Mitigation of Doppler Effect in High-speed Trains through Relaying

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***Abstract*—Provisioning high quality of service to the users on board of high-speed trains is a challenge due to strong signal attenuation of carriage, frequent and simultaneous handovers of users, and/or Doppler effect. In this paper, we propose a novel concept of data relaying via a moving relay, such as vehicle on a nearby road, to mitigate a negative impact of Doppler effect. To this end, we propose a moving relay selection algorithm considering not only the channel quality between the train, base station and the moving relays, but also a relative speed and a direction of movement. This allows us to mitigate the negative impact of Doppler effect on the communication capacity by reducing the relative speed between the train and the base station via the intermediate relay moving in the same or similar direction as the train. The simulation results demonstrate that the proposed concept is able to boost the communication capacity by up to 140% with respect to no relaying.**

***Index Terms*—high-speed trains, moving relay, relaying, Doppler effect, relay selection**

I. Introduction

During the last decade, we have been witnessing a rapid development of high-speed railway (HSR) all around the globe [1][2]. The provisioning of high quality of service (QoS) to the users on board of the HSR is, however, a challenge since [3]: i) the user equipment (UE) located on board of the train experiences a significant signal attenuation loss caused by the carriage, ii) frequent and simultaneous handover of all UEs on board resulting in a lot of signaling overhead imposed on the network, or iii) severe Doppler effect resulting from a high relative velocity between the UEs on board of the train and a base station (BS).

In order to improve QoS and performance of the users in high-speed trains, various mobility and radio resource management techniques are employed. In [4], the authors propose a novel handover scheme for LTE-Railway (LTE-R) modifying a handover decision to prevent late handovers. The authors in [5] suggest improved interference alignment algorithm with users' mobility prediction. In both above-mentioned papers the UEs communicate with the BS directly. Thus, the challenges discussed earlier are not fully addressed, as the UEs still experience strong signal attenuation due the carriage, each UEs perform handover on its own, and Doppler effect is still the issue.

A convenient way to address the first two challenges is to deploy moving relay nodes (MRNs) attached to the train rooftop, as initially proposed by IEEE 802.16j standard [6] and later on introduced also by 3GPP organization [7]. For example, the authors in [8] analyze the performance gain and benefits of the MRNs with respect to a direct mode, i.e., the mode where the MRNs are not used and the UEs on board of train communicate directly with the BS. The authors in [9] propose a seamless handover scheme deploying two MRNs on the train, one at the front of the train and the second one at the train's rear. Consequently, one MRN can perform handover while the other MRN can still serve the UEs on board. The service continuity during handover of the MRN is also considered in [10], where detailed performance analysis of handover mechanism based on queuing theory is provided.

The authentication problem of group of UEs performing simultaneous handovers while connected through the MRN is addressed in [11][3]. In [11], the authors propose to aggregate authentication messages from all MRNs on the same train so that the authentication process is done simultaneously for all UEs. The paper [3] proposes the authentication of MRNs to be performed in advance using software defined networking controller to avoid handover interruption of the UEs on board.

Besides the challenge related to the handovers, some studies focus on various radio resource management techniques to improve the performance of the users exploiting the HSR. The minimization of transmission power of the BSs and the MRNs in downlink is delivered in [12]. The objective of the authors is to minimize power consumption of the MRNs while still ensuring QoS to the UEs via a dual decomposition method. Similarly, the energy-efficient power allocation for downlink while considering buffer size constraints at individual transmission nodes is proposed in [13]. To provide adequate services to the users in high speed trains, a use of millimeter waves (mmWaves) is suggested in [14][15].

Although all the previous papers address, in various degree, the first two challenges, the problem of Doppler effect cannot be easily solved by the MRNs only. The Doppler effect, however, can significantly degrade the communication capacity and, thus, affect QoS provided to the users [16].

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Even though the Doppler effect can be efficiently mitigated by various mechanisms serving specifically for this purpose, such as inter-carrier interference mitigation by iterative approaches or complex channel prediction [16], this is valid only for limited velocities. As demonstrated in [17], the Doppler effect is practically eliminated for velocities "only" up to 130 km/h. Still, in case of the high-speed trains moving easily with a speed over 300 km/h, the Doppler effect causes severe inter-carrier interference (in case of multicarrier modulation) or late acquisition of channel state information resulting in severe degradation in the communication capacity offered to the users on board [16].

