Multiple antenna techniques for device pairing of a mmWave high capacity backhaul system

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***Abstract*—In this paper we provide a study of multi antenna techniques for a high capacity millimeter wave (mmW) backhaul system. More specifically, we focus on practical design of beamalignment solution using Received Signal Strength (RSS) measurements in the radio frequency (RF) paths. In this regard, we show simulation results related to the probability of beam misalignemnt as a function of control parameters, such as, sampling time of the Received Signal Strength (RSS) signal, scanning step of the beams and memory In addition, we also consider the study of multiple-input-multiple-output (MIMO) transmission for high-speed train (HST) scenario.**

I. Introduction

Millimeter-wave communication is considered one of the key innovations of 5G, due to the large available bandwidth and potential to enable tens of Gbps data rate as well as massive MIMO and beamforming [1]–[3]. However, many challenges for hardware implementation, signal processing and algorithms are still open especially, for a 28GHz technology.

The EU-KR H2020 5GCHAMPION project [4] is, for instance, one of the first research project delivering a prototype of mmW RF-transceiver at 28GHz, which is integrated with pre-commercial 5G base-band and core networks components. One big challenge addressed in the project, especially when considering hardware constraints, is the initial access procedure in which both transmitter and receiver need to discover via one or multiple directions in order to, for instance, maximize the signal-to-noise ratio (SNR).

In this paper, we focus on two fundamental challenges: $i)$ practical design for beamalignment with RF-based RSS measurements and $ii)$ MIMO techniques for HST application scenario. The first one is motivated by the intention of shifting some functionalities of the base-band to the RF unit so as to free resources MIMO processing. However, in so doing hardware constraints should be considered. The second one is motivated by the need of connecting moving hot-spots with high reliable, high-capacity links.

The reminder of the paper is as follows. In Section II and Section III challenges $i)$ and $ii)$ are described together with simulation results. In Section IV, concluding remarks are provided.

II. Practical design of RF-based beam alignment

A. System model

We consider the problem of beam-alignment between a pair of devices forming a mobile mmW backhaul link. We assume that one device has fixed location and is connected to the core network, whereas the other is mobile and serves as moving hot-spot, for instance, in bus or high-speed train. The fixed and the mobile devices are, hereafter, referred to as fixed Terminal radio unit (TRU) a remote radio unit (RRU), respectively.

Both TRU and RRU utilize multiple antennas to establish a directive communication via beamforming. For simplicity, let us assume that in both devices a uniform linear array (ULA) with N elements is mounted and beamforming is performed in the analog domain with phase-shifters.

In this study, we focus on the initial radio frame synchronization procedure, which is prior any other type of communication between the TRU and the RRU. Following the approach in [5], we assume that the TRU will periodically send a primary synchronization signal (PSS)[1] to different directions. At the receiver side, the RRU will seek for the PSS signal also by sequentially sound different directions. As described in Section I, we tackle a solution with RF-based RSS measurements in order to reduce the computational load at the base-band.

In light of the above the received signal model is given by

$$y(t) = \mathbf{w}^{\mathrm{H}}\mathbf{H}\mathbf{f}p(t-\tau) + \mathbf{n}(t), \tag{1}$$

where $\mathbf{p}(t)$ is the vector of transmitted PSS waveforms of duration T_s, periodicity T_p, and power $P = \frac{1}{T_s}\int_0^{T_s} \|p(t)\|^2 dt$.

In the RF radio module we implement an power measurement system as indicated in Figure 1. More specifically, a log-power detector is used to measure the input power in the receiving RF path and its output is read and converted in digital values by the microcontroller.

[1] We simplify the PSS signal model by considering that PSS is allocated only in one subband

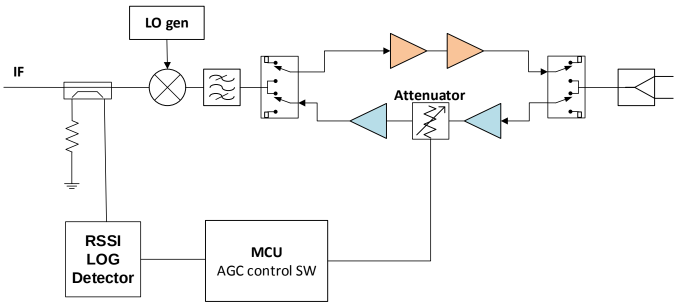

Figure 1. Circuit for AGC in the RF unit [6], [7]. Power detector is implemented with an RSSI log-detector and it is controlled by a micro-controller.

