Achieving Resilience in mmWave Communications by Using Non-reconfigurable Reflecting Surfaces

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***Abstract*—Millimeter wave (mmWave) spectrum is associated with abundance of available spectrum and excellent spectrum reuse, but also has the significant downside of decreased resilience. Communication can be disrupted when the line of sight (LOS) path is blocked, or the link quality may degrade due to obstacles. These issues are exacerbated by mobility. One possible countermeasure against such signal shadowing and blockage is the use of intelligent reconfigurable surfaces (IRSs). However, while IRSs have the advantage to form a beam directly targeting the user, user-tracking and the need to orchestrate the IRS are very challenging. A practical solution towards improving the resilience is the use of non-reconfigurable reflecting surfaces (NRRSs), which enable communication through reflections by creating additional signal paths via a pre-configured reflection pattern. With sufficient number of reflections through NRRSs, the probability of communication outage is significantly reduced. The additional signal paths in NRRS-assisted networks can be very useful in scenarios characterized by repetitive mobility patters, especially since the cost and complexity are heavily reduced compared to IRS. While the benefits of IRS deployment have been extensively studied, most analyses are limited to the simulation domain. In contrast, this paper provides practical insights derived from measurements conducted on a mmWave band testbed. Results reveal that even with a few NRRSs, the resilience of a mmWave communication link could be dramatically improved resulting in close-to-zero packet loss. However, the channel becomes highly frequency-selective, which makes the use of advanced physical layers like IEEE 802.11be with adaptive modulation & coding per resource unit (RU) a necessity.**

I. Introduction

As the demand for faster, more efficient wireless communication continues to soar, traditional sub-6 GHz networks are nearing their limits. In this regard, usage of millimeter wave (mmWave) technology arises as a promising solution due to the availability of unprecedented bandwidth needed for ultra-high-speed data transmission [1]. However, the usage of mmWave presents challenges such as greater signal attenuation and susceptibility to obstacles, resulting in possible communication outage and hence reduced resilience. Moreover, aggressive beamforming is needed to overcome signal pathloss and to reach the receiver side where the antenna sizes are relatively small. As a result of very directive communication, supporting mobility becomes a challenge in the mmWave bands [2].

Intelligent reconfigurable surfaces (IRSs), also interchangeably known as reconfigurable intelligent surfaces (RISs), have gained significant attention for their potential to enable ultra-reliable and low-latency communication in 6G and future networks [3]. This interest stems from their ability to manipulate the propagation environment and overcome the random, negative effects of the channel in a real-time, cost-effective manner, while providing high performance gain [4]. An IRS consists of many reflective elements and its main principle relies on the ability to adjust the phase and amplitude of incoming signals, scattering them in an almost uniform manner. By configuring these elements such that the incident waves are reflected towards a specific direction, IRS enables passive beamforming [5], making it indeed one of the key potential enablers for alleviating the challenges of mmWave technologies.

Apart from theoretical studies focusing on how to optimize the usage of IRS, starting from efficient configuration optimization of the surface itself to its integration in future networks [6], there is a growing interest in IRS fabrication and its incorporation into communication testbeds. For instance, the authors in [7] provide a comprehensive dataset of IRS-assisted channel measurements in the 5 GHz band.

One of the most beneficial applications of IRS is illuminating areas where line of sight (LOS) communication is not possible, and as mentioned before, mmWave technologies are prone to result in such situations due to the narrow beam characterizing these frequency bands. Despite the main principle of an IRS being its reconfigurability, there may be instances where the blockages in an environment are predictable and not highly variable over time. An example of this is an industrial setting where obstructions arise from the repetitive, similar movements of a mobile device, e.g., an industrial robot, within the area [8]. This would simplify IRS control and ease phase shift optimization, thus satisfying the ultra-low latency requirements of industrial internet of things.

Given that altering the layout of such an environment would be costly, a feasible solution to maintain seamless communication is to create artificially redundant signal paths. Non-reconfigurable reflecting surfaces (NRRSs) are a cheap possible solution for this. They operate on the same principle as an IRS in reflecting an impinging signal in a specific direction; however, they are pre-configured and cannot adjust their reflection direction. They enable communication through reflections by creating additional sufficient strong signal paths [9]. Unlike reflectarrays, NRRS does not require an associated feed to actively generate and transmit electromagnetic waves [10]. We believe that the usage of such NRRS might be a potential countermeasure against signal shadowing and blockage, and hence would dramatically improve the resilience of mmWave networks under mobility.