During the last decade, the relaying has been found as an attractive option to boost the performance of mobile networks. Besides the MRNs, as discussed above, the mobile operators can also utilize the fixed relay nodes, flying relay stations [18], or even the UEs can relay data for other UEs [19]. Consequently, considering the advancements in intelligent transportation systems (ITS) and in vehicle to everything (V2X) communication [20], it is reasonable to assume that even the vehicles themselves can act as the relaying stations, labeled in the rest of the paper as vehicular relaying node (VRN). Hence, in this paper, we leverage the fact that the MRN(s) can exploit the VRN(s) moving along the roads or highways. The natural and obvious benefit of the VRN adopted to act as a go-between the BS and the MRN is an increased capacity or spectral efficiency, as the distance between the transmitter and the receiver is effectively reduced. Nevertheless, the ***fundamental idea and novelty*** of this paper is based on the fact that ***if the VRN is moving in the same or similar direction*** as the train, the ***relative velocity between the MRN(s) and the VRN is cut down*** when compared to the relative velocity between the MRN and the BS. Consequently, the negative impact of Doppler effect can be mitigated resulting in a higher communication capacity and/or spectral efficiency between the train and the base station.

The contribution of our paper is the following:

- We ***propose*** and ***investigate a relaying concept***, where the capacity of the UEs traveling on board of high-speed trains ***is enhanced by intermediate moving relays*** helping to ***suppress*** the Doppler effect.
- We ***propose*** low-complexity yet effective ***relay selection algorithm*** that considers not just the channel quality between individual transmission hops (i.e., the channel quality between the MRN and the VRNs and the channel quality between the MRN and the BS), but also a negative impact of the high velocity is taken into account. Thus, the ***VRNs moving in the similar direction as the train*** are preferably selected. Besides, we also ***discuss practical issues*** and suggest how to tackle them.
- We ***investigate the performance*** of the proposed concept by means of the simulations and analyze the results for both half-duplex and full-duplex VRNs.

The rest of the paper is organized as follows. The next section introduces the system model and formally defines the problem. Section III describes the proposed relaying concept, outlines the proposed relay selection, and also discusses practical implementation issues. Then, the simulation scenario and the simulation results are presented in Section IV and Section V, respectively. The last section provides our conclusions and contemplates future works.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider one MRN mounted on the train communicating either directly with the BS or through one of the N VRN stations, located between the BS and the MRN (see Fig. 1). The communication links between the MRN and the BS, the MRN and the VRN, and the VRN and the BS are facilitated by in-band communication exploiting radio resources of the mobile network. The UEs communicate with the MRN via out-band communication, such as WiFi similarly as in [10], where the MRN is connected to WiFi router that distributes WiFi signal through multiple access points placed at strategic locations throughout the train.

We further assume the bottleneck in the communication between the UE and the BS is the part between the BS and the MRN while the capacity provided by high-speed WiFi (e.g., by 802.11n, 802.11ac, etc.) is always higher than the capacity between the BS and the VRN. Thus, we focus only on the maximization of the capacity between the BS and MRN. To this end, if the MRN communicates directly with the BS, the capacity per one Hz (i.e., the spectral efficiency) of the communication link between the BS and the MRN in downlink is expressed as:

$$c_{bm} = log_2 \left(1 + \frac{g_{bm} p_b}{\sigma}\right), \quad (1)$$

where g_{bm} is the channel gain between the BS and the MRN, p_b is the transmission power of the BS, and σ is the noise spectral density.

In case the n-th VRN acts as a go-between the BS and the MRN, the channel capacity of the MRN depends on both the first communication hop (i.e., the hop between the BS and the n-th VRN) and the second communication hop (i.e., the hop between the n-th VRN and the MRN). We investigate the performance of the system for two relaying cases: i) the VRNs

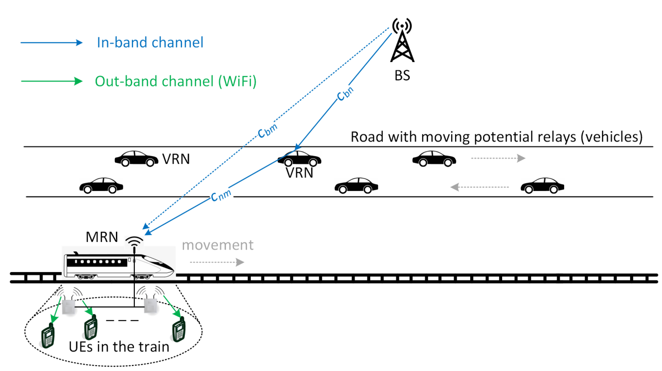

Fig. 1: Illustrative example of the system model.

operate in half duplex or ii) the VRNs employ full duplex as expected in 6G networks.

