Spatial Multiplexing Over a Line-of-Sight Millimeter-Wave MIMO Link: A Two-Channel Hardware Demonstration at 1.2Gbps Over 41m Range

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***Abstract*—This paper presents recent experimental results from a novel hardware prototype of an outdoor millimeter-wave line-of-sight (LOS) MIMO link. The system architecture establishes multiple parallel data channels using antenna element spacing derived from the principles of diffraction-limited optics. A millimeter-wave carrier frequency reduces the antenna array size to reasonably compact dimensions. This system architecture is scalable to larger one-dimensional and two-dimensional arrays supporting data rates >320Gbps. A two-channel LOS hardware prototype has been constructed and tested in an outdoor environment. The hardware prototype achieved bit error rates (BER) <2x10^{-6} for two channels operating at 600Mbps each over a link range of 41m.**

***Index Terms*—Millimeter-wave, MIMO, channel separation**

I. INTRODUCTION

The ability to support increased data rates without simultaneously increasing channel bandwidth motivates interest in MIMO communication links. MIMO links establish multiple parallel communication channels using closely spaced transmitter and receiver antenna elements. Demonstrated approaches to low frequency (<10GHz) MIMO exploit multipath signals in non line-of-sight (NLOS) environments [1].

An alternative approach, which we term millimeter-wave MIMO, establishes (Fig. 1) multiple parallel links in a LOS environment [2]. The basic theory for this system architecture first appeared in [3]. In this configuration, the transmitter and receiver use either 1×n linear or n×n rectangular arrays of antenna elements spaced according the relationship

$$D = \sqrt{R \cdot l / n} \tag{1}$$

where D is the antenna element spacing, R is the link range and λ is the carrier wavelength [2].

Based on this result, a 4×4 (16-element) square antenna array of dimensions nD×nD= 3.4m×3.4m would operate at 1km link range using a 60GHz carrier. The bandwidth available in the 60GHz band is sufficient for 10Gbps QPSK transmission per antenna pair per field polarization. A 4×4 link exploiting both field polarizations [4] could therefore support a 320Gbps aggregate data rate. Such an outdoor link would supplement optical fiber links carrying high-capacity traffic. In contrast, for indoor applications, a linear 1×4 link operating at 10m range would require an array of length nD=34cm.

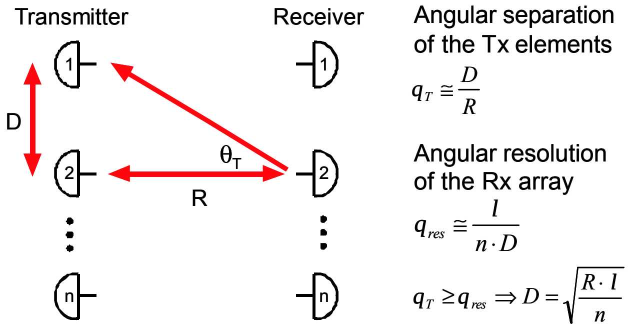


Fig. 1 LOS MIMO system analysis using the principles of diffraction-limited optics.

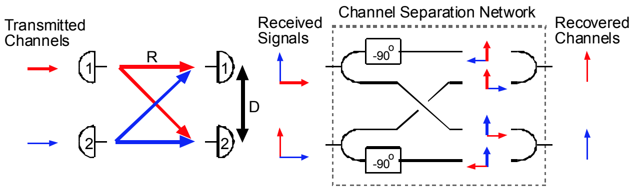


Fig. 2 Two-channel LOS MIMO system diagram. Transmitter and receiver signals are represented as vectors in the I/Q plane.

Recent work in the field of LOS MIMO has highlighted the potential for this system architecture. Theoretical work has shown that one-dimensional and two-dimensional LOS MIMO links are robust to small deviations in individual antenna alignment and array positioning [2], [5], [6]. Experimental results at 5 GHz, using offline software based receivers, and 60GHz channel sounding measurements have appeared in the literature [7], [8].

