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Self-Interference Channel Measurements for In-Band Full-Duplex Street-Level Backhaul Relays at 70 GHz

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***Abstract*—This paper reports measurements of self-interference (SI) channels in an in-band full-duplex (IBFD) relay scenario for millimeter-wave street-level backhauling. The street-level backhauling suffers from clutters surrounding the relay devices and hence SI originating from the environment may be dominant. An ultrawideband channel sounder operating at 70 GHz carrier frequency is used to measure the SI channels in a chamber, indoor window-side, indoor and outdoor corner scenarios. The transmit and receive antennas are waveguide-fed lens antennas. The measurements showed that cross-polarized feeding of waveguides to the lenses provided higher isolation than co-polarized feeding. In the corner scenario, observed minimum isolation level is 85 dB in the frequency domain, and 100 dB in the delay domain. The results confirmed that isolation is not limited by the direct coupling because of the high directivity of the lens antenna, but by the environmental coupling. Further link budget analysis for outdoor-to-indoor backhauling showed that the IBFD relay with practical transmit power is capable of enhancing the signal-to-noise ratio and hence extending the coverage, as SI at the relay receiver can be almost the same level as thermal noise.**

***Index Terms*—Millimeter-wave, in-band full-duplex, backhaul, relay, self-interference.**

I. Introduction

Millimeter-wave street-level point-to-point (P2P) radio backhaul links are subject to high attenuation of wave propagation because possible obstruction of foliage and buildings. Introduction of high-gain directive antennas is essential. While such a countermeasure is sufficient in a P2P link having a line-of-sight (LOS), it is difficult to maintain the link quality even with directive antennas if the LOS is subject to blockage. Possible scenarios are illustrated in Fig. 1, where the link connection has to be available 1) beyond building corners and 2) inside a building. In such cases, introducing a signal relay in the middle of a link may be a viable approach to ensure LOS between end terminals and a relay and to reinforce the P2P link connectivity. Relays may also be a more cost effective solution than deploying small-cell base stations to increase radio service coverage. One drawback of conventional relay is reduced spectral efficiency because the two access links from/to the relay use different frequency tones or time slots to avoid interference, which is so called a half-duplex relay. Furthermore, duplexing the two access links in the time domain causes extra latency of the P2P link, which is another drawback of the conventional half-duplex relay.

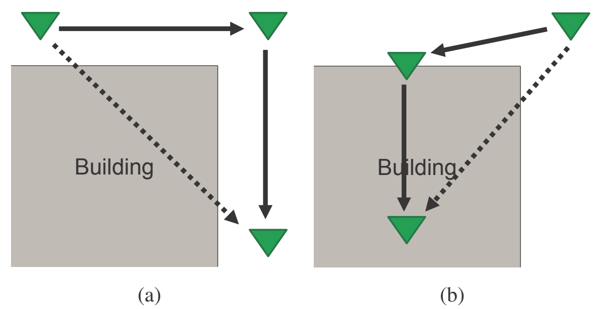
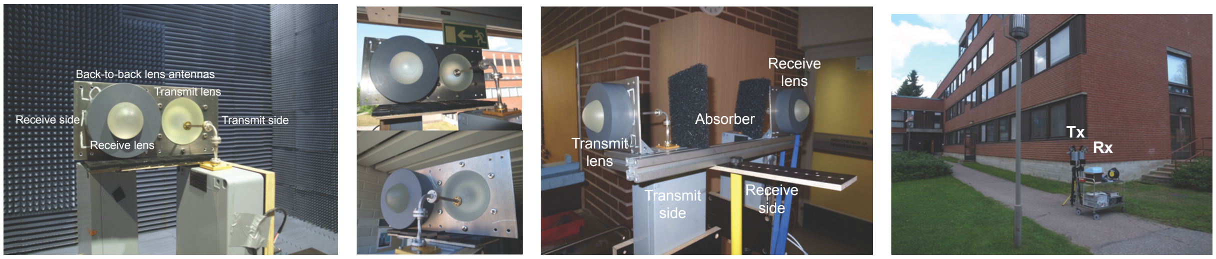


Fig. 1. Scenarios where relay deployment may be crucial for the E-band backbone networks, i.e., provision of data links for (a) beyond a corner and (b) indoor.