In case of half duplex, the data transmission between the BS and the MRN is done within one time slot with a duration of t_s. The time slot is further divided into two parts. In the first part, with a duration of $t_1 < t_s$, the VRN receives data from the BS. In the second part of the time slot, with a duration $t_2 = t_s - t_1$, the VRN retransmits data to the MRN. To make the half duplex relaying efficient, we derive t_1 so that the capacity of the first hop between the BS and n-th VRN (c_{bn}) and the capacity of the second hop between the n-th VRN and MRN (c_{nm}) are equal. Hence, none of the communication hops acts as a bottleneck. Consequently, t_1 is calculated as:

$$t_i = t_s \frac{c_{nm}}{c_{bn} + c_{nm}}, \tag{2}$$

Then, the channel capacity per Hz of the first hop between the BS and the n-th VRN in case of half duplex is calculated as:

$$c_{bn}^{HD} = t_1 log_2 \left(1 + \frac{g_{bn} p_b}{\sigma}\right), \tag{3}$$

where g_{bn} is the channel gain between the BS and the n-th VRN. Similarly, the channel capacity per Hz at the second communication hop, that is, between the n-th VRN and the MRN is expressed as:

$$c_{nm}^{HD} = (t_s - t_1)\, log_2 \left(1 + \frac{g_{nm} p_n}{\sigma}\right), \tag{4}$$

where g_{nm} is the channel gain between the n-th VRN and the MRN and p_n is the transmission power of the n-th VRN.

In case of full duplex, the MRN is able to receive and transmit data simultaneously. We assume full duplex relaying without self-interference, that is, without the interference caused by the transmission part of the VRN to its receiving part, as the self-interference can be efficiently mitigated (see, e.g., [21]). Then, the channel capacity per Hz on the first and second hop is calculated as:

$$c_{bn}^{FD} = log_2 \left(1 + \frac{g_{bn} p_b}{\sigma}\right), \tag{5}$$

$$c_{nm}^{FD} = log_2 \left(1 + \frac{g_{nm} p_n}{\sigma}\right). \tag{6}$$

While the overall channel capacity provided to the MRN in case of the half duplex is equal to c_{bn}^{HD} (or c_{nm}^{HD}), the overall capacity for the full duplex transmission between the BS and the MRN is calculated as min(c_{bn}^{FD}, c_{bn}^{FD}), since one of the hop always acts as bottleneck. The relaying gain if the MRN exploits the n-th VRN (using either half duplex or full duplex relaying) is, then, calculated as:

$$G_n = \min\left(c_{bn}^{FD/HD}, c_{nm}^{FD/HD}\right) - c_{bm}. \tag{7}$$

Both the capacity and the relaying gain is degraded by Doppler effect if the relative velocity between the transmitter and the receiver (v_{tr}) is high. In this paper, the impact of Doppler effect on the capacity is modeled according to [17], where the authors show roughly a linear decrease in the capacity for v_{tr} higher than 130 km/h. Hence, the degradation δ_{tr} due to Doppler effect between any transmitter and any receiver is calculated as:

$$\delta_{tr} = \begin{cases} 1 & v_{tr} \leq 130 \\ 1.13 - 0.001 v_{tr} & v_{tr} > 130 \end{cases} \tag{8}$$

where v_{tr} is a relative velocity between the transmitter and the receiver.

The objective of our work is to exploit the VRNs and to select a suitable VRN dynamically considering the speed and direction of the VRNs with respect to teh train to maximize the relaying gain between the BS and the MRN. Hence, the objective is formulated as:

$$\boldsymbol{X} = \underset{x_n}{\text{argmax}} \quad x_n G_n \\ \text{s.t.} \quad \text{a)} \sum_n x_n \leq 1 \tag{9}$$

where x_n is association parameter specifying whether the MRN exploits the n-th VRN ($x_n = 1$) or not ($x_n = 0$) and the constraint limits the number of VRNs used by the MRN to 1.

III. Proposed Relaying Concept

This section first describes the fundamental principal of the proposed concept and introduces the proposed relay selection. Then, we also discuss the potential practical issues and their solution.

A. Fundamental idea

Conventional techniques for the relay selection maximizing the capacity or spectral efficiency assume only the channel quality between individual nodes. As long as the relative speed between the transmitter and the receiver is below critical value (i.e., $v_{tr} < 130$), this approach is fairly sufficient. Nevertheless, high speed train usually moves with much higher velocity than this critical value resulting in a significant degradation in the capacity, since the experienced capacity between the source (base station) and the relay (vehicle) and between the relay and the destination (train) is strongly affected by mutual speed of individual nodes due to Doppler effect.