This paper takes a first step towards this goal by presenting experimental results from a NRRS-assisted network using a wideband transmission (802.11be EHT, 320 MHz) and operating in the 28 GHz spectrum. Our results reveal that even with a few NRRSs the resilience of a 28 GHz communication link could be dramatically improved resulting in close-to-zero packet loss. However, the introduction of artificial reflections creates challenges as the channel becomes highly frequency-selective making the use of advanced physical layers like 802.11be with adaptive coding & modulation (ACM) per radio resource unit (RU) a necessity. Such challenges and potential future directions towards the utilization of NRRSs in future mmWave networks are discussed.

II. Related Work

The potential applications of IRS are extensive, as their ability to modify propagation channel characteristics can enhance signal quality or attenuate it when necessary. According to the literature, one of the primary categories of IRS utilization is the improvement of signal coverage. Several derivatives of IRS's capability to focus the signal in one direction include illuminating obstructed areas, optimizing signal paths to reduce unnecessary transmissions, enabling disaster recovery, and facilitating adaptive wireless power transfer.

For example, the authors in [11] compare the signal coverage of an IRS-assisted system to the case of no IRS and the results indicate that signal coverage can be effectively extended by using a passive IRS alone, instead of installing an additional AP or active relay. As an example, the coverage can be extended to about 66% by utilizing their joint beamforming proposed scheme. Moreover, the improvement in signal precision reduces the need for extra spectrum resources for re-transmission and minimizes additional interference [12]. The study in [8] points out the promising applications of IRS in challenging environments such as underwater and underground communications, where they can mitigate harmful multipath propagation and reduce path loss. Similarly, in industrial settings, IRS can redirect signals to avoid absorption and reflection by metallic objects, whereas in disaster areas, IRS patches can act as ad hoc nodes to maintain connectivity and assist search and rescue operations despite infrastructure damage. The beam focusing capability of IRS has also gained attention in the wireless power transfer line [13], mainly because beamforming is enabled without active, power-hungry components, and because IRS can be mass-produced at very low cost.

IRSs can also provide better interference management by attenuating undesired signals and improving the signal to interference and noise ratio (SINR) metric. The authors in [14] address the challenge of spectrum sharing between multiple-input multiple-output (MIMO) radar and multi-user multiple-input single-output (MISO) communication systems, using an IRS to manage the interference from base station (BS). Simulations confirm that the IRS effectively controls interference and enhances radar detection probability. An IRS can also adjust the propagation environment to optimize spectrum usage by enhancing spectrum sensing techniques. In [15], the authors propose a novel IRS-enhanced energy detection scheme for single-user spectrum sensing, cooperative spectrum sensing, and diversity reception. The results reveal that the proposed scheme achieves a lower probability of miss detection compared to benchmark ones. Eavesdropping mitigation is another potential use case of IRS, which has been investigated in multiple works. Increasing the number of reflecting elements provides greater gains in secrecy performance compared to increasing the number of transmit antennas [16].

Apart from the numerous potential benefits of IRS, its deployment is also associated with several challenges. To start with, the IRS is usually operating at a certain frequency band, and it may have a negative impact on nearby signals at other frequencies. The likely necessity for operator cooperation in future IRS-assisted networks is pointed out in [17]. A similar work concerning pilot contamination is presented in [18], where the authors propose orthogonal IRS configuration for combating the negative impacts from nearby deployed IRS. Additionally, there are challenges such as the necessity for a control link for the IRS, the different requirements for scheduling, network planning and resource management that have to be addressed upon the incorporation of IRS into existing infrastructure [19].

Moreover, channel state information (CSI) acquisition presents a cascaded channel estimation challenge, requiring the estimation of BS-IRS and IRS-user equipment (UE) channels based on noisy observations of their product, while the practical limitation of IRS phase shifts to discrete values due to hardware quantization levels renders as well an optimization problem [20]. Lastly, the prospect of a malicious IRS, hacked and optimized to degrade the performance of the communication also exists [21].

This paper presents the results of measurements in the mmWave band, focusing on the improvements and challenges in communication performance that arise from integrating NRRS into a real-world testbed. First and foremost, a great advantage is that there is no need to estimate individual channels, as NRRSs are non-reconfigurable. Additionally, the channel estimation and equalization capabilities of 802.11be are sufficient for enabling communication over an NRRS-assisted channel. Due to the low complexity, the findings aim to highlight the potential applications of NRRS in future network deployments.

