A System Level Evaluation of SRTA-PI Transmission Scheme in the High-Speed Train Use Case

Alessandro Grassi, Giuseppe Piro, Gennaro Boggia
Department of Electrical and Information Engineering, *Politecnico di Bari*, Bari, Italy
CNIT, Consorzio Nazionale Interuniversitario per le Telecomunicazioni
{name.surname}@poliba.it

Dinh-Thuy Phan-Huy
Orange Labs Networks
Orange, Chatillon, France
dinhthuy.phanhuy@orange.com

Abstract—**Traditional wireless systems are not able to offer broadband connectivity to very fast vehicles, such as train moving at up to 500 km/h. Channel aging, high penetration loss, frequent handovers, and Doppler spread phenomena, in fact, significantly impair the achieved throughput. Recent research activities related to 5G communication technologies are formulating novel approaches and methodologies able to reach better results. Among them, the Separate Receive and Training Antennas with Polynomial Interpolation is emerging as a promising transmission scheme, able to effectively improve the performance of communication systems based on Multiple-Input Multiple-Output physical layer. It is specifically suitable for high-speed use cases, where the adoption of predictor antennas on moving vehicles may combat the channel aging phenomenon and improve the resulting Channel State Information. Unfortunately, the current scientific literature did not explain the behavior of that solution in concrete situations, yet. To bridge this gap, the work presented herein deeply investigates, from the system level perspective, the performance gain offered by the aforementioned approach with respect to baseline transmission techniques, in various realistic scenarios. Specifically, computer simulations demonstrate how the Separate Receive and Training Antennas with Polynomial Interpolation technique is able to reach a throughput gain up to 100% with respect to the baseline approach, also when the speed is set to 500 km/h.**

Index Terms—**5G, high-speed train, SRTA-PI, system-level performance evaluation**

I. INTRODUCTION

The quality of Internet connectivity in very fast trains (moving at a speed higher than 250 km/h) is significantly impaired by several phenomena, including additional interference due to Doppler spread, higher penetration loss introduced by train cars, scarce validity of Channel State Information (CSI) feedback in Multiple-Input Multiple-Output (MIMO) transmission scheme, and frequent handovers caused by the high velocity [1]. Nevertheless, many people daily commute on trains, and they expect service levels comparable to those that are in stationary environments. Therefore, the *high-speed train* use case is being seriously addressed in the 5th Generation (5G) vision and related research activities [2].

The emerging 5G communication technology is called to offer higher levels of coverage, reliability, energy and spectrum efficiency, while supporting a guaranteed data rate of at least 50 Mbps at speeds up to 500 km/h [3]. Preliminary answers to these challenging issues come from [2] and [3]. These contributions assume that trains can be connected to the cellular network with antenna arrays, deployed on the rooftop and acting as relay nodes for passengers inside. In this way, the impact of the penetration loss can be removed, and advanced techniques can be implemented for addressing the remaining problems without requiring additional complexity for the end user. For instance, the effect of the Doppler spread can be reduced through dedicated waveforms and/or modulation schemes [4]. Handover functionalities can be lightened by avoiding random access procedures, as discussed in [5]. Moreover, to address the channel aging problem, the Separate Receive and Training Antennas with Polynomial Interpolation (SRTA-PI) technique was recently proposed in the context of the EU H2020 FANTASTIC-5G project [6] and described, in its preliminary formulation, in [7]. The current scientific literature, however, does not clearly demonstrate the performance gain offered by SRTA-PI in real scenarios, from the system level perspective.

Based on these premises, the work presented herein provides an important step forward of the current state of the art by deeply investigating the behavior of the SRTA-PI technique in realistic *high-speed train* use cases. To this end, SRTA-PI has been firstly implemented in the LTE-Sim simulation tool [8]. Then, its performance have been evaluated in different operating conditions, by varying the speed of the train, the number of transceivers built on top of the connected train, and the Inter-Site Distance (ISD) of the cellular network. The comparison against the baseline transmission scheme and an ideal communication without impairments due to the high speed is proposed too. Obtained results highlight that SRTA-PI is effectively able to mitigate the channel aging phenomenon, thus reaching a throughput gain up to 100% with respect to the baseline approach, also when the speed is set to 500 km/h. At the same time, they quantify how the remaining issues due to the Doppler spread impact on the overall system performance.

