Reconfigurable Intelligent Surface for 5G NR Uplink Coverage Enhancement

Visa Tapio*, Arman Shojaeifard†, Ibrahim Hemadeh†, Alain Mourad† and Markku Juntti*
*Centre for Wireles Communications (CWC)
University of Oulu, Oulu, Finland
Email: FirstName.LastName@oulu.fi
†InterDigital Europe, Ltd.
London, UK
Email: FirstName.LastName@interdigital.com

***Abstract*—Reconfigurable intelligent surfaces (RIS) have the ability to steer the electromagnetic (EM) waves to a desired direction. This enables the improvement of the wireless link performance by allowing the illumination of receivers otherwise shadowed by buildings or hills. In this paper, a standards-compliant link-level simulator is developed to study the performance improvement offered by a RIS in 5G New Radio (NR) uplink operating at sub-6 GHz bands. At these frequencies the direct channel between the user and base station is rarely completely blocked, but given the stringent power restrictions of devices, the RIS is utilized for enhancing the coverage performance in the uplink direction. In the studied cases, the transmitter (TX) is close to the RIS and a line-of-sight (LoS) path between the TX and RIS is assumed. The channel between the TX and receiver (RX) is modeled as a non-line-of-sight (NLoS) channel with 5G NR clustered delay line A (CDL-A) profile. Both LoS and NLoS channels between the RIS and RX are considered. Under state-of-the-art system settings, the RIS is shown to increase the symbol error rate link performance by 6 dB. When the performance is measured with coded bit error rate, the performance gain in simulated cases is 1 dB. The coverage enhancement is measured with the throughput as a function of the distance between the TX and RX. The distance at which the maximum possible throughput can be achieved is increased about 5%. The coverage can be further extended if a lower than the maximum throughput is accepted.**

***Index Terms*—Intelligent re-configurable surface, beam steering, 5G NR**

I. INTRODUCTION

Reconfigurable intelligent surface (RIS) is a programmable structure that can be used to control the propagation environment by changing the electric and magnetic properties of the surface. By placing RIS in a wireless communications environment, the properties of the radio channels can be controlled, at least partially. This unique capability of RIS technology may enable a number of benefits, including the potential for enhancing reliability and coverage performance through beamforming or range extension.

The ability to control the propagation environment has somewhat changed the conventional wireless system design paradigm, where the radio channel was always seen for the most part as an uncontrollable entity that distorts the transmitted signals. Hence traditionally the transmitter (TX) and the receiver (RX) were designed to equalize the impact of the channel. Envisioned scenarios vary from cases where a single RIS is placed on a wall to direct signals coming from a predetermined direction, e.g., base station, to the environment where almost all surfaces (walls, furniture, clothes, etc.) are covered with a metasurface based IRS [1], [2], [3], [4].

An RIS is typically envisioned to enable communication in millimeter wave and terahertz frequency scenarios where a direct link between a TX and RX is completely blocked as, e.g., in [5], [6], [7]. In this paper, a RIS assisted 5G new radio (NR) physical uplink shared channel (PUSCH) transmission at the 5G FR1 frequency range (410 MHz – 7125 MHz [8]) is considered. At this frequency range, the direct link is very rarely completely blocked. Hence, the RIS is not used to enable the transmission from the TX to RX but to enhance the link performance.

The path losses from the TX to the RX, TX to the RIS, and RIS to the RX are assumed to follow the 5G NR path loss models [9]. The channel delay profile for the TX – RX channel is assumed to follow the 5G NR CDL-A model [9]. The channels between the TX and RIS, and RIS and RX are assumed to be 1-tap line-of-sight (LoS) channels. The effect of the RIS on the path loss between the TX and RX is studied with simulations. bit error rate (BER) performances for a SISO and 2×2 MIMO scenarios are also simulated. The coverage extension is studied by simulating the throughput as a function of the distance between the TX and RX. The RIS is assumed to be close to the TX meaning that the distance from the RIS to the RX is same as from the TX to the RIS.