III. System Model & Problem Statement

The system model we consider consists of a single mmWave stationary transmitter and receiver, both equipped with an electronically steerable antenna array (cf. Figure 1). Additionally, there are N NRRSs deployed with fixed reflection characteristics, precisely aligned with the communication nodes. We assume the presence of a moving obstacle, such as an industrial robot or a human, which can freely move

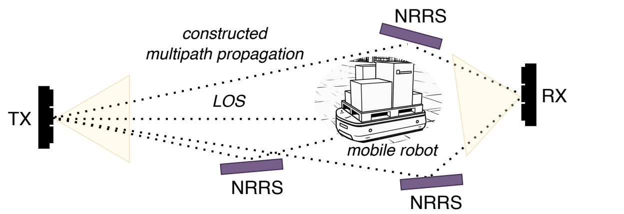

Figure 1. System model: mmWave communication link assisted by NRRSs to combat signal blockage from the freely mobile robot.

and potentially block one of the signal paths: the LOS path or reflections from NRRSs. The system utilizes a wideband OFDM signal as the waveform.

This paper presents experimental results based on tests conducted with real hardware. The goal is to determine whether deploying NRRSs can improve the resilience of a mmWave network—measured by a reduction in outage probability—when mobility occurs in the environment. Moreover, we aim to understand to what extent disadvantages arise.

IV. mmWave Testbed with NRRS

For our study we set up a small indoor mmWave testbed using software defined radios (SDRs) assisted with NRRSs. Specifically, the following hardware was used:

- **SDR**: USRP X410 (National Instruments), master clock rate = 500 MHz, IF=3.2 GHz,
- **Clock**: OctoClock CDA-2990 (National Instruments) for high-accuracy time and frequency reference distribution,
- **mmWave frontend**: BBox Lite 5G (788827-01, TMYTEK), RF=28 GHz, 3 dB beamwidth=25°,
- **mmWave frequency converter**: UD Box 5G (TMYTEK) for up/down conversion of IF band to RF band,
- **NRRS**: XRifle (TMYTEK), passive non-reconfigurable reflecting surface, 51×51 element array, RF=28 GHz, radar cross-section gain $\sim$70 dB,
- **Host**: AMD Ryzen 9 7950X 16-Core, 128 GB RAM, Mellanox 100 Gbe optical (MT27800 family),

Both SDRs (TX & RX) were synchronized using the NI Octoclock. Moreover, the two mmWave frontend were synchronized via the UD Box, which has a OCXO reference clock. For the experiments, we selected three NRRSs with the following angle configuration: i) INC: 0°, REF: 15°, ii) INC: 0°, REF: 30° and iii) INC: 0°, REF: 45°; where INC denotes the incidence angle and REF the reflection angle. These configurations are selected to simplify the testbed construction. They are positioned within the room where the testbed is built to ensure a clear communication path to both the transmitter and receiver nodes, precisely at their respective INC and REF angles. Finally, for the hosts we used commercial AMD Ryzen 9, which were connected to the USRPs with 100 Gbe Ethernet.

On the software side, we used the MATLAB WLAN toolbox to generate and decode the 802.11be OFDM waveform for transmission. Specifically, we used a configuration with a channel bandwidth of 320 MHz, BPSK modulation and a code rate of 1/2 resulting in a PHY datarate of 144 Mbps. Here the transmitter was sending the waveform in the loop (frame duration of $140\mu s$) while on receiver side we captured the signal with the SDR at a sampling rate of $S = 500$ MS/s for later processing in MATLAB. Note, that due to the extremely high sampling rate resulting in a data rate of 4 GByte/s, we used the Data Plane Development Kit (DPDK, https://www.dpdk.org/) and stored the samples in the main memory before writing to the hard drive. Finally, the frequency response for the OFDM signal was computed for each frame from the 802.11be EHT-LTF field, using the least square (LS) estimation technique [22]. The CFR was computed as:

$$\hat{H}[k] = Y[k]/X[k], \tag{1}$$

where $\hat{H}[k]$ represents the estimated CFR, $Y[k]$ denotes the received symbols, $X[k]$ denotes the transmitted symbols and k denotes the subcarrier index. Here, $Y[k]$ captures the distorted signal at the receiver due to the channel effects, and $X[k]$ is the known transmitted reference signal. The missing null subcarriers are obtained using interpolation (moving window median). Finally, the channel impulse response (CIR), characterizing the channel in time domain, is obtained using inverse FFT (IFFT) transformation.