Mathematically, the output of the power log-detector is proportional[2] to the instantaneous power $s(t)$

$$s(t) = 10\log_{10}\left(\frac{1}{T_d}\int_{t}^{t+T_d} ||y_i(t)||^2 dt\right), \qquad (2)$$

where T_d is the integration time tunable by a capacitor.

At the microcontroller, the signal $s(t)$ is sampled with period T_i and samples are stored into a memory-buffer of size N_s. For clarity, let $\mathbf{s}_i \in \mathbb{R}^{N_s}$ be the vector containing the power samples. The set of vector-samples is denoted by $\mathcal{S}$ and is used by the receiver to determine: $i)$ the beamformering vector $\mathbf{w} \in \mathcal{W}$ that maximizes the SNR for a given $\mathbf{f}$ and $ii)$ the begin of the PSS. We assume that the $\mathcal{S}$ is collected during a period $|\mathcal{W}|T_p$, where $|\cdot|$ indicates the cardinality of a set.

As the beamalignemnt procedure occurs in the RF unit, it is paramount of importance to reduce cost (energy and signalling) due to analog-to-digital conversion and memory usage at the microcontroller. In the sequel we shall focus on the detection of the best beamformer.

B. Simulation study

We simulate a test-scenario where TRU and BRU are located 50m away apart, line-of-sight (LOS) condition is assumed and radio channel is characterized by a path-loss decay $\nu = 2.6$. The number of antenna elements in the ULA is $N = 8$ and each element can provide 11dBi gain [7]. As a result, the ULA will give approximately 20dB. The beamcodebook $\mathcal{W}$ is obtained by simply steering the array beampattern by angle step δ_s. The transmitted signal is with constant envelop, power is $P = 30$dBm, $T_p = 10ms$ and T_s $14.3\mu s$. TRU and RRU are time synchronized by means of 1-pulse-per-second (1-PPS) signal, however, the radio frames at the transmitter and receiver are not. Finally, we assume that transmitter is aligned with the direction of departure of the channel. Thus, we focus on the receive beamforming only.

In Figure 2, we show a realization of the averaged RSS signal measured by the log-detector during one radio frame (top) and multiple radio frames (down). It can be noticed that peaks appear when the PSS signal has been received.

[2] Note that proportionality holds only in the linear region of the power detector.

