Testbed SDR Implementation Approach for Millimetre Wave IoT Applications

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***Abstract*—Millimetre wave (mmWave) communication is a promising technology which can fulfil the growing demands for spectrum for future wireless networks. One of the key areas for the development of the mmWave networks is the Internet of Things (IoT) communications within fifth generation (5G) and beyond 5G networks. For significant analysis and development of the compliant IoT systems through testbed implementation, current mmWave spectrum transceivers are too expensive when substantial number of the nodes is required by the IoT applications. Considering all the above, it is suggested to use Software Defined Radio (SDR) transceivers with a lower frequency band and with an increased distance between the nodes. The idea is to scale observation time and distance to emulate mmWave radio without actual mmWave hardware. Using scaling factors for the certain system parameters to keep the signal characteristics in accordance with the mmWave band makes it possible. This approach allows to develop mmWave IoT testbeds with significant improvement in the system scalability and cost-effectiveness without the need to transmit and receive the signal in the mmWave band. In this paper, the concept of SDR-based Hardware-in-the-loop (HIL) system combined with the observation time and distance scaling approach is proposed. As an example, a testbed with a simple Wireless Physical Network Coding scheme is implemented and demonstrated.**

***Index Terms*—IoT, Hardware-in-the-loop, Testbed, SDR, Time-and-Distance-Scaling, mmWave, 5G, B5G**

I. Introduction

Millimetre wave (mmWave) communication provides a very large spectrum from 30 GHz to 300 GHz and wide bandwidth up to 1 GHz [1]. However, the propagation suffers from high path loss due to the short wavelength of mmWave signals [2]. Besides, the power consumption of the devices is very high since power amplifiers and data converters consume excessive power at high bandwidths. Most of the existing mmWave test setups either use mmWave equipment [3, 4] or apply various frequency up-converters [5, 6]. It means that typically used hardware systems are costly in comparison with available centimetre waves band (also known as Super High Frequency (SHF), from 3 GHz to 30 GHz) Software Defined Radios (SDRs) [7]. Adapting this technology provides cost-effective design for the testbed with a possibility to use promising technologies analysis in IoT millimetre wave networks. Moreover, spectrum sharing can be considered in order to add more flexibility to the system. Scaling the observation time and distance provides the basis for building a cost-effective and reliable system for Extra-high frequency analysis. As a result, it would be possible to implement and research novel algorithms and scenarios including spectrum sharing, wireless physical network coding (WPNC) [8] and other techniques and to create fully applicable real-time testing systems for mmWave network analysis.

In this paper, we propose to use the centimetre waves band SDR transceivers for implementing, validating and testing the millimetre wave based IoT algorithms for applications in various use cases on a hardware plus software testbeds. Section II presents system model of the Wireless Physical Network coding as an application for the mmWave band application analysis. Section III introduces the proposed approach for the observation time and distance scaling. Section IV describes Hardware-in-the-loop technique for the testbed development and demonstrates the proposed testbed implementation both in software and hardware parts. Finally, Section V provides experimental results of the simple WPNC scheme implementation. The conclusions are drawn in the Section VI.

II. System Model

We consider possible applications for this testbed such as the mmWave WPNC system including relays and user devices with a single antenna. In the simplest 2-user WPNC scenario the received signal at each relay node is written by,

$$y = h_1 x_1 + h_2 x_2 + n. \quad (1)$$

where h_1 and h_2 represent the channel coefficients of user 1 and user 2, x_1 and x_1 represent the information signals sent by user 1 and user 2 during the first phase of the WPNC procedure and n is the Additive White Gaussian Noise (AWGN).

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After estimating the channel coefficients, $\hat{h}_k$, then, the relay can detect the transmitted signals $\hat{x}_k$ (the detected signal received from the interacting kth user) considering Maximal Likelihood (ML) detection:

$$(\hat{x}_1, \hat{x}_2) = \arg \min_{(x_1,x_2)\in\Omega} ||y - h_1x_1 - h_2x_2||. \tag{2}$$

where Ω is the set of possible symbols in the constellation.

Using proposed system model, it becomes possible to test simple WPNC scheme with the developed testbed using Hardware-in-the-loop emulation methodology.