V. Experimental Results

A. Carrier Frequency Offset

As a preliminary study, we analyzed the carrier frequeny offset (CFO). The CFO is a result of the misalignment between the transmitter and receiver's local oscillators. Factors such as temperature changes and aging, influence the oscillator frequency to drift slowly, resulting in a slowly varying CFO between a communication pair [23]. Even though the CFO estimation and compensation is part of the post-processing procedure, due to these errors this compensation is performed partially leading to a residual phase offset that is fast time-varying. According to [24], compared to single carrier systems, OFDM systems are more sensitive to frequency offsets, particularly when using small subcarrier spacing. This is necessary because we are transmitting the 802.11be waveform in the 28 GHz band, which was originally optimized for the sub-6 GHz spectrum. In this higher frequency band, the CFO might be too large to be estimated and corrected.

We estimated the CFO from the 802.11be preamble using the MATLAB functions `wlanCoarseCFOEstimate` and `wlanSymbolTimingEstimate`. A histogram over 70k estimated CFO values is shown in Figure 2. The results show

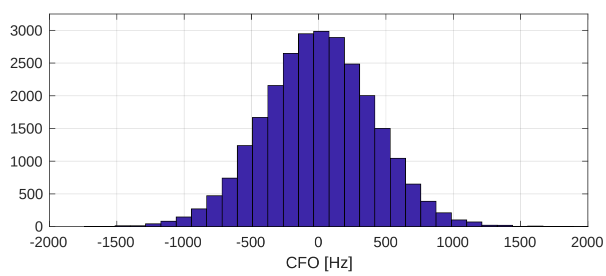

Figure 2. CFO estimated from the 802.11be preamble.

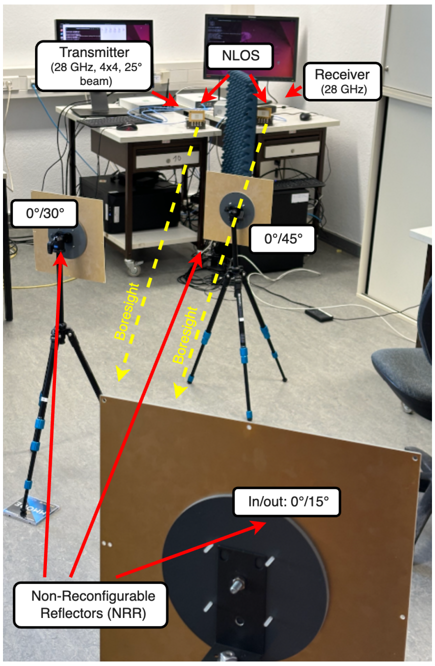

Figure 3. Experimental setup for the **NLOS w/ NRRS** scenario.

that the CFO is sufficiently small to be corrected, i.e., max CFO = $78.125/2 \approx 39\,\text{kHz}$ (half of the subcarrier spacing).

B. Channel Frequency Response

Following, we want to understand how the wideband channel propagation is affected by the existence of NRRSs. Therefore, we estimate the channel frequency response (CFR) of our 320 MHz waveform for the following three scenarios:

- **Cable**: transmission over wired (coaxial) cable as baseline (no mmWave frontends involved),
- **LOS**: 28 GHz point-to-point (P2P) link with perfectly aligned beams (TX & RX) and LOS condition,
- **NLOS w/ NRRS**: 28 GHz P2P link with pure non-line of sight (NLOS) (TX/RX with same boresight angle) but reflections from $N = 3$ NRRSs (see Figure 3).

The CFR for the three cases is shown in Figure 4. The result for **Cable** shows that the channel has a perfect flat response in frequency domain when transmitted over the cable. This is as expected due to the missing multipath. The situation is similar in **LOS** with only small frequency-selectivity due to weak reflections, e.g., from the walls behind. The situation is totally different for **NLOS w/ NRRS** where the channel becomes highly frequency-selective with variability of more than 15 dB across the subcarriers. This can be explained by the strong multipath from the NRRSs resulting in constructive and destructive wave interference. From Figure 5 we see that with increasing number of NRRSs the frequency selectivity significantly increases. With $N = 3$ NRRSs we can observe a variation of more than 20 dB.