An on-frequency, or in-band full-duplex (IBFD), relay solves the drawbacks of conventional relays. The relay performs reception and transmission of two access links simultaneously to avoid reduced spectral efficiency and extra latency. A technical challenge in realizing the IBFD relay is to ensure as high isolation between the transmit and receive antennas so that the two access links do not suffer from self-interference (SI). In the low frequency regime, reduction of the SI requires sophisticated transceiver designs including antennas, radio frequency and digital cancellers particularly when it comes to compact relay equipment [1]. On the other hand, having high isolation at the millimeter-wave frequency range is much more promising with compact equipment because of the possibility to form directive beams pointing opposite direction to each other. Existing literature shows feasibility of bidirectional IBFD communications where up and downlink data transfer takes place using the same time/frequency resource. Extremely high isolation between the transmitter and receiver is realized by highly



(a) (b) (c) (d)

Fig. 2. Scenarios and antenna configurations of self-interference measurements: a side-by-side configuration (a) in a chamber and (b) at indoor window-side, and a corner configuration (c) indoor and (d) outdoor. Tx and Rx in (d) stand for transmit and receive sides, respectively.

directive antennas as demonstrated at 40 GHz backhaul link [2]. The use of antennas radiating or receiving orthogonal polarizations realized by patches or slots is shown effective in improving isolation, as demonstrated in the bidirectional IBFD on-chip transceivers and antennas at 60 GHz [3]–[5], 28 GHz [6] and 15 GHz [7]. Finally, SI channel measurements for bidirectional IBFD link at 60 GHz in indoor scenarios [5], [8] shows up to 70 dB isolation in the delay domain. None of the above-mentioned works cover SI channel analysis in a relay scenario. Our interests are street-level backhauling where SI due to surrounding clutters in the environment may be dominant. This paper reports SI channel measurements for IBFD relays at 70 GHz. In particular, we address the following aspects.

1) Identification of achievable isolation level under the influence of various electromagnetic coupling mechanisms in antennas and from surrounding environments.
2) Simple link-budget analysis for the demonstration of coverage extension with IBFD relays.

The remainder of the paper is organized as follows. Section II describes SI measurements including measurement apparatus and the observed SI levels in the frequency and delay domains for each IBFD relay scenario. Section III analyzes link budget for outdoor-to-indoor backhauling. Section IV summarizes findings from the measurements and link budget analysis as conclusions.

II. Self-Interference Channel Measurements

A. Channel Sounder

The measurement of electromagnetic coupling between the transmit and receive antennas of a relay device should take into account practical antenna configurations and propagation scenarios. Concerning antennas, both types and placement of antenna elements affect the coupling. It is practical to choose antenna elements that show high directivity in order to maintain the signal quality of data connection link. Such highly directive antennas are also advantageous in improving the electromagnetic isolation between the transmit and receive antennas at the relay device. In this work, two identical 64-mm-diameter elliptical integrated lens antennas are used. The measured directivity is 33.6 dB and gain is 28.3 dBi at 75 GHz using the WR10 open-ended waveguide as a feed. These lens antennas are designed using the principles introduced in [9]. The antenna elements are installed on a fixture having some flexibility in antenna element locations. The directions of antennas can also be changed so that they are suitable for side-by-side and corner configurations as illustrated in Figs. 2(a) and 2(c), respectively. The side-by-side relay can be installed at an entrance point of a backhaul link to a building where one antenna receives signals from an outdoor terminal and another antenna forwards signal to indoor terminals. Two antenna elements were separated by 0.15 m according to the distance between centers of the two lenses. Similarly, the corner relay can be placed both at indoor and outdoor crossings. The distance between two lenses can be modified in the range of 0.35 and 0.50 m.

The lens shapes a narrow beam to concentrate energy for a specific direction of the radiating space. The direction of energy concentration depends on the feeding structure at the bottom interface of the lens [9]. In this measurement, an open waveguide is used as a feeding structure and attached to the bottom interface of the lens. The feeding location at the interface makes the direction of energy concentration different, and therefore, several different feeding locations were tested in the isolation measurements.

Schematic of the channel sounder for ultrawideband SI measurements is shown in Fig. 3. The intermediate frequency (IF) signal is swept from 3 to 8 GHz with a vector network analyzer (VNA) and the frequency up and downconverters are used for radio frequency (RF) signals in the 69-74 GHz range. Typically, the frequency sweep is performed using 2001 equally divided frequency steps. The 5 GHz bandwidth leads to a 0.2 ns resolution in the delay domain, corresponding to 6 cm in distance, and the maximum detectable delay with 2001 frequency steps is 400 ns, which corresponds to 120 m in distance. A local oscillator (LO) feeds 16.5 GHz sinsoidal signals to the frequency converters.