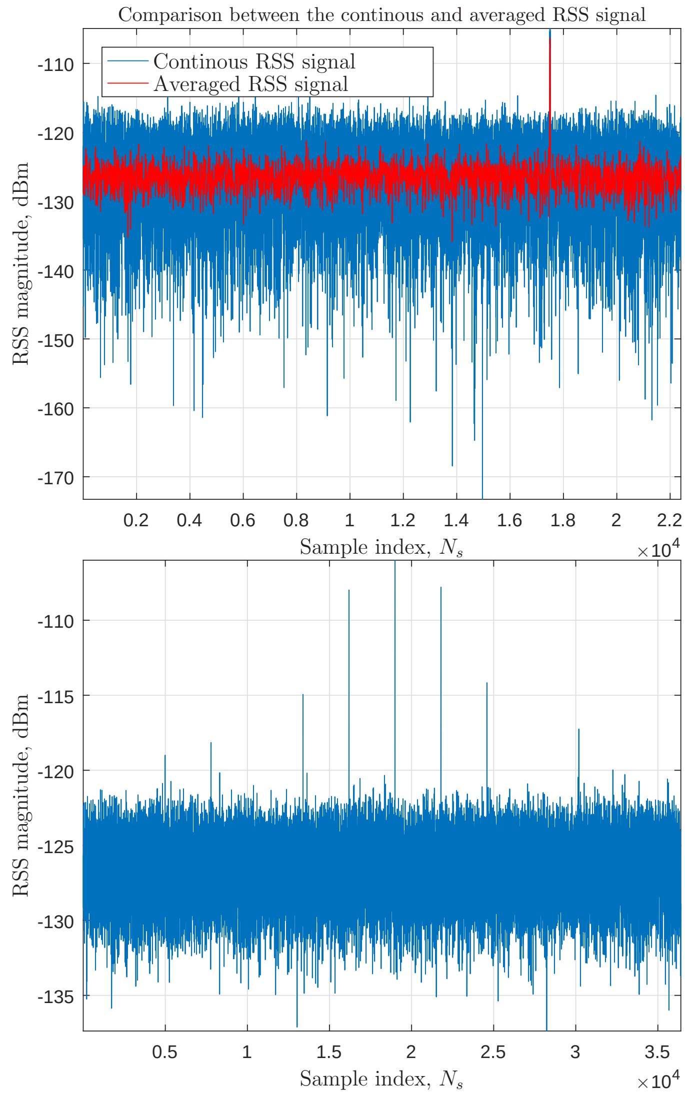

Figure 2. Top: comparison between the continous and averaged RSS signal. Down: Average RSS signal across the dull scanning period.

Their locations (sample index) relate to arrival of the PSS, whereas the magnitudes depend on the transmission power and the total "equivalent" channel gain, $i.e.$, $10\log_{10}\left(\|\mathbf{w}^{\mathrm{H}}\mathbf{H}\mathbf{f}\|_2^2\right)$. We use the sample index of the maximum of the RSS signal to identify the beamformer providing the maximum SNR amongst all those used during the observation time.

In Figure 3 the result of the probability of misalignment is shown and, more specifically, we illustrate the impact of the sampling time T_i, the buffer size N_s as well as the beam scanning step δ_s. The following conclusions are in order.

First, by comparing the results obtained with the same δ_s, we can observe that the shorter T_i, the lower the probability of misalignment is. This is easy to understand as, for a given buffer size, the higher the sampling frequency of the RSS signal, the more accurate the RSS calculation is. However, there is an increase of the number of signaling for analog-to-digital conversion (ADC) conversion.

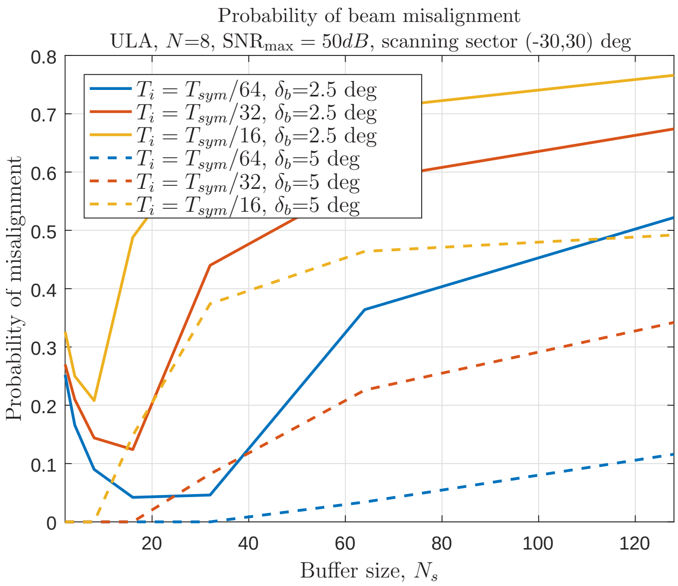

Figure 3. Probability of beam misalignment with RSS based measurements in the RF unit. Impact of different hardware design parameters.

Second, we observe that for a given T_i, there exists a range buffer size values that can minimize the probability of misalignment. Our intuition is that both the mean and the span of this optimal range depends on the ratio T_s/T_p. More specifically, the larger the ratio, the bigger the mean and the span are as more samples can be accumulated within the duration of the PSS signal.

Third, we notice that by increasing the step-size δ_s, the lower the probability of misalignment is. However, by increasing δ_s beams are going to be more and more a part from each other leaving sub-sectors with low SNR.