This paper is structured as follows: Section II describes the state of the art on communication strategies at high mobility;

Section III explains the considered SRTA-PI in more detail; Section IV presents simulation assumptions and results; Section V concludes the paper with some final remarks and draws future works.

II. EXISTING SOLUTIONS

Many solutions have been proposed to provide connectivity to trains [1] [9], including new system architectures, on-board signaling to support railway operation, and specific radio technologies.

For instance, Radio-over-Fiber targets railway condition [10] and assumes to deploy a large number of remote antenna units alongside the track, where the antennas are controlled by a base station via a fiber optical link. To reduce costs, these antennas are designed to be as simple as possible, thus moving processing tasks to remote base stations. Radio-over-Fiber supports fast handover procedures and enables the *moving cell* concept (i.e., the frequency reuse pattern moves along with the train at the same speed to avoid inter-frequency handovers). However, its effectiveness depends on the specific technology adopted at the radio interface, and it requires a lot of dedicated infrastructure.

The Leaky Coaxial Cable, proposed in [11], uses a coaxial cable with slits on the outer conductor, which acts as both waveguide and radiating element. These cables can be deployed alongside the tracks, even in places which are normally difficult to reach with wireless links, such as tunnels. While they provide a reliable connection, the overall throughput is limited to 768 kbps, which is far too low for current and future requirements.

Satellite links offered by satellites in geostationary orbit can also be used [12], as they have high geographical coverage and low sensitivity to speed. Unfortunately, they suffer from many other problems: the signal is blocked in bad weather, cities, and tunnels, thus requiring some other complementary technologies to fill the gaps. In addition, latency is quite high.

More recently, some works suggest to use cognitive radio techniques based on Software Defined Radio and artificial intelligence [13] [14]. This approach continuously monitors the radio environment and reconfigures itself when needed, on the basis of previous knowledge or by using genetic algorithms. However, it only covers spectrum allocation, but it does not consider MIMO configurations and the channel aging problem.

Some other technologies, with a more general-purpose attitude, are also considered for the high speed railways scenario. For example Mobile Broadband Wireless Access, defined by IEEE 802.20 specification, was proposed as an alternative to cellular networks, supporting higher data rates and user mobility up to 250 km/h [15]. It was commercialized in some countries, but it did not receive substantial improvements after its first standardization, and became obsolete compared to 3th Generation (3G) and 4th Generation (4G) networks.

WiMax [16] and Long-Term Evolution (LTE) [17] have also been evaluated for connecting fast trains, and they can actually be functional at speeds as high as 350 km/h or even 500 km/h. However, their capacity is greatly reduced compared to static users, and would be insufficient for serving many bandwidth-demanding applications. All of these standards exhibit performance degradation at high speeds mostly because of the channel aging phenomenon. In order to use adaptive MIMO techniques, which have great potential for increasing the capacity, mobile nodes need to send CSI information to the base station, which will be used for adaptive precoding of the next data block. But, when the mobile node is moving at a very high speed, its multipath environment rapidly changes, and the CSI data is no longer accurate by the time it is actually employed for transmission. In this situation, most systems fall back to simpler and more robust techniques, such as transmit diversity, although they lose the multiplexing gain of MIMO. This is especially critical with the foreseeable use of Massive Multiple-Input Multiple-Output (mMIMO) [18], where the base station uses a large antenna array to do highly focused beamforming to mobile users, thus saving energy and reusing spectrum.

In summary, all of these technologies provide some levels of connectivity with high-mobility users, but none of them is truly suitable for large-scale broadband access. Some provide an inherently low throughput because of their design (e.g. Leaky Coaxial Cable (LCX), satellite). Others, such as LTE and WiMax, can have an higher throughput in theory, but it is drastically reduced for fast moving users.