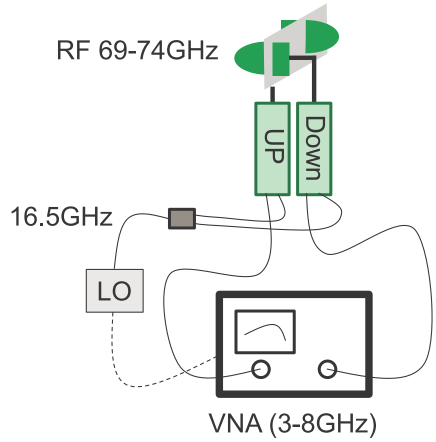


Fig. 3. 70 GHz ultrawideband channel sounder based on a network analyzer and up and down converter.

Phase of the LO is locked to VNA using a 10 MHz reference signal shared from VNA. The frequency converters and lens antennas are attached to tripods, which enable adjustment of the antenna heights below 2.5 m. A direct connection back-to-back calibration is performed before the measurements in order to compensate for the transfer functions of cables, up and down converters, and waveguides attached to the antennas. The calibration always uses an attenuator between the waveguides on the transmit and receive sides, otherwise the down-converter is overloaded and resulting non-linear effects makes the calibration invalid. The output power of VNA and LO is $+7$ and $+13$ dBm, respectively.

B. Measurements in an Anechoic Chamber

The first measurement was performed in an anechoic chamber to study the level of a direct coupling between the transmit and receive lens. The side-by-side relay antenna configuration was chosen. Two different feeding configurations were tested: one with co-polarized feeding and another with cross-polarized feeding. The feeding configuration made significant differences in achieved isolation level as shown in Fig. 4. The isolation level over the frequency is equivalent to the magnitude of the measured channel transfer functions (CTFs). The minimum isolation over the frequency is called frequency domain isolation hereinafter. When the co-polarized feeding was used, the frequency domain isolation with and without the lens was 38 and 48 dB, respectively, according to Fig. 4(a). The three curves in the result with lenses were from different locations of the open waveguide feeding at the bottom of lens interfaces. Lenses are helpful in improving the isolation since it directs power to some other directions than the other antenna. The frequency domain isolation with the cross-polarized feeding is 58 dB as illustrated in Fig. 4(b). Here the use of lenses does not help improve the isolation possibly because the feeding structure provides sufficient electromagnetic decoupling. These results suggest that the cross-polarized feeding must be used to improve the electromagnetic isolation between two antennas. It is noteworthy that this measurement did not use electromagnetic absorber to reduce direct coupling between the transmit and receive lenses.

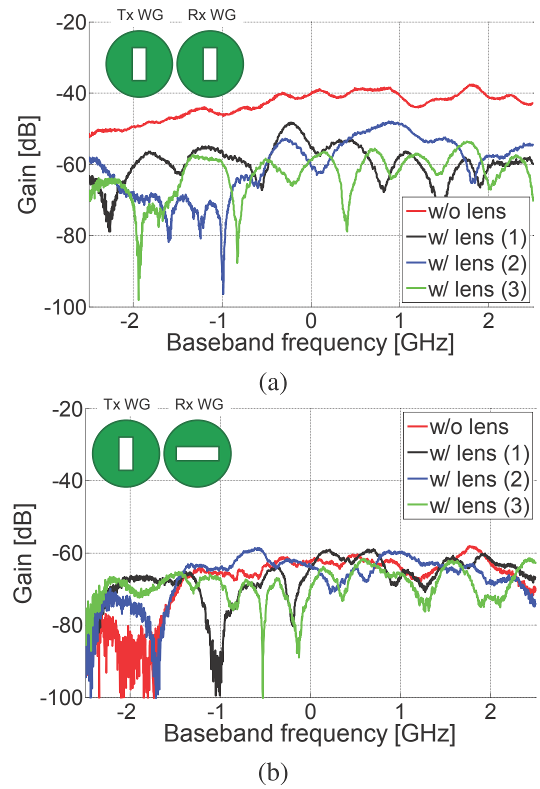
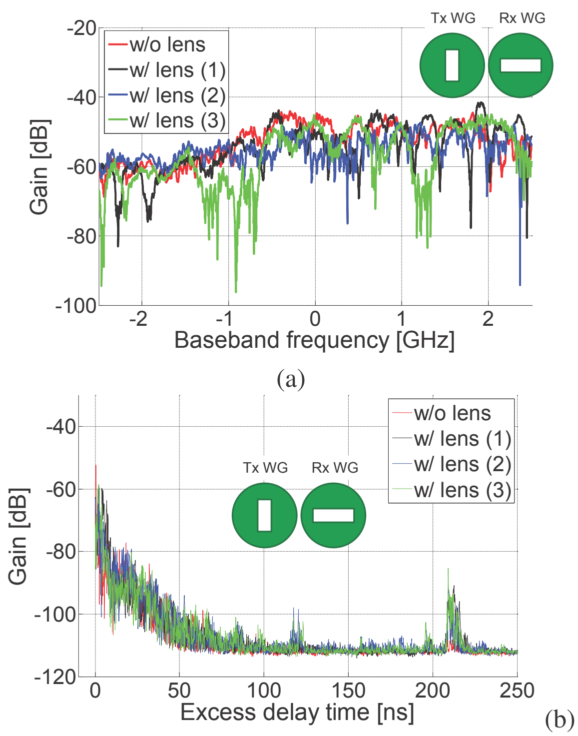