A LOS indoor MIMO link using 1×2 linear arrays and operating at 1.2Gbps over 6 meter range was reported in [9]. We here report experimental results from a hardware

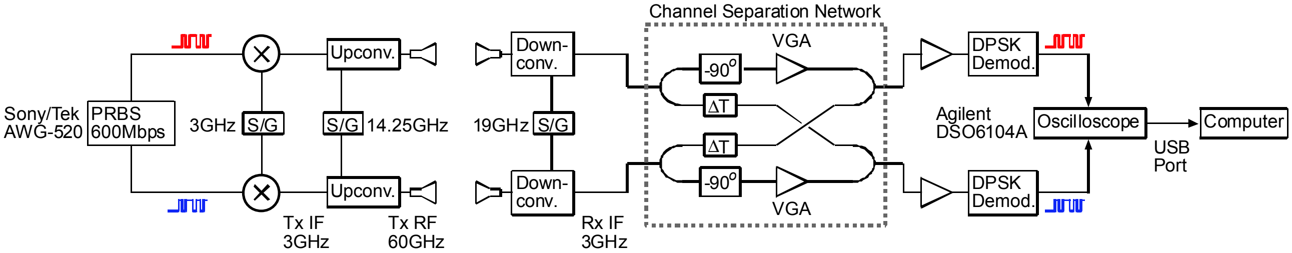


Fig. 3 Two-channel MIMO hardware prototype block diagram. The transmitter is a two stage upconverter design that transmits BPSK modulated data. The receiver consists of a 60GHz downconversion block, channel separation network placed at the 3GHz IF frequency, DPSK data demodulator, and data capture hardware.

prototype of a 60GHz outdoor MIMO LOS link using 1×2 linear arrays and operating at 1.2Gbps over a 41m link range.

II. MILIMETER-WAVE MIMO LOS SYSTEM ARCHITECTURE

LOS MIMO links can be analyzed using the principles of diffraction limited optics [2], [3]. To recover the transmitted signals at the receiver array without degradation in the signal to noise ratio (SNR), the angular separation $q_T = D/R$ of the transmitter elements (Fig. 1) must be larger than the receiver array's angular resolution $q_R = l/nD$. From this, we find (Eq. 1) the Rayleigh-limited antenna-spacing D. Although the channels can still be separated using arrays with spacing smaller than (Eq. 1), the system SNR is greatly degraded [2].

Fig. 2 shows a system diagram of a MIMO link using 1×2 linear arrays. Transmitter and receiver signals are represented as vectors in the I/Q plane.

For this simple array, operating in the Rayleigh limit (Eq. 1), the path length from a transmitter to an oblique receiver antenna is

$$D(1,2) = D(2,1) = \sqrt{R^2 + D^2} \cong R + \frac{l}{4}, \qquad (2)$$

while the path length to a direct receiver is $D(1,1)=D(2,2)=R$. The $\lambda/4$ path length difference produces a 90^O relative phase shift (Fig. 2) between the direct and oblique paths. In this particularly simple case, to separate the two transmitted channels the receiver must simply sum the receiver antenna array signals after providing -90^O phase shifts. For either larger linear arrays or for rectangular arrays, the receiver must separate the channels through a more general set of vector summations. A proposed architecture for a generalized channel separation network has already appeared in the literature [10].

III. MIMO HARDWARE PROTOTYPE

The hardware prototype (Fig. 3) was constructed from commercially available millimeter-wave and RF components, and consists of a two-element (1×2) transmitter and a two-element receiver.

A. Transmitter

The transmitter (Fig. 4a) consists of a baseband data source, BPSK modulator and 60GHz upconverter stages. The baseband data source generates two independent Pseudo Random Bit Sequences (PRBS) at 600Mbps with sequence length 2^{17}-1. The PRBS data streams are generated using different maximal length shift register feedback configurations, ensuring that the two channels carry independent data. A 3GHz IF carrier with BPSK modulation is obtained by applying these data signals, in bipolar format, to the baseband port of a mixer operating with a 3GHz local oscillator. Using a second mixer, the 3GHz BPSK signal is then upconverted to 60GHz. A 58-62GHz bandpass filter suppresses both the mixer image response and LO feedthrough. The transmitter uses 24dB$_i$ standard gain horn antennas.