C. Resilience under Mobility

Here we study the resilience of the two scenarios, i.e., **LOS** and **NLOS w/ NRRS** under mobility. Figure 6 shows

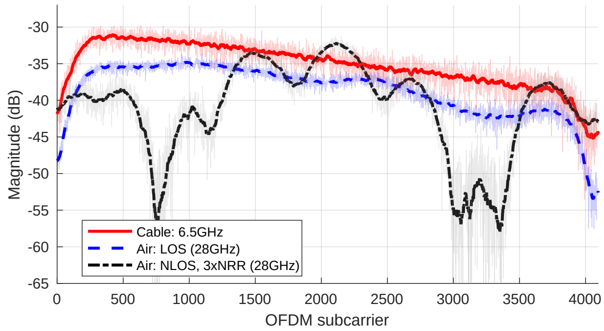

Figure 4. CFR of EHT transmission (320 MHz) for three different channels.

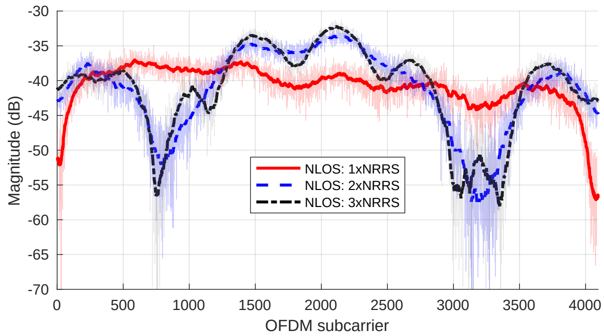

Figure 5. The impact of the number of NRRSs on the frequency-selectivity of the EHT transmission.

the experimental setups with a person walking along the red trajectory with constant speed and blocking with its body the LOS and/or reflecting signals at certain times. The whole experiment took 10 s. A study considering the influence of human mobility in mmWave communication is provided in [25], where it is shown that IRS deployment can decrease outage probability. The authors optimize the location of the IRS based on the mobility of the human. Unlike this work, in our scenario the resilience is achieved by the multiple artificial reflections of the NRRSs, resulting in lower outage probability. In other words, communication outage only occurs if all the links are simultaneously blocked; the probability of which decreases as the number of redundant links increases. As performance metric for resilience, we selected the packet success rate (PSR) computed over the duration of the full run. Note that the transmitter sent packets at a rate of 7.1 kHz.

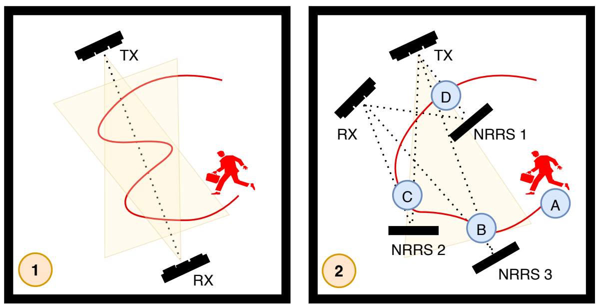

Figure 6. Two experimental setups with a person walking along red trajectory for the two scenarios: **LOS** scenario (left) and **NLOS w/ NRRS** (right).

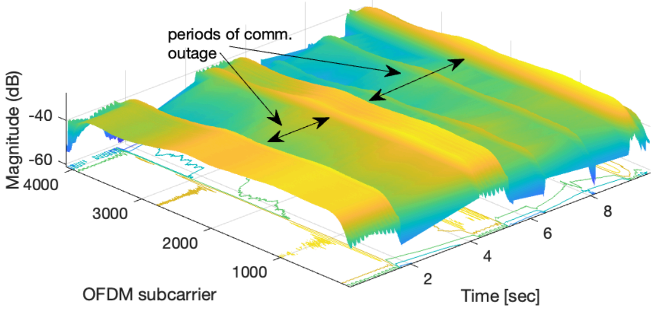

Figure 7. Measured CFR under mobility for the **LOS** scenario.

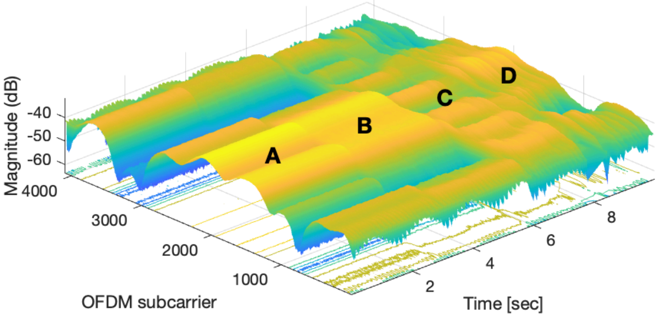

Figure 8. Measured CFR under mobility for **NLOS w/ NRRS** scenario.