Fig. 4. Isolation levels of side-by-side relay antennas in an anechoic chamber with (a) co-pol and (b) cross-pol feeding. The measurements were performed without absorbers between the transmit and receive sides. The three curves with lenses correspond to measurements with different waveguide feed locations to the lenses.

C. Indoor Window-Side Measurements

The second measurement was performed at the end of a corridor in a building, where a large window is equipped and possibly serves as an entry point of a millimeter-wave backhaul link provided by an outdoor terminal. The side-by-side lens setup with cross-polarized feeding of waveguides is reported here. CTFs in Fig. 5(a) shows significantly lower frequency domain isolation than that in chamber because of coupling through surrounding environment. The reduction of isolation was about 17 dB. In order to analyze the coupling mechanism, the inverse fast Fourier transform was applied to the CTF to obtain a channel impulse response (CIR) depicted in Fig. 5(b). The figure indicates that the significant coupling mechanisms are the direct coupling as well as scattering from nearby objects that appears as peaks with shorter delays than 30 ns. It is interesting to find long-delayed peaks at 220 ns because of reflections from the other end of the corridor. Comparing CIRs before and after introducing the lenses, we find that direct coupling is reduced by 10 dB thanks to directivity of the lenses, while it slightly increased the coupling due to the reflection from other end of the corridor. The minimum isolation level given by the maximum magnitude of the CIR is referred to as delay domain isolation hereinafter.



(a)

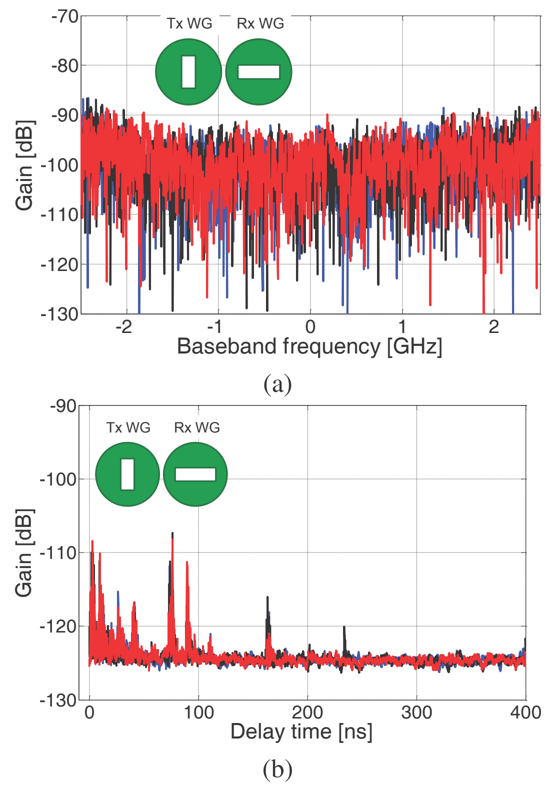
(b)

Fig. 5. Isolation levels of side-by-side relay antennas in an indoor window-side scenario described in (a) CTFs and (b) CIRs. The measurements were performed without absorbers between the transmit and receive sides. The three curves with lenses correspond to measurements with different waveguide feed locations to the lenses.