III. PREDICTOR ANTENNAS

The family of Separate Receive and Training Antennas (SRTA) techniques tackles the channel aging problem at its roots, by exploiting multiple receiving antennas and the predictable movement of vehicles. The reference scenario considers a moving vehicle that receives a downlink transmission, moving almost in a straight line (which is always true at high speeds). At the base station, a mMIMO array is employed to create a beamforming pattern focused on the receiver antenna, based on the latest received CSI. If the environment remains mostly unaltered, then the transmitted signal propagates through it and creates a multipath fading profile, which remains constant over a relatively long observation period [7]. As the vehicle moves along, it sees different points of the multipath profile at different times, thus experiencing a rapidly time-varying radio channel.

The SRTA scheme leverages the concept of Predictor Antenna (PA) for exploiting the relative time-invariance of the fading profile [19]. All the receiving antennas are placed on the rooftop, regularly spaced along the direction of movement, and the first one of them is designed as the PA. At any given time, it receives pilot signals from the base station and estimates the channel to create a CSI report. Such estimate will quickly be outdated for the PA, but it will later become valid for the other antennas when they occupy the same position where the PA was. In principle, it can be used for beamforming to the other antennas. But for this to work, the Transmission Time Interval (TTI) should be changed adaptively as a function of the speed, the wavelength, and the antenna spacing, so that the vehicle can receive the transmission with the right antenna at exactly the right time. However, current LTE cellular technology only

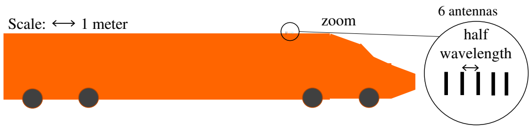

Fig. 1. Example of the antenna configuration for SRTA-PI.

allows a TTI granularity of 1 ms, and even in 5G it will likely be possible to only use multiples and sub-multiples of that. Without a perfect adjustment of the TTI, there would be a residual mis-pointing and the full potential of the PA can't be realized.

To alleviate this problem it is possible to store multiple samples of the channel (possibly with multiple PAs), thus using polynomial interpolation to estimate the intermediate positions, without requiring any change to the TTI length. The resulting technique is named SRTA-PI [7]. The added complexity is proportional to $Nlog(N)$, where N is the number of antennas on the train.

Figure 1 and Figure 2 illustrate the application of SRTA-PI to a high speed train that supports spatial multiplexing of two data streams for speeds up to 500 km/h at 2 GHz, thanks to 6 antennas spaced by half-wavelength, and assuming the latency of an LTE Frequency Division Duplexing (FDD) system.

Figure 2-a) illustrates the delays between channel measurement and precoding. The downlink and uplink transmissions are synchronized and using TTIs of 1 ms. During the n-th TTI, 14 Orthogonal Frequency Division Multiplexing (OFDM) symbols are sent, with 14 different precoders, to track the channel variations within the TTI. During the $(n-2)$-th TTI, the train measures the channel at 4 different times (for which subcarriers with non-precoded pilots are available) and stores the four corresponding CSIs. Then, assuming the lowest possible latency, the train reports the four CSIs to the network during the $(n-1)$-th TTI. Finally, during the n-th TTI, the network uses the reported CSIs to build the precoders.

In Figure 2-a), an arbitrary "current time" t during the n-th TTI is highlighted. Figure 2-b) and Figure 2-c) illustrate the positions in the spatial domain of the train's antennas at t, when they are receiving precoded symbols. These figures also show the earlier positions of the antennas corresponding to the CSIs used to build the current precoders. In these figures, the train is assumed to move at 500 km/h.

Figure 2-b) shows that, when the train has a single antenna, the CSIs cannot help build efficient precoders, as the measured positions are several wavelengths away from the target antenna's position.

Figure 2-c) shows that for a train with 6 antennas, $6 \times 4 = 24$ different positions are measured, and that each of the 2 antennas at the back is "surrounded" by measured positions. Using polynomial interpolation over the 24 measurements, the channels of these two antennas can be accurately determined and used for precoding, even though these samples are irregularly spaced and form clusters of very close positions [7].