(a)

(b)

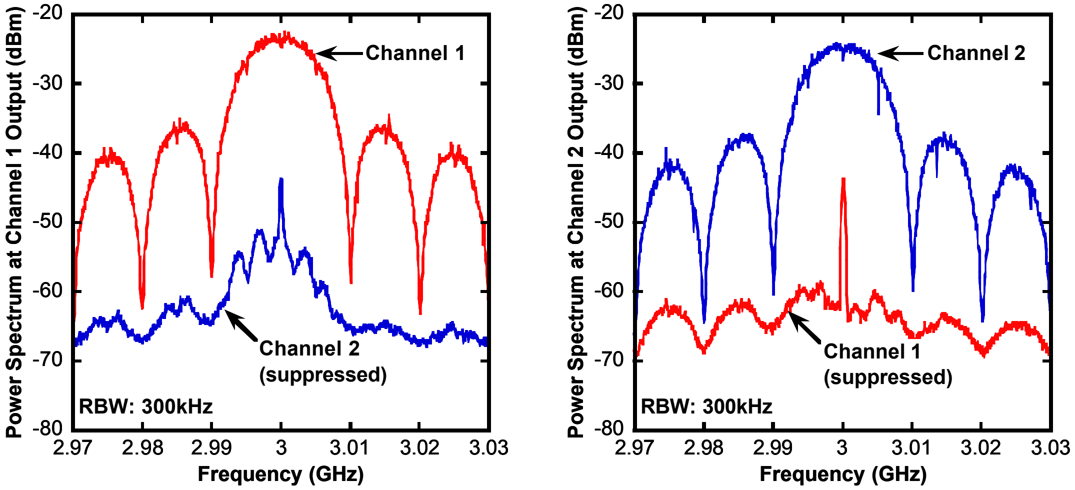
Fig. 4 Photographs of the (a) transmitter and (b) receiver hardware prototype.

TABLE I
LINK BUDGET

TX Antenna Gain	24	dB$_i$
RX Antenna Gain	40	dB$_i$
Geometric Path Loss	-36.3	dB
Atmospheric Loss	-1.1	dB
Receiver Noise Figure	8	dB
Link Margin	13	dB
Transmitter Power	-16.5	dBm
Receiver Power	-53.9	dBm