D. Indoor Corner Measurements

The third measurement concerns a scenario where the relay device is installed at an indoor corner. The same measurement setups as the chamber campaign are used, except for the power output level of the VNA and the LO. We configured those levels so that the down-converter does not suffer from power saturation, and they are -10 dBm and $+20$ dBm, respectively. At the output of the VNA, a 30-dB amplifier (MITEQ AMF-4D-005180-24-10P) and 10-dB attenuator are connected to improve the signal dynamic range. In this measurement, electromagnetic absorbers working at the frequency band of interests are installed to reduce the direct coupling. Separation of the transmit and receive lens varies from 0.35 to 0.50 m in order to obtain multiple realizations of the SI channel. Cross-polarized feeding of the waveguides is considered.

Figure 6 shows the CTF and CIR of the SI channel. Because of larger separation between the transmit and receive lenses than the side-by-side configuration that allows us to install the absorbers in-between, the frequency and delay domain isolation is significantly improved to 86 dB and 107 dB, respectively. It is noteworthy in CIR in Fig. 6(b) that the coupling due to surrounding environments can be higher than the direct coupling, which are -110 and -105 dB respectively. The strong multipath appears at 80 ns. It was not possible to identify the scatterer causing this multipath uniquely, given a single CIR at our disposal.



(a)

(b)

Fig. 6. Isolation levels of corner relay antennas in an indoor corridor described in (a) CTFs and (b) CIRs. The measurements were performed with absorbers between the transmit and receive sides. Each figure has three curves from isolation measurements with different waveguide feed locations to the lenses.

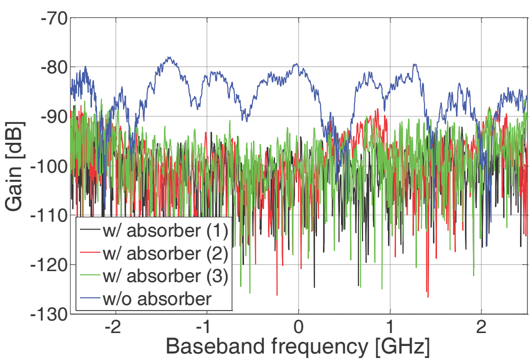
E. Outdoor Corner Measurements

The last measurement is at an outdoor building corner. Isolation is measured using the same settings of the measurement system as the indoor corner measurements reported in Section II-D. Measured CTFs and CIRs shown in Fig. 7 show similar trend as those of the indoor corner scenario. The frequency and delay domain isolation is 86 dB and 103 dB, respectively. We also found here that the coupling due to surrounding environments can be higher than the direct coupling as apparent from the green curve in Fig. 7(b). Furthermore, the level of coupling due to surrounding environments

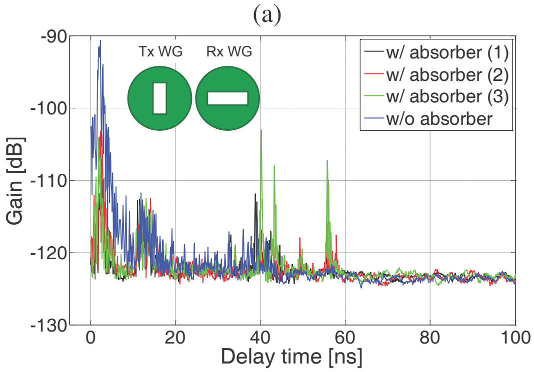
TABLE I
OBSERVED ISOLATION LEVELS BETWEEN TX AND RX WITH LENS AND CROSS-POLAR FEEDING.

Measurements	Frequency domain	Delay domain
Chamber side-by-side	58 dB	N/A
Indoor side-side	41 dB	58 dB
Indoor corner	86 dB	107 dB
Outdoor corner	86 dB	103 dB

depends on waveguide feed locations beneath the lens as they determine main beam directions. Finally, the results without the absorbers are overlaid in the figure as a reference. They show that the absorbers are effective in reducing the direct coupling by at least 10 dB.



(a)



(b)

Fig. 7. Isolation levels of corner relay antennas at an outdoor building corner described in (a) CTFs and (b) CIRs. Three curves "with absorber" in each figure are from different locations of the feed waveguide to the lenses.

F. Summary of Isolation Levels

The observed frequency and delay domain isolation levels are summarized in Table I. As defined earlier, the isolation levels are given by maximum magnitudes of the CTF and CIR, respectively. The measurements with side-by-side lenses show significantly lower isolation than corner measurements due to lack of absorbers between the lenses. It is hard to relate the isolation levels fully with clutter environments given our limited number of measurements.

TABLE II
PARAMETER SETTINGS FOR THE IBFD RELAY LINK STUDY.