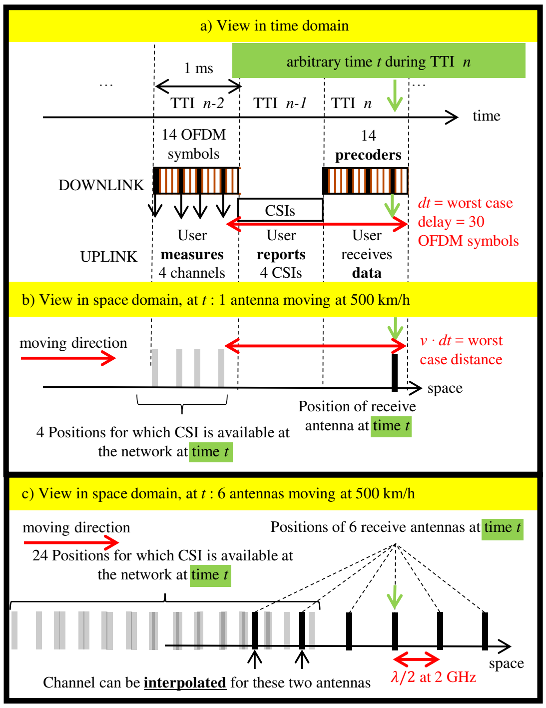

Fig. 2. Illustration of the SRTA-PI approach.

More generally, N is derived as follows. First of all, closer antennas provide a better spatial sampling of the channel. However, to avoid coupling between antennas, we space them by $\lambda/2$ where λ is the wavelength. Then, one must make sure that one antenna is always "surrounded" in the space domain by earlier measurements, even in the worst case in terms of delay dt between channel measurement and data transmission. During dt the train moves by $v \cdot dt$. Hence, the distance between the last antenna and the front antenna, given by $(N-1)\lambda/2$, must verify:

$$v \cdot dt \leq (N-1)\lambda/2 \tag{1}$$

If the system needs to send P data streams to P receive antennas instead of 1, then the condition (1) becomes:

$$v \cdot dt \leq (N-P)\lambda/2 \tag{2}$$

which is equivalent to:

$$N \geq v \cdot dt \frac{2}{\lambda} + P \tag{3}$$

With LTE at 2 GHz, $dt = \frac{30}{14} 1[ms] = 2.1429ms$ (as illustrated in Figure 2), $\lambda = 15cm$, $N \geq 5.9683$, and $N = 6$.

IV. SIMULATION SETUP AND RESULTS

This work evaluates the effectiveness of SRTA-PI in scenarios involving a very fast train (up to a speed of 500 km/h) using computer simulations, carried out through an extended version of LTE-Sim [8].

Three different configurations are considered. The first one is the baseline scenario, based on the simple OFDM-based transmission scheme. It has no means to combat the effects of