III. Proposed Approach

For the practical part, we consider possible applications for this testbed such as the mmWave WPNC scenarios including relays with multiple antennas and users having a single antenna. At each relay node, the received signal is combined of the two signals belonging to the two users trying to communicate with each other. If the relay knows the full channel state information (CSI), the estimated symbols are obtained by considering maximum likelihood (ML) detection through the mmWave channel.

In the experimental part, Hardware-in-the-loop (HIL) technique is adopted to create flexible and powerful testbed for IoT 5G and beyond 5G applications. The testbed could be used to perform network performance validation, channel quality estimation and other related network analysis. Hardware design of the nodes is considered to fulfil the need for portability, low cost and low power consumption. The joint hardware plus software testbed should allow to develop more flexible and more efficient network realization relevant to the IoT millimetre wave communications. Embedded system performance is usually assessed through testbeds with real devices operating in realistic scenarios and under realistic conditions that can replicate the deployment environment. If there is a large number of nodes, the devices should be low cost and battery-powered: then Commercial-Off-The-Shelf (COTS) nodes may be used. However, these usually implement a defined communication standard such as IEEE 802.15.4 [9]. However, such radios are not flexible enough to evaluate new techniques and applications. In this case, more flexible hardware is needed, using Field Programmable Gate Array (FPGA) and Digital Signal Processing (DSP) components. However, the mentioned equipment is usually much more expensive than commonly used IoT nodes and requires connection to a power source, making it impractical to use for large-scale IoT networks. The aim of this work is to keep the cost of each node at a reasonable level while guaranteeing enough flexibility and power to allow for full system performance assessment at a reasonable scale, i.e., a few tens of nodes (up to 50 devices in the system). The testbed is designed to be scalable in order to test theoretically any number of nodes in the system.

In this context, the following aspects were considered: the cost of the final device, its energy consumption and its form factor. The device should have the necessary computational power to meet the requirements imposed by the IoT and spectrum sharing algorithms [10, 11, 12]. At the same time, it must be compatible with the requirement to be portable, i.e., powered by (rechargeable) batteries. The suggested design is to use several SDR boards to implement HIL system. The most appropriate hardware could be used to develop the new customized boards, working together with virtual nodes, which compose the network, i.e., the full testbed. The same time cost effective SDR boards operate in centimetre waves band and below. The arguments considered above lead to a proposal to scale observation time and distances between the hardware nodes relatively so that the transmitted and received power and signal Time of Flight (ToF) of the scaled system would be similar with the required millimetre wave system. Also, a corresponding antenna design selection and evaluation should be considered.

In order to correctly assign all scaling factors, we need to go through all the changes in the system parameters step by step. At first, we start assigning a scaling factor to wavelength, increasing it in "α" times (as the main goal is to use lower frequencies). Since the wavelength is expressed in meters, all the system parameters expressed in meters should be multiplied by "α". It means that the distance between nodes will be increased in "α" times. To keep transmitted and received power of the signal unchanged we need to select the appropriate antenna. To do so we consider an effective antenna aperture formula (3) according to [13].

$$A_e = D\frac{\lambda^2}{4\pi}, \tag{3}$$

where A_e is an effective antenna aperture, D is an antenna directivity and λ is the wavelength.

Equation (3) shows that in order to keep the signal power unchanged, the aperture of the antenna should be increased in "α^2" times (according to the wavelength scaling factor). As the signal power is unchanged due to the antenna aperture scaling, the next parameter to be considered is a signal Time of Flight. In order to keep it unchanged we need to divide system clock by "α" (as we call it - observation time scaling). The time scaling coefficient is calculated according to (4):

$$\tau = \frac{d}{c}, \tag{4}$$

where τ is the Time of Flight, d is a distance between transmitter and receiver and c is a speed of light. The distance between the transmitter and receiver antennas should be large enough that the antennas are in the far field of each other $d \gg \lambda$[14, 15].

As a final part of the scaling approach we need to scale the bandwidth as it is directly related to the system clock. Therefore, the bandwidth should be also divided by "α".