For the **LOS** scenario, the results are shown in Figure 7 where for each correctly received packet the magnitude of the CFR, i.e., OFDM subcarrier, is shown. We can clearly observe two gaps of multiple seconds duration where no successful packet transmission was possible resulting in full communication outage, i.e., PSR=0. During that time, the LOS path between the transmitter and receiver was fully blocked by the person, while the surrounding reflections where not sufficient for communication. The overall PSR was only 0.352.

The results for **NLOS w/ NRRS** are totally different (cf. Figure 8), where there was never a communication outage although at no time did a LOS between transmitter and receiver exist. Here the communication took place over the reflections generated by the NRRS. At time **A**, all 3 reflections from NRRS 1-3 were unblocked. However, at times **B**, **C** and **D**,

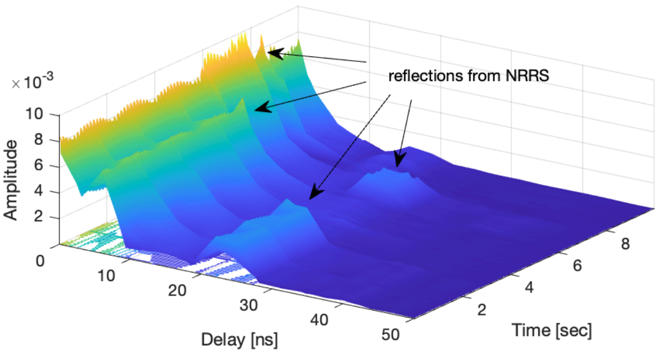

Figure 9. PDP for the **NLOS w/ NRRS** scenario under mobility.

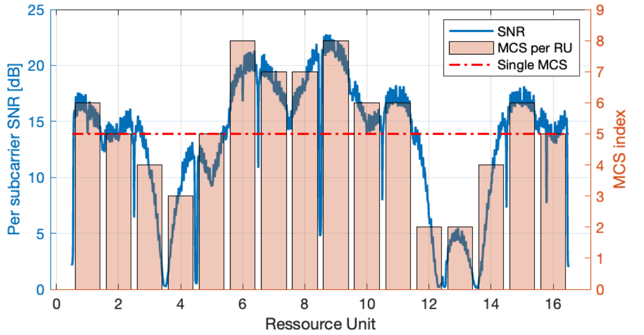

Figure 10. Two different MCS selection strategies: 1) single best MCS for all RUs, vs. 2) best MCS for each RU.

the path towards NRRS 3, 2 and 1 was blocked respectively. Over the entire measurement period only a few packets were lost sporadically resulting in a overall PSR=0.998.

Figure 9 shows how the PDP computed from CFR changed over time. Note, that the PDP depicts the received signal power for each multipath component (MPC) as a function of the propagation delay. Here we can clearly see how new taps (i.e., reflections) appear and disappear. It is noteworthy to mention that there is no communication possible for the **NLOS w/out NRRS** case, hence for that case, PSR=0.

VI. Discussion

As we have seen, the resilience of a mmWave communication network can be substantially increased through the intelligent use of inexpensive NRRSs. However, also difficulties arise such as the emergence of frequency-selective wideband channels with variation of $> 15\,\text{dB}$ (cf. Figure 5). This can be addressed by using advanced physical layers like 802.11be, which allow the assignment of modulation coding scheme (MCS) per radio RU; such that for the transmission of RUs with high channel gain a higher MCS can be used. As an example, we consider the CFR from Figure 5 for the 3 NRRS case. We used the physical layer abstraction as suggested by TGax evaluation methodology [26] to compute the effective data rate for the two cases: 1) single best MCS for all RUs, vs. 2) best MCS for each RU (cf. Figure 10). Specifically, we computed the effective signal to noise ratio (SNR) from the per subcarrier SNR, which gives the equivalent packet error rate (PER) performance in an additive white Gaussian noise (AWGN) channel, from which the PER was derived taking into account the selected MCS. Our results show an increase in effective data rate by around $6.5\,\%$ when it is possible to adapt the MCS per RU. Note that in a multi-user scenario, the frequency selectivity can be exploited for opportunistic scheduling and thus, a higher gain would be expected.

Another challenge is the practical implementation. In our scenario, we carefully placed the NRRSs such that the transmitter could communicate with the receiver via its reflection. This is a complex task due to the directionality of the NRRS and also requires knowledge of the movement trajectory of the obstacle (here, a person). However, this is an example scenario proving that the resilience can be improved via NRRSs, and a more systematic study of the number and configuration of the NRRSs is left for future work.