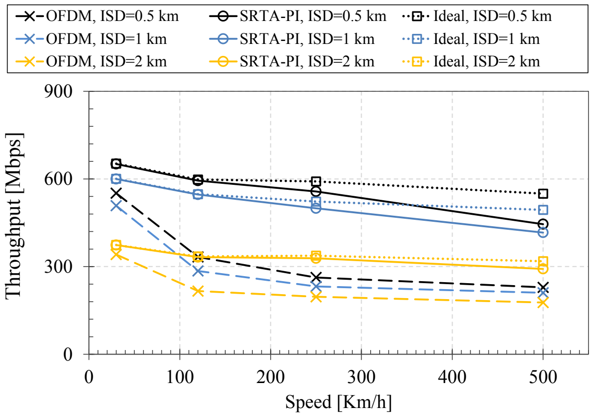

Fig. 3. Total throughput with 2 receiving units on the train

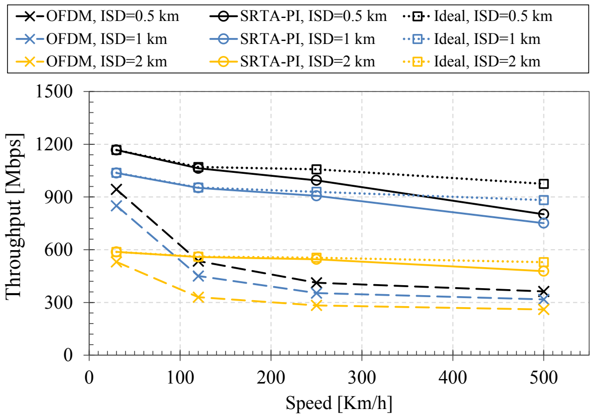

Fig. 4. Total throughput with 4 receiving units on the train

high speed and suffers from both channel aging and Doppler spread. The second one uses SRTA-PI. It removes the channel aging issue, but Doppler spread is still present. Finally, the later scenario models an ideal communication where neither channel aging or Doppler spread are considered. It is used as an ideal solution reaching upper bound performance.

The base stations are configured with mMIMO arrays with 256 antennas and configured according to the two-stage Joint Spatial Division and Multiplexing (JSDM) precoding scheme [20]. The handover time is assumed to be negligible by using a solution such as [5]. The 3rd Generation Partnership Project (3GPP) 3D channel model for suburban environments [21] is taken into account. The bandwidth is set to 100 MHz, centered at 2 GHz. Each base station uses a total transmit power of 53 dBm, and a round-robin scheduler that can serve up to 8 users simultaneously. From the network perspective, the ISD is set to 0.5, 1, and 2 km. During simulations, the train moves on a straight line, with three-sectored base stations placed at both sides of the track in an hexagonal grid, traveling for 1400 m. There are two rows of base stations at each side, where the first one is used for service and the second one for modeling interference from the rest of the network. The speed is set to 30, 120, 250, and 500 km/h, and the typical acceleration of trains is slow enough that the speed can be treated as constant for our purposes. On top of the train there are a number of receiving units, which act as independent user equipments from the point of view of the network. Each one of them has 6 antennas and implements the SRTA-PI technique as described in Section III. Each receiving unit can receive up to two spatially multiplexed streams, and the received packets are relayed to the users using on-board WiFi hotspots, thus avoiding interference issues with the cellular connection. Results have been averaged over 30 independent simulation runs.

Figure 3, Figure 4, and Figure 5 show the total throughput achieved with 2, 4, or 8 receiving units on the train, respectively. By increasing the number of receiving units, the throughput improves considerably because more data stream can be sent in parallel, but the increment is somewhat less than linear. This is because at least some of the receiving units are co-scheduled on the same base station, and thus they share the same total transmit power.

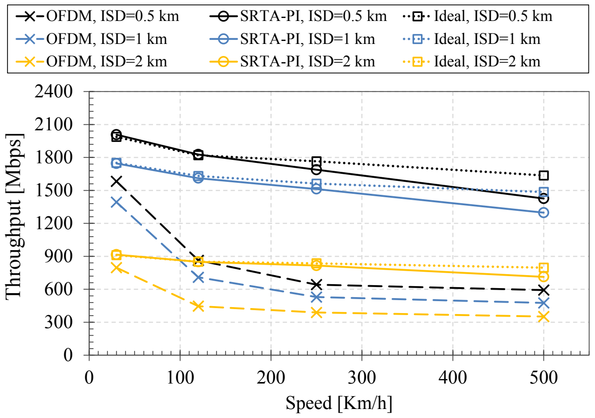

Fig. 5. Total throughput with 8 receiving units on the train

In all the cases, the performance of the baseline technology (labeled as OFDM) is the most sensitive to the speed, as its throughput is reduced by around 50% to 65% when the speed increases from 30 km/h to 500 km/h. Instead, SRTA-PI performs much better, as its throughput is already higher by 10-25% at the lowest speed, and the loss at 500 km/h is limited to about 20-30%. This sums up to a throughput gain of 100% or more at the highest speed, in most scenarios. However, there is still a throughput loss of 8-20% compared to the ideal case.

With respect to the ISD, the first increment from 0.5 km to 1 km results in a limited throughput loss, ranging from 6 to 19% across all technologies and speeds. Instead, the loss from 1 km to 2 km is more severe, as it varies from 15 to 47%.