IV. Testbed

A. Methodology

The proposed workflow using the observation time and distance scaling approach is taken as a reference design rule to implement the IoT algorithms testing system. The first version of the system was designed using MATLAB / GNU Octave and GNU Radio toolkit implementation and was tested on a personal computer (PC). After this, the workstations were connected to the SDR boards which were tuned and connected using coaxial cables with 10 dB attenuators. The coaxial cables could be used instead of antennas as the antennas and the cables are both linear time-invariant systems and are equivalent [16]. It is assumed that scaling of the observation time and the distances between antennas of the nodes would allow correct implementation of the network environment with proper fading and path loss parameters and other factors. The scaling technique adoption for the HIL testbed, after additional research and fine-tuning leads to a cost-effective and fully compliant network implementation for the mmWave and IoT cases analysis.

The scheme of the proposed testbed is shown in Figure 1. Another approach is to transform the MATLAB / GNU Octave code into a C code representation, which is possible to be implemented within the MATLAB / GNU Octave suite, and then use Vivado High Level Synthesis (HLS) to obtain a hardware description (after some iterations). Vivado HLS allows one to drive the implementation by using a program in the C code. In both cases, the indicated flow supports the design of solutions able to perform floating-point operations and to evaluate the impact of some choices on the project, e.g. fixed-point operations to perform algorithms.

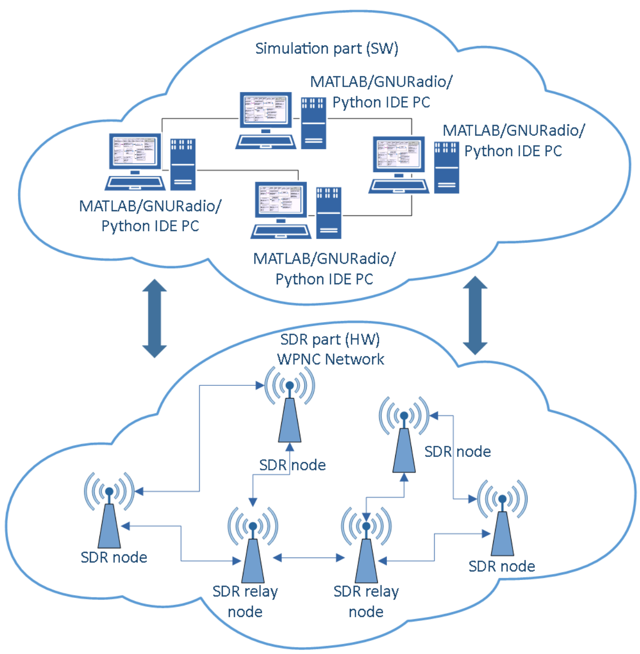

Fig. 1. Hardware testbed workflow.

B. Implementation

In the experimental part, the testbed consists of several hardware and software nodes based on the SDR system interconnected with workstations. The proposed testbed architecture consists of two main parts: 1) the workstations with MATLAB / GNU Octave / GNU Radio toolkits and Python integrated development environment 2) SDR boards with required parameters.

As a first test, a GNU Radio software package is used for the transmitter and receiver implementation together with a SDR hardware platform BladeRF 2.0 micro (available operating frequencies from 1 GHz to 6 GHz) as an SDR transceiver. For the collision domains emulation, 10dB attenuators are used. The implemented two nodes WPNC scheme with BladeRF transceivers is shown in Figure 2.

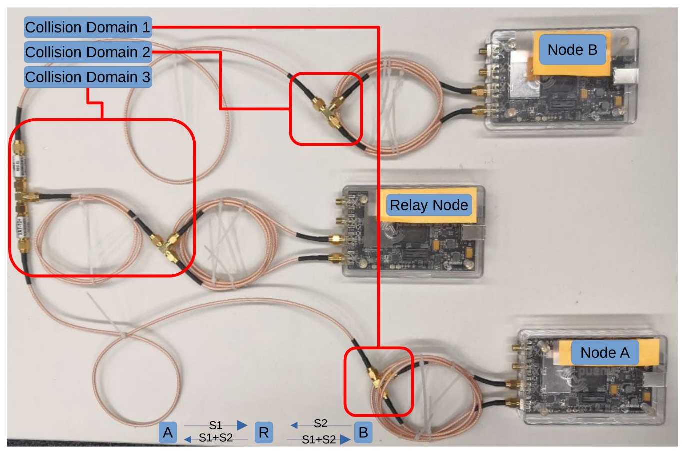

Fig. 2. Implemented HIL WPNC testbed.