Given the promising results regarding the additional reflection paths provided by the NRRS, which enhance network resilience, future work will focus on understanding the impact of introducing randomness into the system, i.e. random placement and alignment of NRRS. The hypothesis is that randomness and redundancy will continue to improve resilience. Moreover, the random placement and alignment of NRRSs will lead to cost-efficient deployments as less manual work for deployment is required. To test this, upcoming studies will analyze measurement results from random placements and alignments of NRRS in similar testbeds. Additionally, future research will extend towards multi-user systems in order to understand issues of scalability, i.e. number of NRRS required as a function of the number of users in the system.

VII. Conclusions

We presented results from experiments in a 28 GHz indoor testbed which reveal that the deployment of only few inexpensive non-reconfigurable reflecting surfaces (NRRSs) is able to dramatically improve the resilience in mmWave communication networks under mobility in the surrounding. However, as the channel becomes highly frequency-selective, advanced physical layers like introduced in 802.11be become a necessity. As future work, we plan to extend our study towards scenarios with multiple moving objects and multiple mmWave links. Moreover, we want to exploit the advantages from multi-beam steering in mmWave, which is promising as the number of required NRRSs can be reduced.

Acknowledgments

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References

[1] S. Rangan, T. S. Rappaport, and E. Erkip, "Millimeter-Wave Cellular Wireless Networks: Potentials and Challenges," *Proceedings of the IEEE*, vol. 102, no. 3, pp. 366–385, Mar. 2014.

[2] S. A. Busari, K. M. S. Huq, S. Mumtaz, L. Dai, and J. Rodriguez, "Millimeter-Wave Massive MIMO Communication for Future Wireless Systems: A Survey," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 2, pp. 836–869, 2018.

[3] C. Pan, H. Ren, K. Wang, J. F. Kolb, M. Elkashlan, M. Chen, M. Di Renzo, Y. Hao, J. Wang, A. L. Swindlehurst, X. You, and L. Hanzo, "Reconfigurable Intelligent Surfaces for 6G Systems: Principles, Applications, and Research Directions," *IEEE Communications Magazine*, vol. 59, no. 6, pp. 14–20, Jun. 2021.

[4] I. Yildirim, A. Uyrus, and E. Basar, "Modeling and Analysis of Reconfigurable Intelligent Surfaces for Indoor and Outdoor Applications in Future Wireless Networks," *IEEE Transactions on Communications*, vol. 69, no. 2, pp. 1290–1301, Feb. 2021.

[5] S. Gharbieh, R. D'Errico, and A. Clemente, "Reconfigurable Intelligent Surface Design using PIN Diodes via Rotation Technique – Proof of Concept," in *European EuCAP 2023*, Florence, Italy: IEEE, Mar. 2023.

[6] Y. Liu, X. Liu, X. Mu, T. Hou, J. Xu, M. Di Renzo, and N. Al-Dhahir, "Reconfigurable Intelligent Surfaces: Principles and Opportunities," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 3, pp. 1546–1577, 2021.

[7] S. Tewes, M. Heinrichs, K. Weinberger, R. Kronberger, and A. Sezgin, "A comprehensive dataset of RIS-based channel measurements in the 5GHz band," in *IEEE VTC 2023-Spring*, Florence, Italy, Jun. 2023.

[8] S. Kisseleff, S. Chatzinotas, and B. Ottersten, "Reconfigurable Intelligent Surfaces in Challenging Environments: Underwater, Underground, Industrial and Disaster," *IEEE Access*, Nov. 2021.

[9] J. Gordon, C. Holloway, and A. Dienstfrey, "A Physical Explanation of Angle-Independent Reflection and Transmission Properties of Metafilms/Metasurfaces," *IEEE Antennas and Wireless Propagation Letters*, vol. 8, pp. 1127–1130, Sep. 2009.

[10] Z. Fu, X. Zou, Y. Liao, G. Lai, Y. Li, and K. L. Chung, "A Brief Review and Comparison Between Transmitarray Antennas, Reflectarray Antennas and Reconfigurable Intelligent Surfaces," in *2022 TOCS 2022*, Dalian, China, Dec. 2022, pp. 1192–1196.

[11] Q. Wu and R. Zhang, "Intelligent Reflecting Surface Enhanced Wireless Network: Joint Active and Passive Beamforming Design," in *IEEE GLOBECOM 2018*, Abu Dhabi, United Arab Emirates: IEEE, Dec. 2018, pp. 1–6.