Figure 6 shows the distribution of the Modulation and Coding Scheme (MCS) index selected for transmission, for each speed and each technology. Higher MCS values directly relate to higher Signal to Interference and Noise Ratio (SINR), and result in higher spectral efficiency. At 30 km/h, all the rows are quite

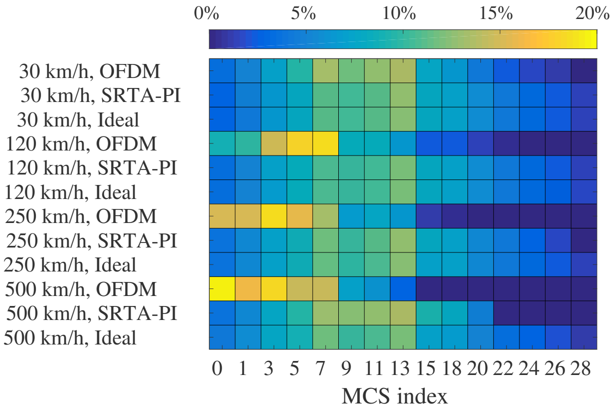

Fig. 6. Distribution of the MCS index for different speeds and technologies

similar, with most of the values located between 7 and 13. However, as the speed increases, the distribution of OFDM is progressively shifted towards lower values, and MCS indexes above 13 are never used at the higher speeds. On the contrary, for SRTA-PI and the ideal case the most frequent values remain the same, and only some of the higher MCS indexes are avoided at higher speeds. This confirms that removing the transmission impairments caused by the high speed has a strong effect on the perceived channel quality, and thus on the final throughput.

V. CONCLUSION

This work evaluated the performance of the Separate Receive and Training Antennas with Polynomial Interpolation technique, when applied to Massive Multiple-Input Multiple-Output downlink transmission toward a fast-moving train. Results show that most of the throughput loss experienced by Orthogonal Frequency Division Multiplexing at high speeds can be attributed to delayed Channel State Information, i.e. the channel aging phenomenon. Such loss can be largely avoided with Separate Receive and Training Antennas with Polynomial Interpolation, which enables advanced channel prediction using the Predictor Antenna concept. Analysis of the Modulation and Coding Scheme distribution confirms that the perceived channel quality remains high even at 500 km/h when Separate Receive and Training Antennas with Polynomial Interpolation is employed. The conducted study also shows how the total throughput is affected by parameters such as the Inter-Site Distance and the number of receiving units, which is useful information for the dimensioning of actual systems. However, there is still a throughput loss compared to the ideal case, which is caused by the Doppler spread. Future studies can address this issue by employing waveform and/or modulation techniques with higher tolerance to Doppler environments.

ACKNOWLEDGMENTS

This work is supported by the FANTASTIC-5G project, which receives funding from the European Union's Horizon 2020 research and innovation programme under the grant agreement ICT-671660.

REFERENCES

[1] D. T. Fokum and V. S. Frost, "A survey on methods for broadband internet access on trains," *IEEE communications surveys & tutorials*, vol. 12, no. 2, pp. 171–185, 2010.

[2] NGMN Alliance, "5G White Paper," 2015.

[3] F.-G. Project, "Deliverable D2.1: Air interface framework and specification of system level simulations," Call: H2020-ICT-2014-2, Project reference: 671660, Flexible Air iNTerfAce for Scalable service delivery wiThin wIreless Communication networks of the 5th Generation (FANTASTIC-5G), Tech. Rep. D2.1, May 2016.

[4] R. Hadani, S. Rakib, M. Tsatsanis, A. Monk, A. J. Goldsmith, A. F. Molisch, and R. Calderbank, "Orthogonal time frequency space modulation," in *Wireless Communications and Networking Conference (WCNC), 2017 IEEE*. IEEE, 2017, pp. 1–6.

[5] S. Barbera, K. I. Pedersen, C. Rosa, P. H. Michaelsen, F. Frederiksen, E. Shah, and A. Baumgartner, "Synchronized RACH-less handover solution for LTE heterogeneous networks," in *Proc. of International Symposium on Wireless Communication Systems (ISWCS)*. IEEE, 2015, pp. 755–759.