The preliminary transmitter system model is shown in Figure 3. The signal generation works as follows: Data for transmission is set in the Encoder block. After that the "Differential Encoder" is implemented and converted from the "string" data type to the "float" data type. Then, they are fed to the input of the "Repeat" block which repeats each input value 160 times. The "Low Pass Filter" serves to sample the signal. The Multiply block is used to multiply two signals: transmitted data signal and a sinusoidal signal generated by the Signal Source block. The MultiplyConst block is used to amplify the generated signal. The "Frequency Mod" block performs frequency modulation of the signal amplified in the previous block. The modulated signal is fed to the input of the Rational Resampler block for subsequent compression. At the output block "Rational Resampler" is ready for transmitting the signal through the block "Sink osmocom".

The preliminary receiver system model is shown in Figure 4. The signal decoding works as follows: "Osmocom Source"

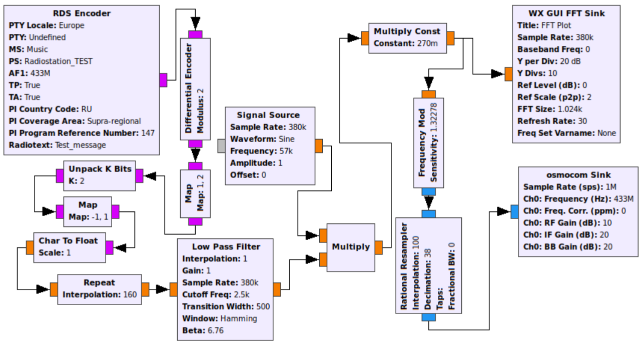

Fig. 3. Preliminaty test transmitter system model in GNU Radio toolkit.

is a receiving unit. The "Band Pass Filter" block allocates the band of the received signal and suppresses noise. The "WBFM Receive" block is responsible the frequency demodulation. The "Frequency Xlating FIR Filter" block is used as an analyser to isolate a narrow frequency band from the broadband signal of the receiver. The signal demodulation operation is performed using the "MPSK Receiver" block since the signal is transmitted with Binary Phase-Shift Keying (BPSK) modulation. The Differential Decoder block analyses the difference between two adjacent samples. The result is the correctly transmitted data.

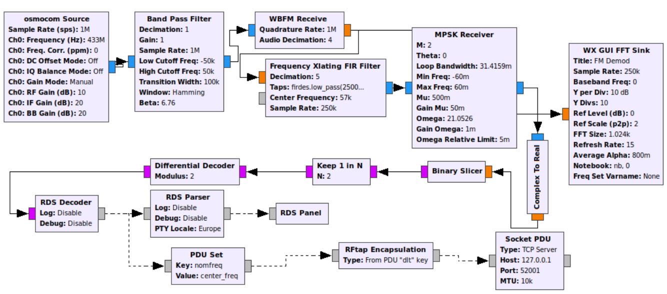

Fig. 4. Preliminary test receiver scheme in GNU Radio.

V. Experimental Results

Before the initial testbed launch, the WPNC scheme was simulated using Python script signal generation. It uses Phase-shift keying (PSK) modulated signals for the transmission and utilizes Zadoff-Chu synchronisation for the correct timing. First and second phases of the WPNC simulation without noise are shown in Figures 5 and 6.

The simulation showed that WPNC works as expected with simple signals without any noise. For the next part of the simulation some noise is added. Is it required to evaluate the ability of the WPNC scheme to operate in conditions close to reality. First and second phases of the WPNC simulation with noise are shown in Figures 7 and 8.

Noisy channels also showed a possibility for the simple WPNC scheme to decode initial signal. As a next step, the

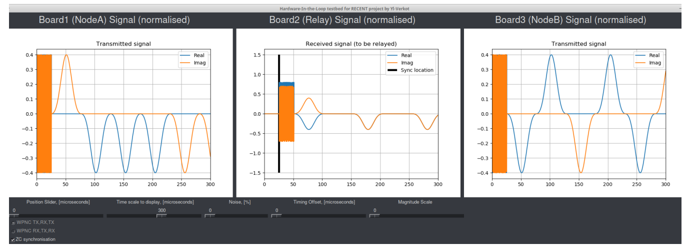

Fig. 5. WPNC simulation, phase 1, no noise.