In light of the above, our approach for beam alignment is to use relatively wide δ_s steps to guarantee coverage, large T_i and small buffer size.

III. MIMO TECHNIQUES FOR MMW HST BACKHAUL LINK

In the next study, we assume that beam alignment, synchronization and channel estimation is successfully performed and focus on MIMO processing for high-speed train scenario.

To begin with, we consider the study in [8], which shows that there exists, under some conditions, a link with good SNR between a RRU receiver on the top of a HST and a TRU along the railway. Based on those results, we have evaluated the possibility of using MIMO schemes to enhance the throughput on this link, especially when Doppler is present. Distances between TRU and RRU of around 100 to 800m are considered.

We assessed the feasibility of spatial-multiplexing (SM) as described in [9] under the name V-BLAST. This scheme allows to theoretically increase the data rate by a factor of the number of transmit antennas, provided that i) the number of receive antennas is strictly higher than the number of transmit antennas, ii) antennas are decorrelated and iii) the channel is more or less frequency selective and that the SNR is quite high.

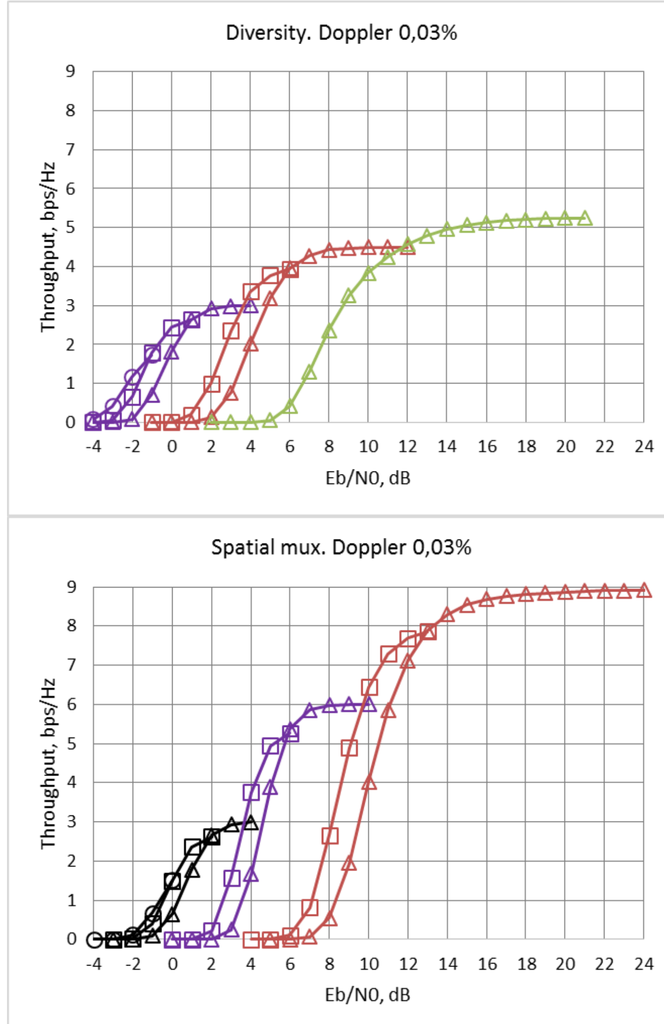

Figure 4. Throughput of Spatial Multiplexing and Diversity Schemes with 0.03 % residual Doppler. In the Diversity plot, purple, red and green lines refer to 16QAM, 64QAM and 128QAM. In the Spatial multiplexing plot, black, purple and red lines refer to QPSK, 16QAM and 64QAM.

In order to realize a comparison with this SM scheme, a “Diversity” scheme has been implemented, with the same number of antennas. With this scheme, the transmit antennas all transmit the same data. A urban microcell street canyon channel with LOS [10] has been simulated thanks to the free software Quadriga [11]. In this study we considered 2 transmit and 4 receive antennas. The antennas are directive, with 8 degree aperture. The optimal antenna spacing has been measured and is 2λ for the Diversity scheme and 50λ for SM. Doppler, due to the high speed of the train, has been simulated together with the channel model. In our work, we pre-compensated the Doppler at the transmitter with an estimation of the speed of the train (note that how to estimate the speed was nevertheless out of the scope of the study). When the speed is not accurately estimated, Doppler that remains at the receiver is hereafter called “residual Doppler”.

