Effects of mm-Wave Propagation Channels on Technology Choices for 5G on-Frequency Repeaters

Shabbir Ahmed, Robabeh Amirkhanzadeh Antiohos, Mike Faulkner
College of Engineering and Science, Victoria University, Melbourne, Australia
Email: shabbir.ahmed@live.vu.edu.au

***Abstract*—Wireless systems at mm-wavelengths have poor in building coverage, which is encouraging the study of on-frequency relays and repeaters. Such devices suffer from loop-back interference (LI) that can increase noise and distortion and cause device instability. Cancelling loops can be used to null the strongest multipath LI components. We conduct LI measurements to ascertain the reduction of LI vs the number of cancelled paths. The required number of cancelled paths appears to increase with the square root of the channel bandwidth as more paths are resolved. DSP cancelling appears to be the the most practical solution because of the difficulty of implementing wideband delays and the absence of a significant direct path leakage between the repeater's transmit and receive antennas.**

I. Introduction

The rapid growth of the wireless communications industry and the ever increasing demand for higher data rates have reinforced the need for more spectrum. This has motivated wireless engineers to look into unused/underutilised mm-wave frequencies in the spectrum bands of 28 and 60 GHz. Researchers in [1], [2], [3] have all reaffirmed that while some buildings may allow outdoor-to-indoor communication at 28 GHz, most modern concrete buildings with tinted glass windows have high penetration losses for both 28 and 60 GHz bands. At 28 GHz, a standard concrete wall has penetration losses above 100 dB and tinted windows have losses of about 30-40 dB, penetration losses at 60 GHz are considerably higher. On the other hand, mm-wave frequencies show good propagation through indoor materials. Most modern indoor environments use drywalls and clear-glass as partitions; these have penetration losses of about 7 dB and 4 dB respectively at 28 GHz. Therefore, the major challenge is to get signals from outdoors to indoors and vice versa. Thus, there is a need for wideband relays to support indoor user terminals from base-station infrastructures deployed outdoors.

Currently most relays work in frequency translation mode where transmission and reception are on different frequencies. Nonetheless, there is a push for same frequency full-duplex (FD) operation to maximize spectrum usage [5]. Unfortunately, FD relays are susceptible to multipath loop-back interference (LI) between the relay Tx and relay Rx (Fig.1). The outdoor repeater antenna is likely to be directional, pointing at the serving base-station, and at mm-wave frequencies a good back to front ratio is possible in a small form factor. Direct LI is therefore suppressed, but multipath LI from reflections off walls and metallic objects is still present.

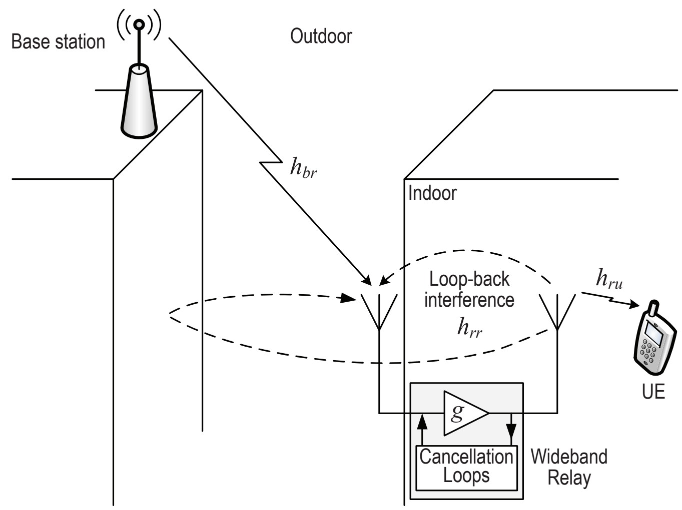

Fig. 1. Wideband repeater downlink operation.

LI limits the relay gain (for stability) and can overdrive the relay receiver causing blocking and third-order intermodulation problems. LI can be reduced by cancelling the major LI multi-paths. DSP cancellation can be used for low powered interfering multi-paths that do not overwhelm/desensitize the receiver. However, analog RF feedback cancellation loops are required for the stronger interfering multi-paths whose distortion components may desensitize the receiver. In this paper, we evaluate the complexity trade off of the feedback system for different bandwidths at mm-wave frequencies. We show that based on measured relay LI channels, that the application of analog cancelling becomes increasingly difficult as the bandwidth if the transmitted signal increases.

