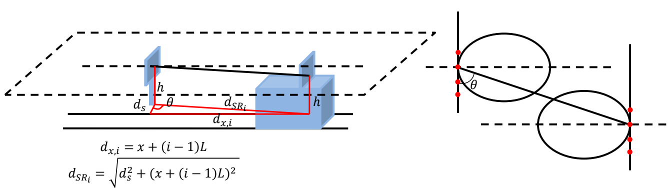

Fig. 3: Left: Geometry for the multi-hop transmission between RRH and selected ith relay. Right: Illustration of ULA geometry and antenna diagram at RRH and selected relay.

Assume that the transmit power in milliwatt (mW) for both the RRH and each relay node over the total transmission bandwidth is P. The receiving power $P_{\text{RX,SR}_i}$ for the selected relay in dBm can be obtained with the following link budget calculation. For simplicity, the transmit and receive coax loss, connector loss, and the miscellaneous losses such as fading margin and body loss have been omitted.

$$P_{\text{RX,SR}_i} = 10\log_{10}(P) + G_{\text{TX,SR}_i} + G_{\text{RX,SR}_i} - P_{\text{PL}}(d_{\text{SR}_i}), \quad (5)$$

where $G_{\text{TX,SR}_i}, G_{\text{RX,SR}_i}$ denote

$$G_{\text{TX,SR}_i} = G(\theta,\phi), G_{\text{RX,SR}_i} = G(\theta,\phi),$$
$$\theta = 90° - \arctan\frac{5}{x+(i-1)L}, \phi = 0°.$$

The path loss $P_{\text{PL}}(d_{\text{SR}_i})$ can be calculated according to (4). It can be noticed that the receiving power $P_{\text{RX,SR}_i}$ is merely a function of the transmitting power P, the selected relay i and the distance x along the railway track between the RRH and the first relay.

The receiving power $P_{\text{RX,RR}}$ for relay to relay transmission in dBm can be achieved in similar manner

$$P_{\text{RX,RR}} = 10\log_{10}(P) + G_{\text{TX,RR}} + G_{\text{RX,RR}} - P_{\text{PL}}(L), \quad (6)$$

where $G_{\text{TX,RR}}, G_{\text{RX,RR}}$ denote

$$G_{\text{TX,RR}} = G(\theta',\phi'), G_{\text{RX,RR}} = G(\theta',\phi'),$$
$$\theta' = 90°, \phi' = 0°.$$

It should be noticed that the receiving power $P_{\text{RX,RR}}$ is merely a function of the transmitting power P.

B. Optimal Relay Selection for the Multi-hop Transmission

Assume that the multi-hop transmission occupies a bandwidth of B. Let NF denote the noise figure and KT denote the thermal noise power per Hz at room temperature. The output noise floor for the system in dBm reads

$$P_{\text{N}} = \text{NF} + \text{KT} + 10\log_{10}(B). \quad (7)$$

According to Shannon's formula, the achievable transmission rate $C_{\text{SR}_i}, C_{\text{RR}}$ (in bit/s/Hz) are denoted as

$$C_{\text{SR}_i} = \log_2\left(1 + 10^{\frac{P_{\text{RX,SR}_i} - P_{\text{N}}}{10}}\right) \quad (8)$$

$$C_{\text{RR}} = \log_2\left(1 + 10^{\frac{P_{\text{RX,RR}} - P_{\text{N}}}{10}}\right). \quad (9)$$

According to (3), given the transmitting power P for the RRH/relay nodes and the instantaneous train position x of the first relay node along the railway track, we can maximize the average data rate for the multi-hop transmission by selecting the optimal relay node

$$\begin{aligned} \max_{i} \quad & \left(\frac{1}{C_{\text{SR}_i}} + \frac{N-i}{C_{\text{RR}}}\right)^{-1} \\ \text{s.t.} \quad & C_{\text{SR}_i} \quad \text{defined in (8)} \\ & C_{\text{RR}} \quad \text{defined in (9)} \\ & P_{\text{RX,SR}_i} \quad \text{defined in (5)} \\ & P_{\text{RX,RR}} \quad \text{defined in (6)} \\ & P_{\text{N}} \quad \text{defined in (7)} \\ & 1 \le i \le N, \quad i \in \mathbb{N}. \end{aligned} \quad \text{(P)}$$

Problem (P) is a non-linear integer programing, a full search through all possible relay candidates can be used to select the optimal relay. By solving the aforementioned problem, the optimal multi-hop transmission scheme can be found, given the current location of the train and the transmitting power at the RRH and relays.