Parameter	Value
RF	69-71 GHz
Ambient temperature	293 K
Thermal noise level at terminals and relay	-81 dB
Transmit power of source and relay	0 dBm
Frequency domain isolation at relay	80 dB
Lens antenna gain [9]	28 dBi
Link margin at destination	10 dB
Implementation loss at destination	10 dB
Required SNR at 10^{-4} bit error rate [10] 16QAM/QPSK	15/11 dB

III. LINK BUDGET ANALYSIS

We finally study link budget of an IBFD relay link to demonstrate the impact of observed SI levels. Let the isolation between the transmit and receive antennas at the relay device be 80 dB. Also let us consider 2 GHz signal bandwidth that leads to -81 dBm of thermal noise level in the relay receiver at 293 K temperature. In this case, the relay transmitter can radiate up to approximately 0 dBm such that the SI is in the same level as the thermal noise. Assume a scenario in Fig. 8(a) where the source (S) provides data connection to indoor destination (D) through a window wall located 10 m away from the source. The window penetration loss is 20 dB. It is also assumed that the source, relay, and destination are geometrically lined up to each other. In this case, it is beneficial to install the relay (R) right next to the window. The end terminals and the relay are equipped with the same lens antenna with 28 dBi gain. We assume a decode-and-forward relay, where a clean copy of symbols transmitted from the source is available at the relay if the source-relay link has a sufficient signal-to-noise ratio (SNR). Under the parameter settings of Table II, SNR at the destination for the source-destination and relay-destination links is depicted in Fig. 8(b). Free space signal attenuation was considered for the link pathloss. The required SNR for transferring 16 quadrature amplitude modulation (16QAM) and quadrature phase shift keying (QPSK) over additive Gaussian white noise channels with 10^{-6} bit error level is 15 dB and 11 dB [10], which we consider as sufficient SNR for successfully decoding symbols at the relay. Adding a link margin of 10 dB, the required SNR at the destination for the two modulation schemes are shown as straight lines on Fig. 8(b). It is apparent from the figure that indoor coverage, i.e., the distance from source beyond 10 m, is drastically improved. The furthest distance of communications with 16QAM and QPSK becomes 40 m and 60 m from the source when using the relay, compared to 10 m without the relay. The increased SNR due to the IBFD relay leads to clear coverage improvement thanks to the small-enough SI at the relay receiver.

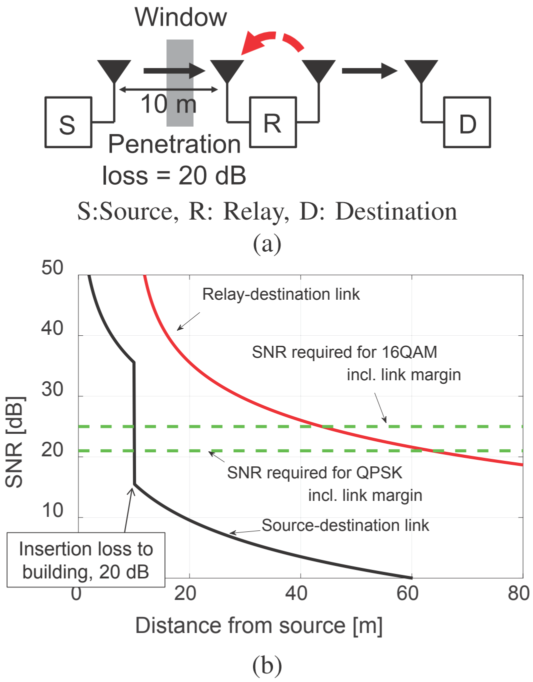


Fig. 8. Link budget analysis involving an IBFD decode-and-forward relay for an outdoor-to-indoor 70 GHz link: (a) considered scenario and (b) receive SNR at the destination with and without an IBFD relay installed next to the window.

IV. Conclusions

This paper described SI channel measurements for studying IBFD relays. The measurements showed that cross-polarized feeding of waveguides to lenses provided at least 10 dB lower SI level than co-polarized feeding. Furthermore, the use of absorbers reduce the direct coupling such that its level is comparable to coupling due to clutters in the surrounding environment. Finally, in the corner configuration, frequency and delay domain isolation is 85 and 100 dB, respectively. These values can be considered as practical isolation levels of IBFD backhaul relays equipped with lens antennas. From the simple link budget analysis, coverage extension by an IBFD relay is apparent. The isolation levels in the frequency and delay domains are relevant for waveforms in the respective domains, e.g., orthogonal frequency division multiplexing and single carrier transmission schemes.

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