II. Relays and Loop-back Interference

Relays can be characterised into 3 types, depending on how sophisticated they are. LI will therefore have a different impact on each one. They all contain a variable gain stage which aims to keep the Tx power stable (at full (or specified) power).

Decode and Forward Relays decode a complete packet which is then remodulated and transmitted. Noise and interference is removed in the process but end to end latency is high. LI causes inter packet interference (IPI) that is removed in the relay, unless the IPI is too large and the packet is destroyed.

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Amplify and Forward Relays amplify and retransmit the signal on a symbol or packet basis. The LI and noise accumulates, reducing the SINR of the retransmitted signal.

Repeaters amplify and retransmit with minimal delay. Provided any latency is within the length of an OFDM symbol's cyclic prefix (CP) there is no ISI. However noise still accumulates and channel delay spread increases. Instability is possible if the loop gain is greater than one.

The traditional solution to the above problems is to reduce the relay gain or output power. This reduces the relay coverage or forces a higher transmit power from the base (resulting in increased interference in the outside cell). All these disadvantages can be avoided if the LI can be cancelled.

III. The Repeater Channel

Fig. 1 shows the downlink operation of the proposed wideband repeater. A directional outdoor antenna points towards the serving base-station and an omnidirectional antenna serves the indoor user equipment (UE). The overall channel impulse response from base-station to UE is given by convolution of the three component channels, base-relay, h_{br}; relay-relay, h_{rr}^T; and relay-UE, h_{ru}.

$$h_{bu} = g h_{br} \otimes h_{rr}^T \otimes h_{ru} \tag{1}$$

where g is the relay gain, and the effective total impulse response of the LI channel due to the relay,

$$h_{rr}^T = 1 + g h_{rr} + g h_{rr} \otimes g h_{rr} + ... \tag{2}$$

for a measured LI channel,

$$h_{rr} = \sum_{n=1}^{N} h_n \delta (t - \tau_n) \, . \tag{3}$$

The following section discusses our LI channel measurements.

IV. Channel Measurements

Fig. 2 shows our measurement setup. The horn antennas used are directional with 17° 3dB beam width. Antenna 1 is placed outdoors emulating the repeater's directional outdoor antenna. Antenna 2 is placed indoors emulating the repeater's omnidirectional indoor antenna by rotating the antenna in all directions and selecting the strongest direction of arrival. The window is closed except a slight gap to allow a cable connecting Antenna 1 to the vector network analyzer (VNA).

A. Frequency Response

Fig. 3 shows a measured LI frequency response (at 28GHz), taken from a ground floor laboratory facing a small courtyard confined by five story buildings in our University campus. Measurements were take at various bandwidths.

B. Impluse Response (Delay Profile)

The inverse discrete Fourier transform (IDFT) function can be used to get the impulse response or delay profile of the channels. Fig. 5(a) shows the delay profiles of the measured LI channel after a 30dB thresh hold (from the peak multipath) has been applied to remove noise. It is apparent from the delay profiles that there are no significant direct LI path from Antenna 1 to Antenna 2 (a distance of 1.5 meters). This is because Antenna 1 is facing away from Antenna 2. The dominant cause of LI are multipaths reflected off objects and walls facing Antenna 1. Each peak corresponds to a geographical feature. The strongest reflection is from the building opposite behind the courtyard at a distance of 19m.

C. Multipath Cancellation

The signal multipaths can be removed by cancelling loops, one for each cancelled path (Fig. 4). It is important to match the gain, phase and delay for good wideband cancellation. In DSP this is achieved by using the appropriate tap in a delay line or a combination of taps to get a fractional delay. In analog, vector modulators can be used in combination with RF delay lines, usually provided by LC resonant circuits [6]. A number of resonant stages are required if the delay is greater than $\frac{1}{2Bw}$ which impacts chip area and causes insertion loss. At these bandwidths RF cancelling loops are generally not