II. SYSTEM MODEL

The system considered in this paper is a RIS assisted 5G NR physical uplink shared channel (PUSCH). It consists of a TX, RX and RIS as illustrated in Fig. 1. The TX and RX can be single or multi-antenna devices. It is assumed that the RIS is located near the TX, e.g, in the wall of an office where the user is situated. The channel between the transmitter and receiver is assumed to be a non-line-of-sight (NLoS) channel with distance d_1, while the channel from the TX to RIS is assumed to be a line-of-sight (LoS) channel. The RIS to RX can be a NLoS or a LoS channel. The distances between the TX and RIS, and RIS and RX are d_2 and d_3, respectively. At

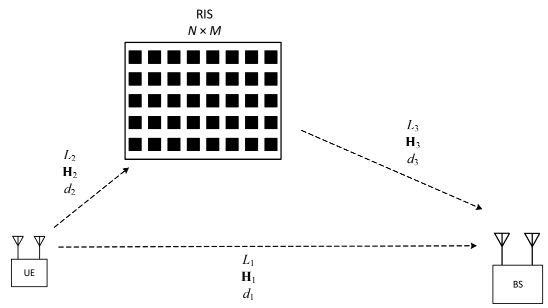

Fig. 1. RIS assisted wireless link.

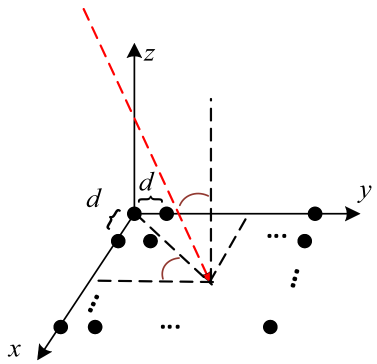

Fig. 2. Signal arriving at RIS

FR1 frequency range the fading channels are often modeled with tapped delay line models (TDL). The TDL models do not include information about the angle-of-arrival (AoA) or angle-of-departure (AoD) needed in the modeling of the reflection in a RIS. Hence, in this paper the fading processes are modeled with clustered delay line (CDL) models since they incorporate the direction information.

III. BEAMFORMING AT RIS

The RIS is used to direct the signal coming from the TX towards the RX. In order to maximize the signal-to-noise-ratio (SNR) at the RX, the RIS should form a narrow beam pointing to the RX.

When an EM wave impinges a planar array from the direction defined with the angle between the z-axis and the propagation direction of the wave (φ) and the propagation direction in $x-y$ plane (ϕ) (see Fig. 2), the signal components on the $x-y$ plane are

$$\mathbf{X}_{\text{RIS}}(x,y) = \mathbf{f}_1\mathbf{f}_2^T h_{\text{BS}\rightarrow\text{RIS}}(\varphi,\phi)x_{\text{BS}}(\varphi,\phi) \tag{1}$$

where $x_{\text{BS}}(\varphi,\phi)$ is the signal sent by a transmitter, e.g., base station (BS), and received by the planar array from (φ,ϕ) direction, $h_{\text{BS}\rightarrow\text{RIS}}(\varphi,\phi)$ is the channel between the base station and array seen by the signal x_{BS}, and vectors $\mathbf{f}_1$ and $\mathbf{f}_2$ are

$$\mathbf{f}_1 = [1 \ e^{j\kappa d\sin u} \ e^{j\kappa 2d\sin u} \ \cdots \ e^{j\kappa(N-1)d\sin u}]^T \tag{2}$$

$$\mathbf{f}_2 = [1 \ e^{j\kappa d\sin v} \ e^{j\kappa 2d\sin v} \ \cdots \ e^{j\kappa(N-1)d\sin v}]^T \tag{3}$$

where $\sin v = \sin\varphi\sin\phi$ and $\sin u = \sin\varphi\cos\phi$ and N and M are the numbers of elements in x and y directions, respectively. The element spacing of the RIS is d and $\kappa = 2\pi/\lambda$ (λ = wavelength). When (0,0,0) in Fig. 2 is selected as a reference point, the relative phase shift at point (n,m) on the planar array is

$$\psi(n,m) = \kappa(nd\sin\varphi\cos\phi + md\sin\varphi\sin\phi) \tag{4}$$

where $\kappa = 2\pi/\lambda$. In order to reflect the signal towards the (φ_r, ϕ_r) direction, the required relative phases of the elements are

$$\psi_r(n,m) = \kappa(nd\sin\varphi_r\cos\phi_r + md\sin\varphi_r\sin\phi_r). \tag{5}$$