IV. Simulation Results

In this section, we provide simulation results for the multi-hop transmission that achieves the best average transmission rate with different train location and under different transmitting power regime. The simulation parameters are listed in table I.

N	L	d_s	h	f_c	B	NF	KT
8	25m	5m	2.5m	30GHz	40MHz	10dB	−174dBm/Hz

TABLE I: Simulation parameters for the multi-hop transmission for train radio.

Consider both RRH and relays are equipped with ULA containing $N_t = 4$ antenna elements, we plot from Fig. 4

to Fig. 6 the average transmission rate as a function of the first relay position x, when 1 to 8-hop relaying are used. The evaluations are performed under low, medium and high transmit power regimes, which correspond to the RRH/relay transmitting power of 0.1mW, 10mW and 1000mW. According to [12], the maximal distance between two adjacent RRHs is 580m. Given the configuration of $N = 8$ cabin train with inter-relay distance $L = 25$m , we vary x from 1m to 380m so as to keep the train under the coverage of one RRH.

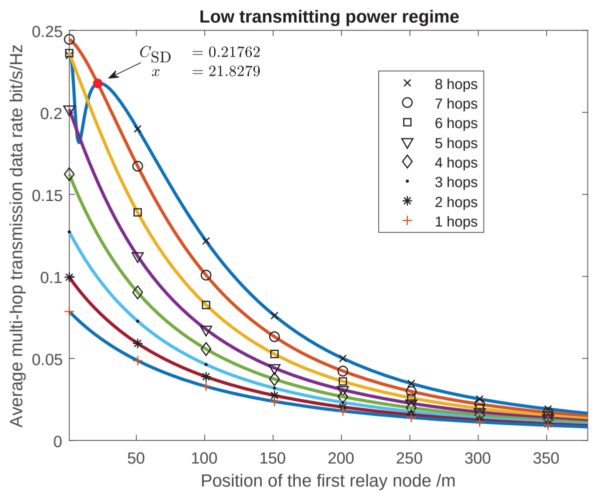

Fig. 4: Average transmission rate vs. first relay position for $1-8$ hop relaying transmission, low transmitting power regime considered.

In Fig. 4, it reveals that in low transmitting power regime, it is more favorable to perform multi-hop transmission and benefit from the shorter communication range and lower path loss in multi-hop relaying so as to compensate the low transmitting power. Furthermore, it should be noticed that when the train is close to the RRH, due to the directivity of the antenna array diagram, a 7-hop transmission leads to the best average data rate. When the distance is larger than 21.8279m , the best transmission strategy will be switched to a 8-hop relaying.

When the system is operating on a medium transmitting power regime, the situation is much more complicated. Fig. 5 exhibits that regarding the position of the train, different multi-hop schemes can be chosen so as to maximize the average data rate. There are four crossover points at 9.2042m, 34.204m, 59.2038m, and 84.2037m. The optimal multi-point relaying scheme will be changed from 4-hop to 5-hop , 5-hop to 6-hop, 6-hop to 7-hop and finally 7-hop to 8-hop relaying, respectively.

Fig. 6 shows that in high transmission power regime, regardless of the train position, it is preferred to have single hop transmission rather than multi-hop relaying.

We now fix the distance from the RRH to the first relay of the train and plot the average transmission rate as a function of the transmitting power. From Fig. 7 to Fig. 9, three schemes with small, medium and large distance between RRH and the

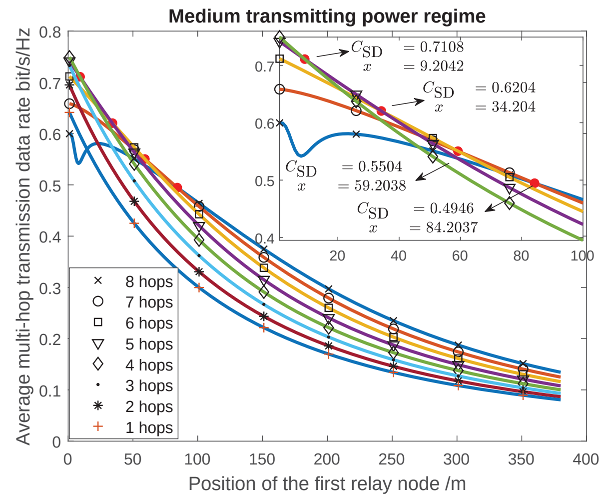

Fig. 5: Average transmission rate vs. first relay position for $1-8$ hop relaying transmission, medium transmitting power regime considered.