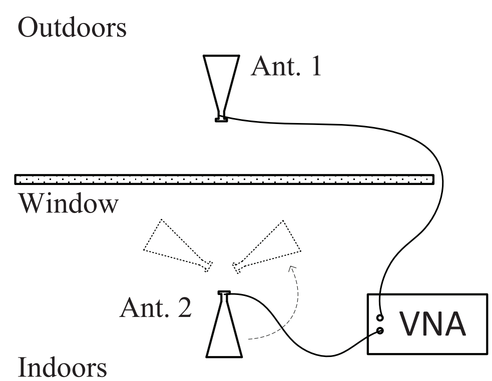

Fig. 2. Measurement setup

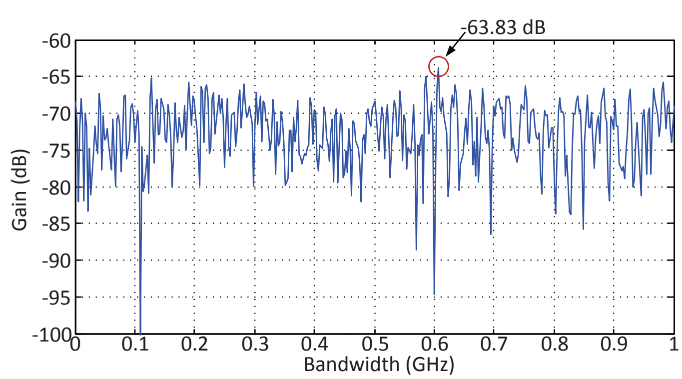

Fig. 3. Frequency response of measured LI channel. Frequency response ($|H_{rr}|$) defining the instability gain of the relay.

practical for delays much beyond that of the direct path. Additional cancelling loops add to cost and energy consumption. It is important therefore to know how the removal of multipaths benefits the reduction in residual LI.

Future 5G communication systems will use a mixture of bandwidths. The highest data rates will use multiple GHz bandwidths (Bw). Fig. 5(b) shows the residual LI power versus the number of cancelled paths in descending order of powers for a channel with 0.25ns time resolution ($Bw = 4$ GHz). For example removing the strongest path reduces the LI by 1.3dB, the strongest two paths by 2.3dB and three path 3.6dB etc. Some 26 multipaths are needed to achieve 10 dB cancellation. A DSP solution is possible but the analog solution would be prohibitively expensive or non effective. Even if only the strongest path was cancelled in analog the benefit of 1.3dB is hardly noticeable.

Channels with reduced bandwidths also need to be investigated. Fig. 6 shows the delay profile with 1 GHz bandwidth (a time resolution of 1 ns). A reduced number of multipaths can be resolved. There are instances like circle 1 and circle 2 in Fig. 5(a) where the multipaths combined in phase to resolve into the larger multipath of circle 1 in Fig. 6(a). And there are also instances where multipaths combined in antiphase to resolve into a reduced multipath. Fig. 6(b) shows the residual LI power versus the number of cancelled multipaths for the 1 GHz bandwidth channel. There is a significant 3.64 dB reduction in LI power for the removal of the first multipath, however, subsequent multipath removals show small reductions and a total of 20 multipaths are required for 10 dB cancellation. The benefit of using an analog cancelling loop for the first tap is clearly improved, but the delay at 128ns is still difficult for practical implementation.

Further investigations are carried out for smaller receiver bandwidths and the number of multipaths required to achieve 10 dB cancellation plotted as set A in Fig. 7. A second set of measurements from a different location in the building is shown marked set B. At the smaller 100 MHz bandwidth the number of cancelled multipaths is reduced to 7 and 5 for sets A and B respectively. Again the delay of 128ns is still appreciably larger that $\frac{1}{2Bw}$ making analog implementation difficult.

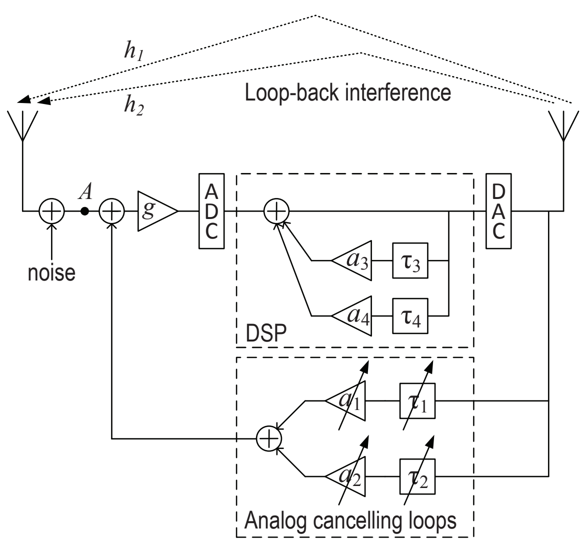

Fig. 4. Cancellation loops. Measurement setup for stability characterization.