This means that the phase of the signal at element (n,m) must be changed by

$$\begin{aligned}\psi_r(n,m) =& nd(\sin\varphi_r\cos\phi_r - \sin\varphi\cos\phi) \\ &+ md(\sin\varphi_r\sin\phi_r - \sin\varphi\sin\phi).\end{aligned} \tag{6}$$

IV. LINK BUDGET FOR A RIS ASSISTED LINK

A. *Single Antenna Transmitter and Receiver*

If the distances d_1, d_2 and d_3 in Fig. 1 are large compared to the RIS dimensions, the average path losses between the transmit antenna and RIS elements are the same for all RIS elements. In this case, assuming isotropic RX antenna and RIS elements, the average power received by a single RIS element is

$$P_{\text{RIS}}^{n,m} = P_{\text{TX}} - L_2 \tag{7}$$

where P_{TX} and L_2 are the transmitted power and path loss between the TX and RIS, respectively. Since the RIS is able to form a beam towards the RX, the power from the RIS received by the RX antenna, assuming isotropic RX antenna, is

$$\begin{aligned}P_{\text{RX}}^{\text{RIS}} &= P_{\text{RIS}}^{n,m} + 20\log_{10}(N\cdot M) - L_3 \\ &= P_{\text{TX}} + 20\log_{10}(N\cdot M) - L_2 - L_3\end{aligned} \tag{8}$$

where L_3 is the average path loss between a RIS element and RX antenna.

The received signal through the path 1 is

$$P_{\text{RX}}^{\text{direct}} = P_{\text{TX}} - L_1 \tag{9}$$

where L_1 is the path loss between the TX and RX. If the powers given by (8) and (9) sum up non-coherently, the averaged received power is

$$P_{\text{RX}} = 10\log_{10}(10^{P_{\text{RX}}^{\text{direct}}/10} + 10^{P_{\text{RX}}^{\text{RIS}}/10}). \tag{10}$$

If the RIS is, in addition to steering the beam towards the RX, is able to control the received signal phase at the RX, the signal through the direct path and via the RIS are summed up coherently in an ideal case. In this case the received power at RIS is

$$P_{\text{RX}}^{\text{ideal}} = 20\log_{10}(\sqrt{10^{P_{\text{RX}}^{\text{direct}}/10}} + \sqrt{10^{P_{\text{RX}}^{\text{RIS}}/10}}) \tag{11}$$

The signal-to-noise-ratio (SNR) at the receiver can be calculated when the signal bandwidth (B) and the receiver noise figure are known. The SNR is

$$\gamma = P_{\text{RX}} + 10\log_{10}(B) - 174 - F_{\text{dB}} \tag{12}$$

where B, P_{RX} and noise figure (F_{dB}) are given in decibel-milliwatts (dBm), hertz (Hz) and decibels (dB), respectively.

B. Multi-antenna TX and RX

When a multi-antenna transmitter and and receiver are used, the path losses between the individual TX, RIS and RX antenna elements can be calculated as in Section IV-A. However, the SNR depends on the signal combining at the receiver.

If the same signal is transmitted from all TX antennas and the TX to RIS, TX to RX and RIS to RX channels are single path LoS channels, the effect of the transmit and receive antenna arrays can be given with array gains. The signal power at the RX received from the RIS in this case is

$$\begin{aligned} P_{\text{RX}}^{\text{RIS}} =& P_{\text{TX}} + G_{\text{TX}}(\varphi_1,\phi_1) + G_{\text{RX}}(\varphi_2,\phi_2) \\ &+ 20\log_{10}(N\cdot M) - L_2 - L_3 \end{aligned} \tag{13}$$

where $\varphi_1,\ \phi_1$ are the zenith and azimuth angles defining the direction from the TX antenna array to the RIS, and $\varphi_2,\ \phi_2$ are the zenith and azimuth angles defining the direction from the RX antenna array to the RIS, respectively. Similarly, the signal power received through the direct link is given as