Figure 1 plots the throughput that can be achieved by the two schemes, computed as γ_{mr}(1-PER) with m the modulation order, r the coding rate, PER the Packet Error Rate (computed by simulations), γ=1 for Diversity and γ=2 for SM. The residual Doppler is around 0.03 of carrier spacing (OFDM with 180 kHz carrier spacing is used). It is worth noting that the SM scheme achieves a higher throughput than the Diversity scheme from a Eb/N0 of 4 dB. For Eb/N0 higher than 18 dB, SM even allows a throughput 1.8 times higher than Diversity.

IV. Conclusions

In this paper we provided a study of multi antenna techniques for a high capacity mmW backhaul system. We focused on a beamalignment solution using RSS measurements using RF signal and showed how hardware design parameters, such as sampling time of the Received Signal Strength (RSS) signal, scanning step of the beams and memory can affect the probability misalignment. In addition, we also studied multiple-input-multiple-output (MIMO) transmission for high-speed train (HST) scenario and the achievable throughput with spatial-multiplexing and diversity techniques.

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References

[1] Z. Pi and F. Khan, "An introduction to millimeter-wave mobile broadband systems," *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 101–107, Jun. 2011.

[2] P. Wang, Y. Li, L. Song, and B. Vucetic, "Multi-gigabit millimeter wave wireless communications for 5g: from fixed access to cellular networks," *IEEE Commun. Mag.*, vol. 53, no. 1, pp. 168–178, Jan. 2015.

[3] R. W. Heath, N. González-Prelcic, S. Rangan, W. Roh, and A. M. Sayeed, "An Overview of Signal Processing Techniques for Millimeter Wave MIMO Systems," *IEEE J. Sel. Topics Signal Process.*, vol. 10, no. 3, pp. 436–453, Apr. 2016.

[4] M. Mueck et al., "5G CHAMPION - Rolling out 5G in 2018," Dec. 2016, pp. 1–6.

[5] C. N. Barati, S. A. Hosseini, S. Rangan, P. Liu, T. Korakis, S. S. Panwar, and T. S. Rappaport, "Directional cell discovery in millimeter wave cellular networks," *IEEE Transactions on Wireless Communications*, vol. 14, no. 12, pp. 6664–6678, Dec 2015.

[6] M. Mueck, V. Ivanov, S. Choi, J. Kim, C. Ahn, H. Yang, G. Baldini, and A. Piipponen, "Future of wireless communication: Radioapps and related security and radio computer framework," *IEEE Wireless Commun.*, vol. 19, no. 4, pp. 9–16, Aug. 2012.

[7] G. Destino, O. Kursu, S. Tammelin, J. Haukipuro, M. Sonkki, T. Rahkonen, A. Pärssinen, M. Latva-aho, A. Korvala, and M. Pettissalo, "System Analysis and Design of mmW Mobile Backhaul Transceiver at 28 GHz," 2017.

[8] J. K. J. A. Sungwoo Choi, Heesang Chung and I. Kim, "Mobile hotspot network system for high-speed railway communications using millimeter waves," *ETRI Journal*, vol. 38, no. 6, pp. 1052–1063, Dec 2016.

[9] G. D. G. R. A. V. P. W. Wolniansky, G. J. Foschini, "V-blast: An architecture for realizing very high data rates over the rich-scattering wireless channel," *IEEE*, pp. 295–300, 1998.

[10] M. Peter, "Measurement Campaigns and Initial Channel Models for Preferred Suitable Frequency Ranges," EU H2020 mmMagic project, Tech. Rep., 2016.

[11] S. Jaeckel, L. Raschkowski, K. BÃ¶rner, and L. Thiele, "Quadriga: A 3-d multi-cell channel model with time evolution for enabling virtual field trials," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 6, pp. 3242–3256, June 2014.