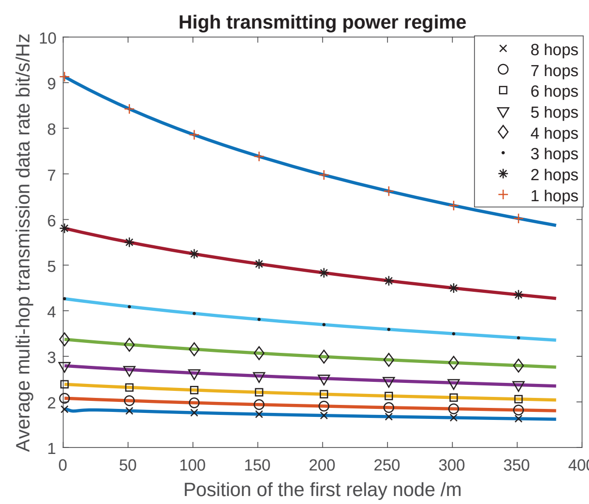

Fig. 6: Average transmission rate vs. first relay position for $1-8$ hop relaying transmission, high transmitting power regime considered.

train are considered, which correspond to the configuration of $x = 50, 200, 350$m respectively. We can observe that as the transmitting power is gradually increasing, fewer hops relaying should be used. Indeed, the optimal multi-hop transmission schemes that maximize the average transmission rate changes eventually from 8 hops relaying to single hop transmission at the cross point transmitting power illustrated in the figures.

V. Conclusion

In this paper, we analyze the multi-hop relaying for train radio system which operates on mmWave band. Optimal multi-hop transmission scheme that maximize the average data rate can be calculated according to the instantanous train relay position and the transmitting power for the RRH and relay

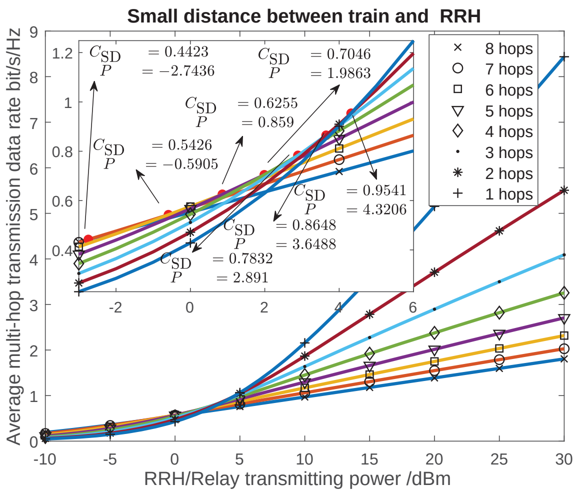

Fig. 7: Average transmission rate vs. transmitting power for $1-8$ hop relaying transmission, small distance between train and RRH considered.

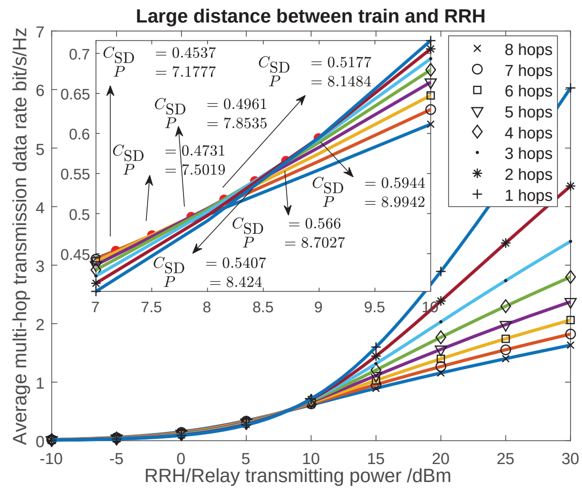

Fig. 9: Average transmission rate vs. transmitting power for $1-8$ hop relaying transmission, large distance between train and RRH considered.