$$P_{\text{RX}}^{\text{direct}} = P_{\text{TX}} + G_{\text{TX}}(\varphi_3,\phi_3) + G_{\text{RX}}(\varphi_4,\phi_4) - L_1 \tag{14}$$

where $\varphi_3,\ \phi_3$ are the zenith and azimuth angles defining the direction from the TX antenna array to the RX, and $\varphi_4,\ \phi_4$ are the zenith and azimuth angles defining the direction from the RX antenna array to the TX, respectively. The TX and RX arrays gains to directions defined by $\varphi_i,\ \phi_i$ are given by $G_{\text{TX}}(\varphi_i,\phi_i)$ and $G_{\text{RX}}(\varphi_i,\phi_i)$. The averaged signal power at the RX is the sum of the powers from the direct path and RIS given by (10).

If multiple streams are are transmitted simultaneously from different TX antennas, statistical properties of the channel must also be considered in addition to the received SNR. The concatenated channel from TX to RIS and RIS to RX forms a keyhole channel. If the signal power received from this channel is larger than the the power received through the direct channel between the TX and RIS, the channel can become ill-conditioned. In order to prevent this, a joint pre-coding at the TX and RIS and combining at RX is needed. The pre-coding and combining is left for future work.

C. Path Loss Models

The environment in the urban micro channel scenario is an open area, such as city or station square. The width of the open area is assumed to be in the order of 50 to 100 m. The base station is assumed to be mounted below rooftop levels of the surrounding buildings, the transmitter antenna height (h_{BS}) is 10 m and receiver antenna height (h_{UT}) is 1.5 – 2.5 m. The path-loss model for the LoS scenario is [9].

$$L_{\text{UMi,LOS}} = \begin{cases} L_{1,\text{UMi}}, & 10 \text{ m} \le d_{2D} \le d_{\text{BP}}^{'} \\ L_{2,\text{UMi}}, & d_{\text{BP}}^{'} \le d_{2D} \le 5 \text{ km} \end{cases} \tag{15}$$

where

$$\begin{aligned} L_{1,\text{UMi}} =& 32.4 + 21\log_{10}(d_{3D}) + 20\log_{10}(f_c) \\ L_{2,\text{UMi}} =& 32.4 + 40\log_{10}(d_{3D}) + 20\log_{10}(f_c) \\ &- 9.5\log_{10}(d_{\text{BP}}^{'2} + (h_{\text{BS}} - h_{\text{UT}})^2) \end{aligned} \tag{16}$$

For the NLoS scenario the path-loss model is

$$L_{\text{UMi,NLOS}} = \max(L_{\text{UMi,LOS}}, L_{\text{UMi,NLOS}}^{'}) \tag{17}$$

where $10 \text{ m} \le d_{2D} \le 5$ km and

$$\begin{aligned} L_{\text{UMi,NLOS}}^{'} =& 22.4 + 35.3\log_{10}(d_{3D}) + 21.3\log_{10}(fc) \\ & 0.3(h_{\text{UT}} - 1.5) \end{aligned} \tag{18}$$

In above equation the center frequency f_c is in GHz. Parameter $d_{\text{BP}}^{'}$ above is defined by

$$d_{\text{BP}}^{'} = 4h_{\text{BS}}^{'}h_{\text{UT}}^{'}f/c \tag{19}$$

where

$$h_{\text{BS}}^{'} = h_{\text{BS}} - h_E \tag{20}$$

$$h_{\text{UT}}^{'} = h_{\text{UT}} - h_E \tag{21}$$

Frequency f is the same as f_c given in Hz and not in GHz as in the path-loss equations. Parameter h_E is the effective environment height. It is assumed to be 1 m.