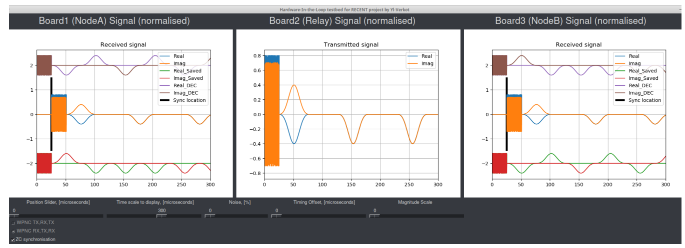

Fig. 6. WPNC simulation, phase 2, no noise.

HIL testbed represented above, is used to provide similar initial signals and WPNC scheme. First and second phases of the WPNC scenario implemented on the HIL testbed are shown in Figures 9 and 10.

The real-time signal processing shows that the used signal generators require additional signal processing for the precise decoding. Nevertheless, the simplest implementation shows that HIL testbed WPNC implementation allows signal transmission and decoding although it requires additional tuning and post-processing.

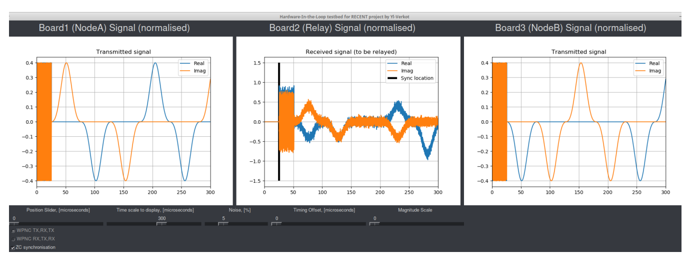

Fig. 7. WPNC simulation, phase 1, with noise.

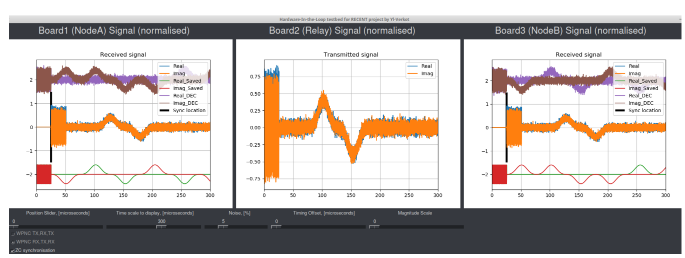

Fig. 8. WPNC simulation, phase 2, with noise.

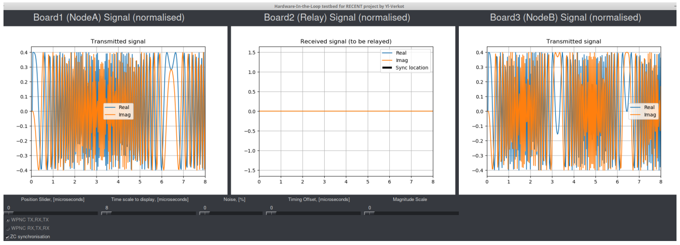

Fig. 9. Signals of the implemented HIL testbed WPNC scheme, phase 1.

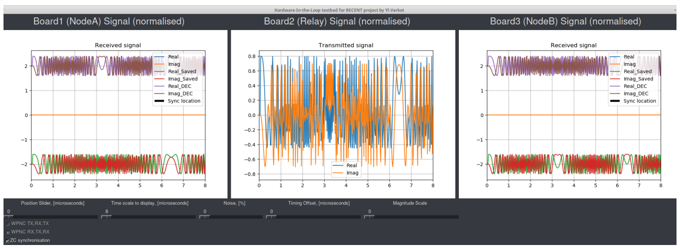

Fig. 10. Signals of the implemented HIL testbed WPNC scheme, phase 2.