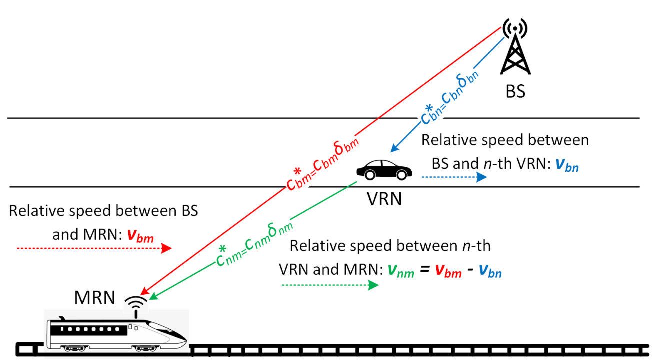

Fig. 2: Fundamental idea of the proposed concept.

Thus, the fundamental idea of the proposal is to exploit the VRN(s) as an intermediate relaying nodes between the BS and the MRN, as illustrated in Fig. 2. Provided that the VRN is moving in the same or similar direction, the relative velocity between the VRN and MRN is lower than the relative velocity between the BS and the MRN. Consequently, the negative impact of Doppler effect on the communication capacity is decreased in the process as well.

In order to determine the relaying gain introduced by any potential VRN, let us first update the calculation of c_{bm}, c_{bn}, and c_{nm} while considering also the potential degradation in the capacity caused by the Doppler effect as follows:

$$c^*_{bm} = c_{bm}\delta_{bm}, \tag{10}$$

$$c_{bn}* = c_{bn}\delta_{bn}, \tag{11}$$

$$c^*_{nm} = c_{nm}\delta_{nm}, \tag{12}$$

where δ_{bm}, δ_{bn}, and δ_{nm} represent the degradation in the channel capacity between the BS and the MRN, between the BS and the n-th VRN, and between the n-th VRN and the MRN, respectively.

Obviously, the MRN should exploit one of the VRN only if the capacity provided by the VRN is higher than the capacity without VRN (i.e., c_{bm}). Thus, the potential relaying gain if the MRN exploits the n-th VRN is calculated as:

$$G^*_n = \begin{cases} 0 & \min\left(c^*_{bn}, c^*_{nm}\right) \leq c^*_{bm} \\ \min\left(c^*_{bn}, c^*_{nm}\right) - c^*_{bm} & \min\left(c^*_{bn}, c^*_{nm}\right) > c^*_{bm} \end{cases} \tag{13}$$

B. Proposed relay selection

In this section, we devise a greedy relay selection mechanism that considers not just the instantaneous channel quality of individual links, but also take the potential degradation of channel capacity due to Doppler effect into account.

The proposed relay selection is described by Algorithm 1. In an initial stage, the MRN is supposed to communicate directly with the BS, thus x_n is initially set to 0 for all n (see line 1 in Algorithm 1). Then, the algorithm continuously estimates whether the MRN should use a help of one of the eligible VRNs or if it is more beneficial to stay attached directly to the BS. To this end, we estimate c^*_{bm}, c^*_{bn}, and c^*_{nm} according to (10), (11), and (12), respectively (line 3). Afterward, the relaying gain provided by each potential VRN (G^*_n) is calculated by means of (13) (line 4). In the next step, Algorithm 1 checks if at least one VRN is able to provide a higher capacity than the direct communication of the MRN with the BS (i.e., if $\max(G^*_n) > 0$) (line 5). If this is the case, the n-th VRN yielding the highest gain is selected as the current relay (line 6) indicated by setting x_n to 1 (line 7). Otherwise, x_n is set to 0 for all VRNs (line 8). The purpose of this step is to ensure that if the selected VRN is not able to provide a positive gain (i.e., if G^*_n is negative, the MRN stops exploiting this particular VRN. The whole process is repeated continuously over time in a predefined time intervals (in our case we suggest each time slot t_s, but the periodicity is a subject of further optimization left for future research due to space limitation).