When both the TX and RIS are in an office, the path loss can be with the InH-Office model in [9]. The path loss for a LoS link is

$$L_{\text{InH,LoS}} = 32.4 + 17.3\log_{10}(f_c) + 20\log_{10}(d_{3D}). \tag{22}$$

For a NLoS channel, the path loss is

$$L_{\text{InH,NLoS}} = \max(L_{\text{InH,LoS}}), L_{\text{InH,LoS}}^{1}) \tag{23}$$

where

$$L_{\text{InH,LoS}}^{1} = 38.3\log_{10}(d_{3D}) + 17.3 + 24.9\log_{10}(f_c). \tag{24}$$

V. NUMERICAL RESULTS

The 5G NR PUSCH model is based on the model available in Matlab 5G Toolbox. The RIS is modeled as a $N \times N$ planar array with isotropic elements. The element distances in horizontal and vertical directions are $\lambda/2$ (λ = wavelength). The channel between the TX and RX is modeled with a clustered delay line (CDL) with the delay profile CDL-A defined in [9]. The average path loss between the TX and RX is assumed to follow the NLos urban micro model in (15) – (21). The channels between the TX and elements of the RIS, and the elements of the RIS and RX are 1-tap channels, i.e., there are N parallel 1-tap channels between the TX and RIS and also between the RIS and RX. These channels are also modeled with the CDL channel model in the Matlab 5G Toolbox. The path loss between the TX and RIS is assumed to follow the LoS indoor channel in (22) – (24). For the channel

TABLE I
SINGLE ANTENNA TX AND RX.

RIS	$h_{\text{RIS}} = 2$ m $d_2 = 10$ m	$h_{\text{RIS}} = 5$ m $d_2 = 10$ m	$h_{\text{RIS}} = 2$ m $d_2 = 5$ m	$h_{\text{RIS}} = 5$ m $d_2 = 5$ m
8×8	-105.8	-105.3	-105.8	-104.6
16×16	-105.5	-101.9	-105.2	-99.8

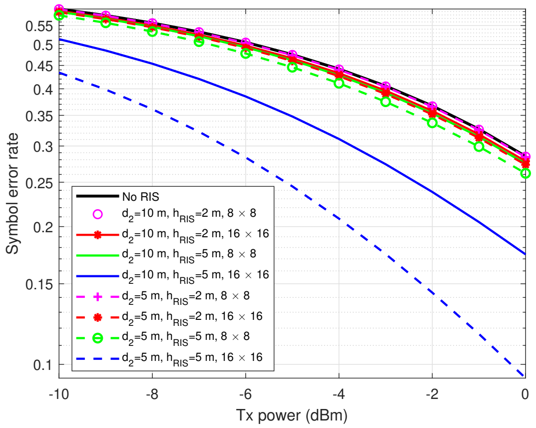

Fig. 3. Symbol-error-rate performance.

between the RIS and RX the path loss is modeled with the urban micro path loss model. The configuration of the RIS is calculated with (6) assuming that the angles φ, φ_r, ϕ and ϕ_r are known.

The BS and UE antenna heights are 10 m and 1.5 m, respectively. The bandwidth of the transmitted signal is 9.36 MHz (52 resource blocks, 15 kHz sub-carriers) and the center frequency is 4 GHz. The noise power is calculated as $10\log_{10}(B) - 174$ dBm, F_{dB} is assumed to be 0 dB (ideal receiver).

The path losses in decibels (dB) between a single antenna TX and single antenna RX with a 8×8 and 16×16 RIS are given in Table I when $d_1 = d_3 = 100$ m. This represent a case where the TX and RIS are located in the same room and the distances from the TX and RIS to the RX in a base station are approximately same. The distance between the TX and RIS as well as the height of the RIS center point (h_{RIS}) are varied. The loss of the direct channel between the TX and RX is -105.9 dB. When the RIS center is at the height of 2 m the 8×8 RIS does not provide gain in the received power. When the RIS center center is at the height of 5 m and the TX is moved close to the RIS, the power gain is 1 dB. When the TX is 10 m away from the 16×16 RIS and the RIS center point is at the height of 2 m, the gain in received power is minimal. When the RIS height is kept the same but the TX is moved closer to the RIS, the gain is slightly increased. If the RIS height is increased to 5 m the gain increases to 4 dB at 10 m distance and to 6 dB at 10 m distance. As can be seen, the height at which the RIS is installed can have considerable effect on the total loss between the TX and RX. The 5 m RIS height is not feasible in most of the office environments, but can be achieved in larger halls (e.g., warehouse or mall).