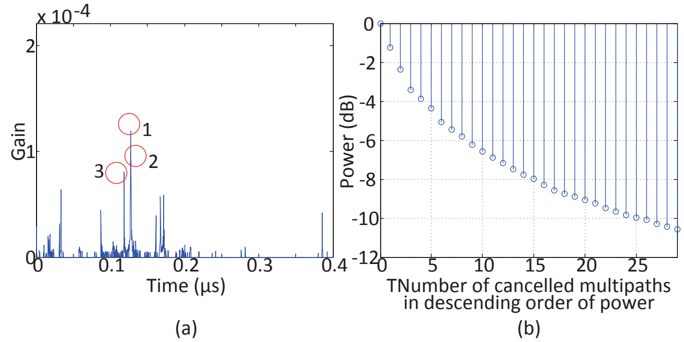

Fig. 5. (a) Delay profile of measured LI channel at 4GHz bandwidth i.e. time resolution 0.25 ns. (b) Residual power vs number of cancelled multipaths in descending order of powers.

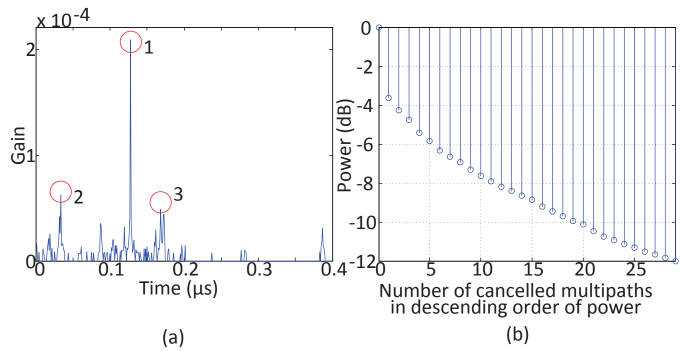

Fig. 6. (a) Delay profile of measured LI channels at 1GHz bandwidth i.e. time resolution 1 ns. (b) Residual power vs number of cancelled multipaths.

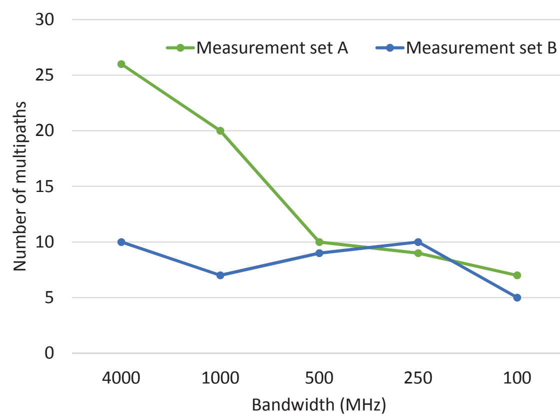

Fig. 7. Number of removed multipaths for 10dB cancellation of LI at different receiver bandwidths.

V. Stability, Noise and Delay Spread

We consider 1 GHz bandwidth for our stability analyses, which is a reasonable target for 5G services. Fig. 3 shows the frequency response ($|H_{rr}|$) of the LI channel. The highest point in the frequency response (red circle) determines the onset of instability. i.e. for stability

$$g + \max\left(|H_{rr}|\right) < 0\,\text{dB}. \tag{4}$$

from which the maximum repeater gain, $g = 64$dB is the point where the gain margin is 0dB.

A. Effective total impulse response (h_{rr}^T) of the LI channel

The effective total impulse response of the LI channel is now characterized for different relay gain settings. Fig. 4 shows the simulation setup. The LI channel is as per Fig.6 and the system is activated with an impulse at the input, A. The output, also taken at A, shows the effect of the relay gain (g) on the total impulse response, h_{rr}^T (Fig. 8). An increase in relay gain feeds back more peaks, and hence, there is a a gain dependant increase in the root-mean-square (rms) delay spread (Fig. 9). The rms delay spread shoots up as the relay gain steps into instability. The rms delay spread peaks at 950ns at about 66dB before falling back down due to the averaging nature of rms delay spread calculation.