[12] C. Zhang, H. Lu, and C. W. Chen, "Reconfigurable Intelligent Surfaces-Enhanced Uplink User-Centric Networks on Energy Efficiency Optimization," *IEEE Transactions on Wireless Communications*, vol. 22, no. 12, 2023.

[13] N. M. Tran, M. M. Amri, J. H. Park, D. I. Kim, and K. W. Choi, "Reconfigurable-Intelligent-Surface-Aided Wireless Power Transfer Systems: Analysis and Implementation," *IEEE Internet of Things Journal*, vol. 9, no. 21, pp. 21 338–21 356, Nov. 2022.

[14] X. Wang, Z. Fei, J. Guo, Z. Zheng, and B. Li, "RIS-Assisted Spectrum Sharing Between MIMO Radar and MU-MISO Communication Systems," *IEEE Wireless Communications Letters*, vol. 10, no. 3, pp. 594–598, Mar. 2021.

[15] W. Wu, Z. Wang, L. Yuan, F. Zhou, F. Lang, B. Wang, and Q. Wu, "IRS-Enhanced Energy Detection for Spectrum Sensing in Cognitive Radio Networks," *IEEE Wireless Communications Letters*, vol. 10, no. 10, Oct. 2021.

[16] Z. Zhang, C. Zhang, C. Jiang, F. Jia, J. Ge, and F. Gong, "Improving Physical Layer Security for Reconfigurable Intelligent Surface Aided NOMA 6G Networks," *IEEE Transactions on Vehicular Technology*, vol. 70, no. 5, pp. 4451–4463, May 2021.

[17] J. Angjo, A. Zubow, and F. Dressler, "Side Effects of IRS: On the Need for Coordination in 6G Multi-Operator IRS-assisted Networks," in *IEEE GLOBECOM 2023, 6GComm Workshop*, Kuala Lumpur, Malaysia: IEEE, Dec. 2023, pp. 1380–1385.

[18] D. Gürgünoğlu, E. Björnson, and G. Fodor, "Impact of Pilot Contamination Between Operators With Interfering Reconfigurable Intelligent Surfaces," in *IEEE BlackSeaCom 2023*, Istanbul, Turkey: IEEE, Jul. 2023.

[19] Y. Zhao and M. Jian, "Applications and Challenges of Reconfigurable Intelligent Surface for 6G Networks," arXiv, cs.NI 2108.13164, Aug. 2021.

[20] X. Yuan, Y.-J. A. Zhang, Y. Shi, W. Yan, and H. Liu, "Reconfigurable-Intelligent-Surface Empowered Wireless Communications: Challenges and Opportunities," *IEEE Transactions on Wireless Communications*, vol. 28, no. 2, pp. 136–143, Apr. 2021.

[21] S. Rivetti, Ö. T. Demir, E. Björnson, and M. Skoglund, "Malicious Reconfigurable Intelligent Surfaces: How Impactful can Destructive Beamforming be?" *IEEE Wireless Communications Letters*, vol. 13, no. 7, pp. 1918–1922, 2024.

[22] J. Heiskala and J. Terry, *OFDM Wireless LANs: A Theoretical and Practical Guide*. Indianapolis, IN: SAMS, 2001.

[23] K. Wu, J. Pegoraro, F. Meneghello, J. A. Zhang, J. O. Lacruz, J. Widmer, F. Restuccia, M. Rossi, X. Huang, D. Zhang, G. Caire, and Y. J. Guo, "Sensing in Bi-Static ISAC Systems with Clock Asynchronism: A Signal Processing Perspective," arXiv, eess.SP 2402.09048, Jun. 2024.

[24] M. Speth, S. Fechtel, G. Fock, and H. Meyr, "Optimum receiver design for wireless broad-band systems using OFDM. I," *IEEE Transactions on Communications*, vol. 47, no. 9, pp. 1668–1677, Sep. 1999.

[25] H. Qin, Z. Liu, and C. Yang, "Indoor mm-Wave Coverage Enhancement: Reconfigurable Intelligent Surface Deployment Strategy Based on Human Mobility Model," *IEEE Communications Letters*, vol. 26, no. 10, pp. 2475–2479, Oct. 2022.

[26] 802.11ax PHY-Focused System-Level Simulation, https://de.mathworks.com/help/wlan/ug/802-11ax-phy-focused-system-level-simulation.html.