The symbol error rate and coded (low-density parity-check coding with code rate 193/1024) BER results for QPSK modulation as a function of the TX power in the same settings as that in Table I are shown in Figs. 3 and 4. The results show clearly the effect of the RIS height on the performance. Interestingly, when the transmit power is increased, the 8×8 RIS with the height of 5 m approaches the BER performance of the 16×16 RIS case. This means, that while the gain provided by the 8×8 RIS in the received power seen in the Table I and Fig. 3 is minimal, it is high enough to capitalize on the coding gain when the transmit power is increased above -6 dBm. In the 2×2 MIMO scenario, the improvement in the BER performance (Fig. 5) provided by the RIS is about the same as in the SISO case. The transmit power in Fig. 5 is for a single element in the TX array.

The coverage enhancement provided by the RIS is measured with the the normalized throughput shown in Fig. 6. In the throughput simulations the HARQ is enabled and the distance between the TX and RX is varied while the TX power is kept constant (-4 dBm). The TX and RX are single antenna devices. The black curve shows the throughput when a RIS is not utilized in the link. The green curve represent a case where the horizontal distance from a TX to RIS 8×8 is 5 m and the RIS is at 5 m height and there is a LoS path between the RIS and RX. In this case the RIS extends the coverage about 5 m. When the RIS size is raised to 16×16, the coverage with lower than maximum throughput can be extended. E.g. the throughput without the RIS goes to zero when the distance between the TX and RX is 160 m, but with the 16×16 RIS the throughput is still almost 60% from the maximum. The dashed black curve shows the throughput when there is no direct link between the TX and RX. When the distance between the TX and RX is shorter than 95 m, the no RIS case gives better performance than the only RIS case, but when the distance increases the RIS only case outperforms the no RIS case. The blue dotted curve and the dashed curve with asterisks show the performance when the TX distance from the RIS is increased to 10 and 20 m, respectively. In all above cases, the link between the RIS and RX has been a LoS channel. In the case where it would been a NLoS channel, the 16×16 RIS does not give any throughput improvement. The magenta curve gives the performance with a 32×32 RIS in the case of a NLoS channel between the RIS and RX. As can be seen the coverage enhancement is small. Larger RIS sizes are not considered since the physical size would rapidly increase to be unrealistic in indoor scenarios (the physical size of a 32×32 RIS at 4 GHz is in the order if 2.3×2.3 m).

VI. CONCLUSION

A RIS is often assumed to be utilized at millimeter or higher frequencies. At these high frequency ranges the direct channel between the TX and RX is typically assumed to be completely blocked when RISs are considered and the RIS is used to enable the transmission from the TX to the RX.

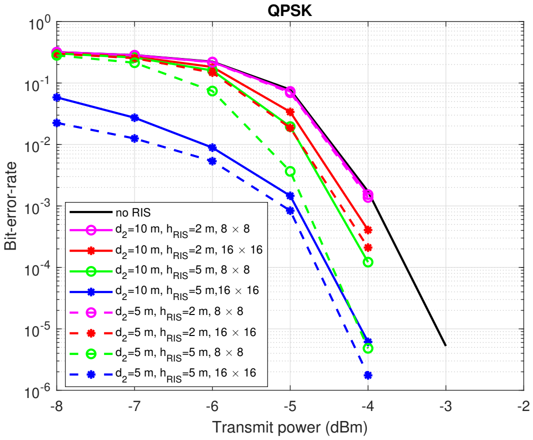

Fig. 4. Bit error rate performance.

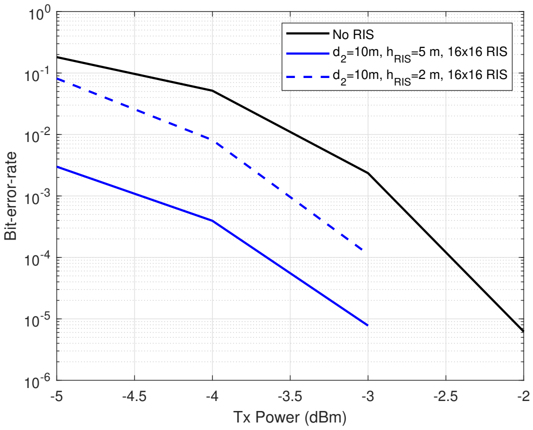

Fig. 5. Bit error rate performance.