[6] F. Schaich, B. Sayrac, M. Schubert, H. Lin, K. Pedersen, M. Shaat, G. Wunder, and A. Georgakopoulos, "FANTASTIC-5G: 5G-PPP Project on 5G air interface below 6 GHz," in *Prof. of European Conference on Network and Communications*, 2015.

[7] D.-T. Phan-Huy, M. Sternad, and T. Svensson, "Making 5G adaptive antennas work for very fast moving vehicles," *IEEE Intelligent Transportation Systems Magazine*, vol. 7, no. 2, pp. 71–84, 2015.

[8] G. Piro, L. A. Grieco, G. Boggia, F. Capozzi, and P. Camarda, "Simulating LTE cellular systems: An open-source framework," *IEEE transactions on vehicular technology*, vol. 60, no. 2, pp. 498–513, 2011.

[9] S. Banerjee, M. Hempel, and H. Sharif, "A Survey of Wireless Communication Technologies & Their Performance for High Speed Railways," 2016.

[10] B. Lannoo, D. Colle, M. Pickavet, and P. Demeester, "Radio-over-fiber-based solution to provide broadband internet access to train passengers," *IEEE Communications Magazine*, vol. 45, no. 2, pp. 56–62, 2007.

[11] K. Ishizu, M. Kuroda, and H. Harada, "Bullet-train network architecture for broadband and real-time access," in *Proc. of 12th IEEE Symposium on Computers and Communications (ISCC)*. IEEE, 2007, pp. 241–248.

[12] D. Sanz, "Satellite Technologies for Broadband Internet Access Onboard High Speed Trains," in *Proc. of 7th World Congress on Railway Research*, 2006.

[13] A. E. Amanna, D. Ali, M. Gadhiok, M. Price, and J. H. Reed, "Cognitive radio engine parametric optimization utilizing Taguchi analysis," *EURASIP Journal on Wireless Communications and Networking*, vol. 2012, no. 1, p. 5, 2012.

[14] M. Berbineau, E. Masson, Y. Cocheril, A. Kalakech, J.-P. Ghys, I. Dayoub, S. Kharbech, M. Zwingelstein-Colin, E. SIMON, N. Haziza *et al.*, "Cognitive radio for high speed railway through dynamic and opportunistic spectrum reuse," in *Proc. of Transport Research Arena (TRA) 5th Conference: Transport Solutions from Research to Deployment*, 2014.

[15] W. Bolton, Y. Xiao, and M. Guizani, "IEEE 802.20: mobile broadband wireless access," *IEEE Wireless Communications*, vol. 14, no. 1, pp. 84–95, 2007.

[16] M. Aguado, O. Onandi, P. Agustin, M. Higuero, and E. Taquet, "Wimax on rails," *IEEE Vehicular Technology Magazine*, vol. 3, no. 3, pp. 47–56, 2008.

[17] A. Sniady and J. Soler, "LTE for railways: Impact on performance of ETCS railway signaling," *IEEE Vehicular Technology Magazine*, vol. 9, no. 2, pp. 69–77, 2014.

[18] B. Panzner, W. Zirwas, S. Dierks, M. Lauridsen, P. Mogensen, K. Pajukoski, and D. Miao, "Deployment and implementation strategies for massive MIMO in 5G," in *Proc. of Globecom Workshops*. IEEE, 2014, pp. 346–351.

[19] M. Sternad, M. Grieger, R. Apelfröjd, T. Svensson, D. Aronsson, and A. B. Martinez, "Using predictor antennas for long-range prediction of fast fading for moving relays," in *Proc. of Wireless Communications and Networking Conference Workshops (WCNCW)*. IEEE, 2012, pp. 253–257.

[20] A. Adhikary, J. Nam, J.-Y. Ahn, and G. Caire, "Joint spatial division and multiplexing - The large-scale array regime," *IEEE transactions on information theory*, vol. 59, no. 10, pp. 6441–6463, 2013.

[21] 3GPP, "Study on 3D channel model for LTE," 3rd Generation Partnership Project, Tech. Rep. 36873, Jun 2015.