Algorithm 1 Proposed algorithm for relay selection

1: Set $x_n = 0,\ \forall n$
2: **for** each t_s **do**
3: Estimate c^*_{bm}, c^*_{bn}, c^*_{nm}, $\forall n$
4: Calculate $G^*_n, \forall n$
5: **if** $\max(G^*_n) > 0$ **then**
6: $\{n\} \leftarrow \max(G^*_n)$
7: set $x_n = 1$ (assoc. n-th VRN with MRN)
8: **else** set $x_n = 0,\ \forall n$
9: **end if**
10: **end for**

C. Discussion of practical issues

In order to implement the proposed concept into the real networks, several practical issues should be addressed. First critical issue is the estimation of channel quality between individual nodes (i.e., between the BS and the VRNs and between the VRNs and the MRN). Considering the known trajectory of both the MRN and the VRNs that can potentially act as the relays, the channel quality can be determined in advanced by some existing prediction techniques. For example, the channel estimation can be facilitated by the deep neural networks (DNN) as proposed in [22], where the channel quality is estimated accurately enough just knowing the channel information to the BSs. This way, the channel quality can be estimated frequently without any additional signaling overhead besides measurement and reporting of the channel quality to the BS, as performed in the mobile networks notwithstanding.

The second important aspect affecting the relay selection is to determine the direction and the velocity of the MRN and the VRNs to estimate a possible degradation in the capacity due to Doppler effect. Again, the direction of the MRN and the VRNs is easily predictable, e.g., by the evolution of the signal to noise ratio (SNR) between the moving node (MRN or VRN) and the BS. The velocity can be estimated in the similar way, that is, from the slope of the SNR decrease/increase. Besides, the velocity can be measured by GPS and reported to the BS by individual nodes, since the MRN and the VRNs move in outdoor environment with GPS signal typically available.

The third practical aspect is to provide reasonable incentives for the VRNs to act as the relays in the first place. In fact, there are several possible ways to motivate the VRNs to help the MRN. We assume that the VRNs are motivated to relay data by commonly adopted incentives, e.g., based on virtual currency or credits [23]. Still, other incentive methods can be adopted and their effectiveness and suitability can be seen as the future research direction.

The last aspect is to determine who is in charge of the relay selection. Since the prediction of channel quality and the estimation of speed/direction of the MRN and VRNs can be accomplished by the BS, it is convenient to make the relay selection at the BS as well. Still, in theory, the relay selection can be done also by the MRN itself if the required information is available to it.

IV. Simulation Scenario

We consider the simulation scenario as depicted in Fig. 3, where the train (i.e., MRN) moves along the straight line. The railway along which the train moves is located 2500 m far from the BS. The MRN is served either directly by the BS or through the VRN if the capacity of the MRN is improved. Whether the MRN should use or change current VRN is evaluated in every simulation step corresponding to the time slot with a duration t_s set to 10 ms.

The simulations are done for 1000 drops, during each drop, the train moves along the railway from the starting point (0 m) to the end point (5000 m). For each simulation drop, we randomly generate: i) the number of roads between the railway and the BS (between 1 and 3 roads are assumed), ii) the distance between each road and the railway (varying from 200 m to 2300 m), and iii) the starting point, direction, and speed of each VRN that is willing to act as the relay for the MRN. Then, the results are average out over all simulation drops.

The channel model used in the simulations is based on 3GPP for macrocell outdoor environment [24].

We evaluate the performance considering 10 to 100 VRNs willing to relay data. Besides, we also investigate the effect different trains velocity varying between 150 and 500 km/h.

The performance is investigated and compared for three following schemes:

- *No relaying* – The MRN always communicate directly with the BS without any help from the VRNs. This corresponds to state-of-the-art solution considering MRN.
- *VRN: channel-based relay selection (RS)* – The MRN exploits the proposed concept of the VRN, but the VRN selection is done only according to state-of-the-art approach based on the channel quality between individual nodes while moving direction and speed of the VRNs are not considered.
- *VRN: proposed RS* – The MRN can exploit the VRN that is selected according to Algorithm 1 considering also the moving direction and speed of individual VRNs.

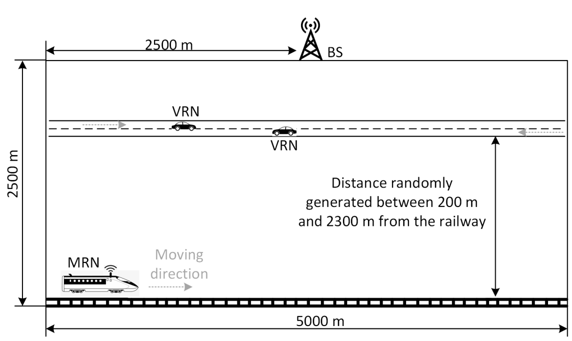

Fig. 3: Simulation scenario.