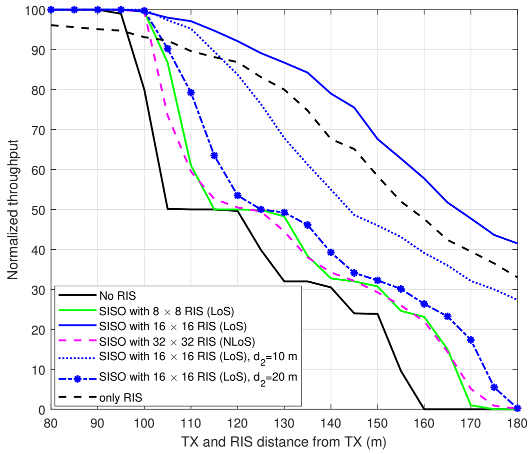

Fig. 6. Normalized throughput.

However, in this paper the use of a RIS in 5G NR PUSCH at 4 GHz is studied with simulations. At this frequency, the direct channel between the TX and RX cannot be assumed to be completely blocked. Hence, the RIS is not used to enable the communication between the TX and RX but to enhance the link coverage. In the simulated case, the coverage with 100% throughput is not improved by utilizing a RIS. However, with lower throughput values the 16×16 RIS can increase the coverage significantly. But this requires that there is a LoS path between the RIS and RX and the RIS is close to the TX. Moreover, the height the RIS is installed at has a major effect on the performance.

ACKNOWLEDGMENT

This research is partially funded by the Academy of Finland 6Genesis Flagship (grant 318927) and by InterDigital Europe, Ltd. This work has been developed also in part within the CELTIC-NEXT AIMM project.

REFERENCES

[1] M. Di Renzo, A. Zappone, M. Debbah, M. S. Alouini, C. Yuen, J. de Rosny, and S. Tretyakov, "Smart radio environments empowered by reconfigurable intelligent surfaces: How it works, state of research, and the road ahead," *IEEE Journal on Selected Areas in Communications*, vol. 38, no. 11, pp. 2450–2525, 2020.
[2] E. Basar, M. Di Renzo, J. De Rosny, M. Debbah, M. Alouini, and R. Zhang, "Wireless communications through reconfigurable intelligent surfaces," *IEEE Access*, vol. 7, pp. 116753–116773, 2019.
[3] Q. Wu and R. Zhang, "Towards smart and reconfigurable environment: Intelligent reflecting surface aided wireless network," *IEEE Communications Magazine*, vol. 58, no. 1, pp. 106–112, 2020.
[4] N. Rajatheva and et al., "White paper on broadband connectivity in 6G," Tech. Rep., Finnish 6G Flagship Program, 2020.
[5] Alexandros-Apostolos A. Boulogeorgos and Angeliki Alexiou, "Coverage analysis of reconfigurable intelligent surface assisted THz wireless systems," *IEEE Open Journal of Vehicular Technology*, vol. 2, pp. 94–110, 2021.
[6] Jiguang He, Markus Leinonen, Henk Wymeersch, and Markku Juntti, "Channel estimation for RIS-aided mmWave MIMO systems," in *GLOBECOM 2020 - 2020 IEEE Global Communications Conference*, 2020, pp. 1–6.
[7] Xinying Ma, Zhi Chen, Wenjie Chen, Zhuoxun Li, Yaojia Chi, Chong Han, and Shaoqian Li, "Joint channel estimation and data rate maximization for intelligent reflecting surface assisted terahertz MIMO communication systems," *IEEE Access*, vol. 8, pp. 99565–99581, 2020.
[8] 3rd Generation Partnership Project (3GPP), "Technical Specification Group Radio Access Network; NR; Base Station (BS) radio transmission and reception (Release 17)," TS 38.104 V17.1.0, 3GPP, 2021.
[9] 3GPP, "Study on channel model for frequencies from 0.5 to 100 GHz," 3GPP TR 38.901, version 14.3.0, Release 14, ETSI, 2018.