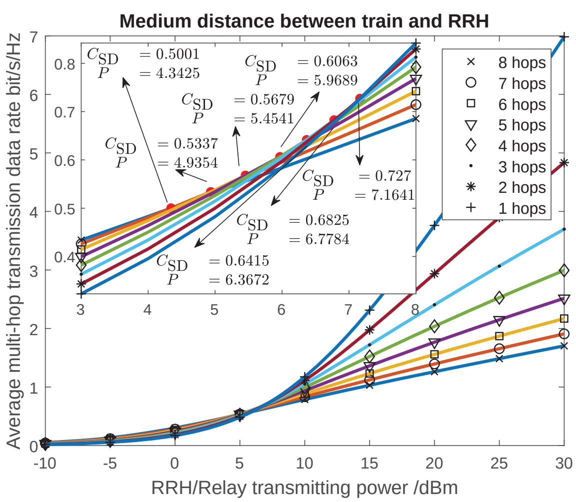

Fig. 8: Average transmission rate vs. transmitting power for $1-8$ hop relaying transmission, medium distance between train and RRH considered.

nodes. As the transmitting power increases, it becomes more beneficial to have less multi-hop transmission. Due to antenna directivity, the optimal relaying scheme can be complicated when the RRH is close to the train. In low and medium transmitting power regime and RRH-train distance range, performing muti-hop transmission can be more advantageous and different hops relaying schemes can dominate the optimal data rate.

References

[1] "TR38.913: Study on scenarios and requirements for next generation access technologies," Technical Specification Group Radio Access Network, 3rd Generation Partnership Project (3GPP), Tech. Rep., June 2018.

[2] F. Hasegawa, A. Taira, H. Nishimoto, A. Okazaki, A. Okamura, G. Noh, B. Hui, J. Lee, and I. Kim, "3GPP standardization activities in relay based 5G high speed train scenarios for the SHF band," in *Proc. Conference on Standards for Communications and Networking (CSCN)*, 2017.

[3] S. Singh, F. Ziliotto, U. Madhow, E. Belding, and M. Rodwell, "Blockage and directivity in 60 GHz wireless personal area networks: from cross-layer model to multihop MAC design," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 8, pp. 1400–1413, October 2009.

[4] D. Gunduz, M. A. Khojastepour, A. Goldsmith, and H. V. Poor, "Multi-hop mimo relay networks: diversity-multiplexing trade-off analysis," *IEEE Trans. Wireless Commun.*, vol. 9, no. 5, pp. 1738–1747, 2010.

[5] H. Q. Ngo and E. G. Larsson, "Linear multihop amplify-and-forward relay channels: Error exponent and optimal number of hops," *IEEE Trans. Wireless Commun.*, vol. 10, no. 11, pp. 3834–3842, 2011.

[6] T. K. Vu, C.-F. Liu, M. Bennis, M. Debbah, and M. Latva-Aho, "Path selection and rate allocation in self-backhauled mmWave networks," in *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, 2018.

[7] D. Hu, J. Wu, and P. Fan, "Minimizing end-to-end delays in linear multihop networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 8, pp. 6487–6496, 2015.

[8] J. Yao, X. Zhou, Y. Liu, and S. Feng, "Secure transmission in linear multihop relaying networks," *IEEE Trans. Wireless Commun.*, vol. 17, no. 2, pp. 822–834, 2017.

[9] N. Abuzainab and C. Touati, "Multihop relaying in millimeter wave networks: A proportionally fair cooperative network formation game," in *Proc. IEEE Vehicular Technology Conference (VTC2015-Fall)*, 2015.

[10] S. Scott, J. Leinonen, P. Pirinen, J. Vihriala, V. Van Phan, and M. Latva-aho, "A cooperative moving relay node system deployment in a high speed train," in *Proc. IEEE Vehicular Technology Conference (VTC Spring)*, 2013.

[11] J. D. O. Sánchez and J. I. Alonso, "A two-hop MIMO relay architecture using LTE and millimeter wave bands in high-speed trains," *IEEE Trans. Veh. Technol.*, vol. 68, no. 3, pp. 2052–2065, 2018.

[12] "TR38.802: Study on scenarios and requirements for new radio access technology physical layer aspects," Technical Specification Group Radio Access Network, 3rd Generation Partnership Project (3GPP), Tech. Rep., September 2017.

[13] "TR36.873: Study on 3D channel model for LTE," Technical Specification Group Radio Access Network, 3rd Generation Partnership Project (3GPP), Tech. Rep., December 2017.

[14] "TR37.885: Study on evaluation methodology of new Vehicle-to-Everything(V2X) use cases for LTE and NR," Technical Specification Group Radio Access Network, 3rd Generation Partnership Project (3GPP), Tech. Rep., December 2018.