TABLE I: Parameters and settings for simulations

Parameter	**Value**
Simulation area	5000x2500 m
Distance between railway and BS	2500 m
Distance between railway and highway	200-2300 m
Number of roads between train and BS	1-3
Number of eligible VRNs	10-100
Train velocity	150-500 km/h
Vehicle velocity	80-150 km/h
Noise spectrum density	-174 dBm/Hz
Time simulation step (t_s)	10 ms
Number of simulation drops	10000

All the simulation parameters are summarized in Table I.

V. Simulation Results

Fig. 4 illustrates the impact of train's velocity on the capacity per Hz. Disregarding the evaluated scheme or whether half or full duplex relaying is employed, the capacity is decreasing with an increasing train velocity. This result is expected, as the detrimental effect of Doppler shift becomes more prominent with the increasing train velocity. Further, we can observe that even in case of half duplex relaying, the capacity can be boosted by up to 29.2% and 35.3% considering the proposed VRN with state of the art channel-based and proposed relay selections, respectively, compared to the case without the relaying. Even more significant enhancement in the capacity is accomplished by the proposed VRN concept with the state of the art channel-based relay selection and the proposed relay selection in full duplex as both outperform no relaying by up to 103.1% and 138.9%, respectively. Consequently, especially in case of full duplex relaying, the proposed VRN concept considering both speed and direction of the VRNs is able to notably increase the capacity, i.e., decrease the negative impact of Doppler effect. Still, the whole proposed VRN concept even with the common channel-based relay selection provides an excellent performance compared to no relaying case.

Fig. 5 investigates the impact of different number of available VRNs that are willing to help the MRN. The results illustrates that, although the capacity is slightly increasing with the number of VRNs, it saturates with a higher number of

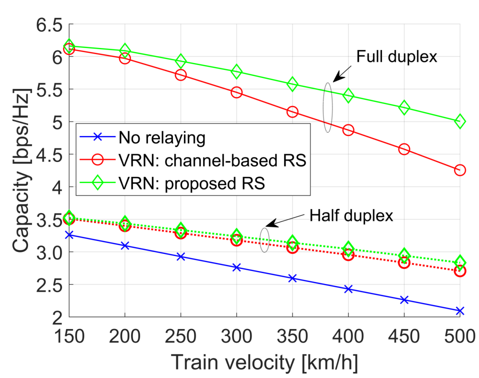

Fig. 4: Spectral efficiency depending on the train velocity, number of potential VRNs is set to 100.

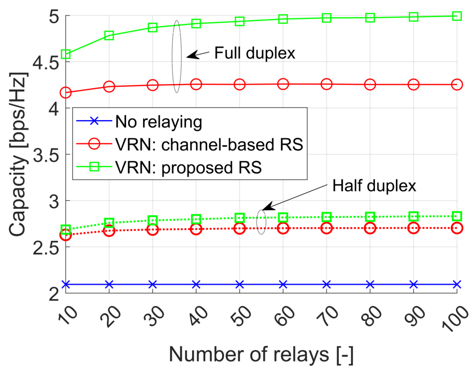

Fig. 5: Spectral efficiency depending on the number of potential relays (i.e., VRNs); train velocity set to 500 km/h.

VRNs (e.g., if there is 60 or more VRNs in case of full duplex relaying with proposed relay selection). Fig. 4 proves that even if the proposed VRN concept uses conventional channel-based relay selection, it provides outstanding performance with respect to no relaying scheme. On top of that, the proposed relay selection is able to further boost the capacity by up to 4.7% and up to 17.4% with respect to the conventional channel-based relay selection exploiting half duplex and full duplex, respectively.

VI. Conclusions

We have proposed a concept exploiting the moving relays facilitated by, for example, vehicles, to improve the communication capacity of the users traveling on board of high speed trains via mitigation of the Doppler effect's negative impact. Furthermore, we have proposed a low complexity algorithm for the selection of suitable moving relay, taking into account not only instantaneous channel quality between all involved nodes (i.e., base station, vehicle, and train), but also moving direction and speed of the vehicles acting as relays between the base station and the train. We have demonstrated that the negative impact of Doppler effect in high speed scenario can be notably suppressed, resulting in a significant boost in the communication capacity.

In the future, the work can be extended by an investigation of the proposed VRN concept also in a train-to-train communication scenario, where the Doppler effect can make the communication between trains infeasible, as the mutual velocities of the trains are added together.

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