VI. Conclusions

In this paper, we have proposed a testbed based on the Hardware-in-the-loop methodology for mmWave communication using centimetre wave band (Sub-6 GHz) SDR equipment. This approach may be suitable for IoT applications in 5G and B5G networks. The main aim of the proposed method is to use observation time and distance scaling to keep the signal parameters as close to the mmWave as possible. This approach allows to build reliable, scalable and cost-effective testbeds for the mmWave network analysis. As a future work, the results of the proposed approach will be compared with the mmWave testbed implementation in order to verify it's working capacity.

References

[1] S. Geng *et al*. "Millimeter-wave propagation channel characterization for short-range wireless communications". *IEEE Transactions on Vehicular Technology*, 58(1):3–13, Jan 2009.

[2] M. Shafi *et al*. "Microwave vs. millimeter-wave propagation channels: Key differences and impact on 5g cellular systems". *IEEE Communications Magazine*, 56(12):14–20, December 2018.

[3] Ricardo Santos, Konstantin Koslowski, Julian Daube, Hakim Ghazzai, Andreas Kassler, Kei Sakaguchi, and Thomas Haustein. Mmwave backhaul testbed configurability using software-defined networking. *Wireless Communications and Mobile Computing*, 2019:1–24, 04 2019.

[4] Valerio Frascolla, Michael Faerber, Emilio Calvanese Strinati, Laurent Dussopt, Vincent Kotzsch, Eckhard Ohlmer, Mehrdad Shariat, Jyri Putkonen, and Giovanni Romano. Mmwave use cases and prototyping: A way towards 5g standardization. In *2015 European Conference on Networks and Communications (EuCNC)*, pages 128–132, 2015.

[5] Tian Hong Loh, David Cheadle, and Philip Miller. A millimeter wave mimo testbed for 5g communications. In *2017 89th ARFTG Microwave Measurement Conference (ARFTG)*, pages 1–4, 2017.

[6] Gosan Noh, Junhyeong Kim, Hee Sang Chung, Bing Hui, Young-Min Choi, and Ilgyu Kim. mmwave-based mobile backhaul transceiver for high speed train communication systems. In *2017 IEEE Globecom Workshops (GC Wkshps)*, pages 1–5, 2017.

[7] John S. Seybold. *Introduction to RF Propagation*. John Wiley Sons, Ltd, 2005.

[8] Bismark Okyere, Leila Musavian, Berna Ozbek, Sherif A. Busari, and Jonathan Gonzalez. A novel joint index modulation and physical layer network coding mechanism for beyond 5g. *IEEE Communications Standards Magazine*, 5(2):100–105, 2021.

[9] N. Salman, I. Rasool, and A. H. Kemp. Overview of the ieee 802.15.4 standards family for low rate wireless personal area networks. In *2010 7th International Symposium on Wireless Communication Systems*, pages 701–705, 2010.

[10] J. Harris *et al*. "Spectrum sharing for m2m applications through whitetime exploitation in wifi networks". In *2016 IEEE Wireless Communications and Networking Conference*, pages 1–6, April 2016.

[11] T. Irnich *et al*. "Spectrum sharing scenarios and resulting technical requirements for 5g systems". In *2013 IEEE 24th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC Workshops)*, pages 127–132, Sep. 2013.

[12] L. Zhang, Y. Liang, and M. Xiao. "Spectrum sharing for internet of things: A survey". *IEEE Wireless Communications*, 26(3):132–139, June 2019.

[13] Steven W. Ellingson. *Electromagnetics, Vol. 2*. Blacksburg, VA: Virginia Tech Publishing, 2020.

[14] M. N. Abdallah, T. K. Sarkar, Vikass Monebhurrun, and M. Salazar-Palma. Defining the starting distance for the far field of antennas operating in any environment. In *2016 IEEE Conference on Antenna Measurements Applications (CAMA)*, pages 1–4, 2016.

[15] Constantine A Balanis. *Antenna theory: analysis and design*. John wiley & sons, 2015.

[16] B.D.O. Anderson, R.W. Newcomb, R.E. Kalman, and D.C. Youla. Equivalence of linear time-invariant dynamical systems. *Journal of the Franklin Institute*, 281(5):371–378, 1966.