B. Effect of LI on noise in relay

To analyze the effect of the measured LI channel on noise in the relay, an initial noise of power 1 is fed into the system as shown in Fig. 4. The system is then run for 40μs and the enhanced noise power is then measured at point A. Fig. 10 shows the loop-back noise enhancement of the system versus the relay gain. A 10dB gain margin (i.e. $g = 54$) generated 0.1dB extra noise.

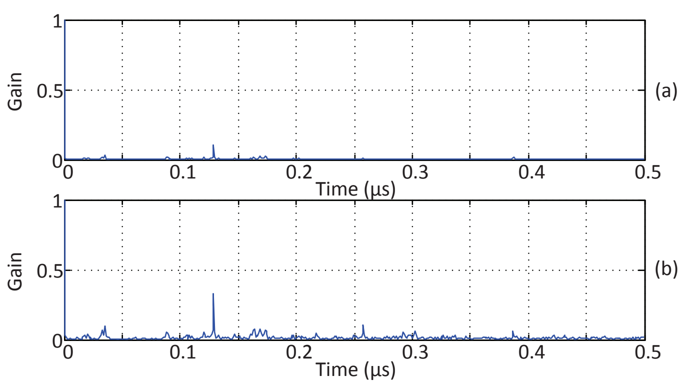

Fig. 8. Effective total impulse response (h_{rr}^T) of the LI channel versus relay gain (g), (a) $g = 54$ dB, gain margin 10dB and rms delay spread = 13.3ns (b) $g = 64$ dB, gain margin 0dB and rms delay spread = 45.4ns

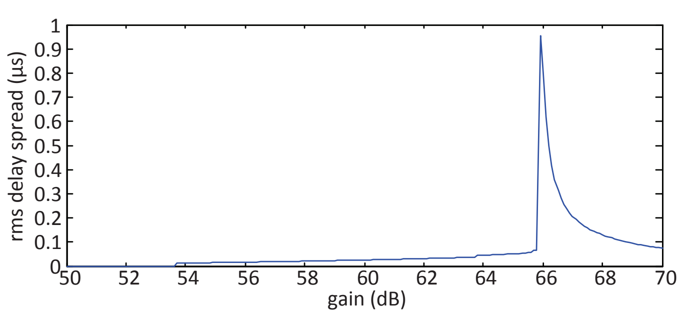

Fig. 9. rms delay spread versus relay gain (g).

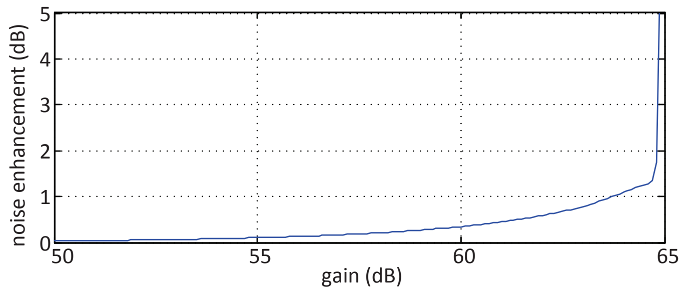

Fig. 10. Loop-back noise enhancement versus relay gain (g).

VI. Conclusion

On frequency repeaters suffer from loopback interference (LI) which artificially increases noise, channel delay spread, and can lead to instability. Cancelling the multipath loop-back signal can be achieved by cancelling each individual channel impulse in DSP or analog RF. RF cancelling loops are constrained to short delays such as the direct path, by implementation constraints. Campus measurement of LI at mm-waves show LI dominated by back reflections from nearby buildings with minimal direct path contribution, due in part, to the good directivity of the base station facing antenna. DSP cancelling is therefore the preferred technology. The number of taps required in the cancelling filter is bandwidth dependant and varies from over 20 at GHz bandwidths down to 7 for 100MHz bandwidths. Based on the limited data set the number of cancelled paths is proportional to the square root of the channel bandwidth.

Acknowledgment

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