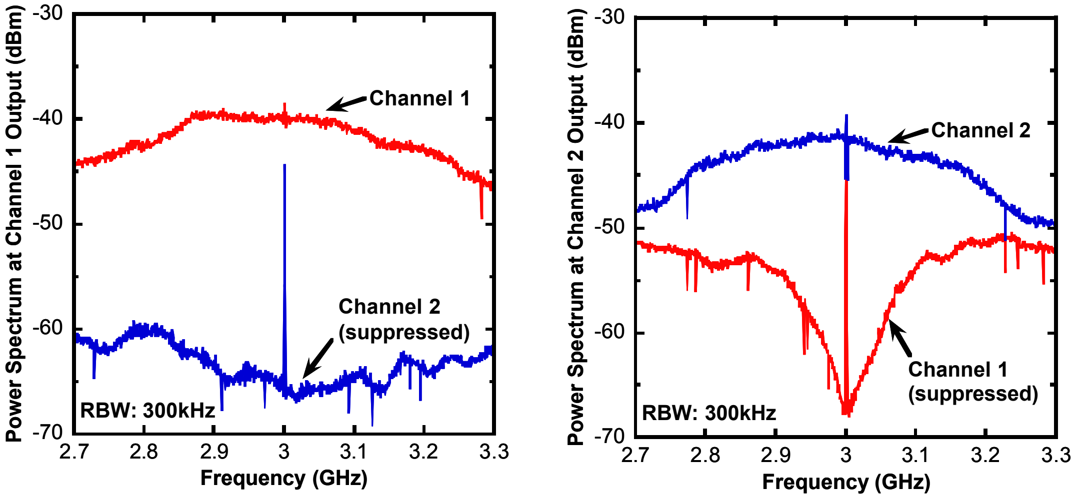
B. Receiver

The receiver (Fig. 4b) uses 40dB$_i$ Cassegrainian antennas and contains a 60GHz downconverter, an IF channel separation network, a data demodulator, and data capture hardware. The downconverter block converts the received



(a) (b)

Fig. 5 Channel suppression network performance at 10Mbps. Power spectrum plots for (a) channel 1 output and (b) channel 2 output.



(a) (b)

Fig. 6 Channel suppression network performance at 600Mbps. Power spectrum plots for (a) channel 1 output and (b) channel 2 output.

signals to a 3 GHz IF and contains a bandpass filter, an LNA, and a mixer.

The channel separation network was placed at the IF frequency. Nominally, this network (Fig. 2) consists of fixed gains and summations after application of -90^O phase shifts. To accommodate variations from the nominal case of the relative gains and phases of the four propagation paths, variable-gain and variable-phase elements were provided in the channel separation network. These elements were manually adjusted to null the cross-channel interference.

After separating the channels, data was demodulated using a Differential Phase Shift Keying (DPSK) demodulator. Carrier recovery at the receiver is therefore not required. The demodulator operates at the 3 GHz IF and consists of a power splitter, a 1-bit-period delay element and a mixer.

The recovered data was captured on a multiple channel oscilloscope controlled by a laptop computer. Both recovered channels were digitized simultaneously for subsequent bit error rate (BER) analysis. The oscilloscope memory size limits the amount of data that can be captured and therefore prevents measurement of error rates below 10^{-6}.

C. Link Budget

Table 1 is a summary of the link budget. The system was designed to have a BER of 10^{-6} and a link margin of 13dB. At a link range of 41m, the geometric path loss is much greater than atmospheric attenuation.

IV. WIRELESS LINK CHARACTERIZATION

The hardware prototype was tested in an outdoor environment at a range of 41m. The transmitter and receiver antenna pairs were separated by D=32 cm (Eq. 1).

Fig. 5 shows channel separation network performance at 10 Mbps data rate. The network was manually tuned to suppress cross-channel interference. Over a 60MHz bandwidth, a 28.8dB maximum channel suppression was achieved. Channel suppression levels for the two channels were within 1dB at this data rate.

The operating data rate was then increased to 600Mbps (Fig. 6). Over a 600MHz bandwidth, cross-channel interference of channel 1 by channel 2 was suppressed by 21dB over the data bandwidth. Cross-channel interference of channel 2 by channel 1 could be suppressed by only 9.7dB. This is a consequence of a strong (and unintended) frequency-dependence to the gain or phase of the components within one summation branch of the channel separation network. Because of this, the cross-channel interference can only be nulled at the center of the IF bandwidth. We are currently re-constructing the network to eliminate this difficulty.

Despite the limited suppression of the interference of channel 2 by channel 1, measured transmission BERs were better than 2x10^{-6} on both channels simultaneously (Table 2). To assess the impact of cross-channel interference on the transmission error rate, the system was tested with both transmitters active and with one transmitter active at a time.

Fig 7. shows the receiver eye patterns. The larger eye closure observed for channel 2 can be attributed to the lower suppression of cross-channel interference for channel 2 (Table 2).

V. CONCLUSION

A millimeter-wave LOS MIMO hardware prototype was built and tested in an outdoor environment. The prototype achieved a BER <2x10^{-6} for a link range of 41m and data rates of 600Mbps per channel. This result demonstrates a new system architecture enabling spatial multiplexing for MIMO links operating in LOS environments [2].

Further work on characterization of the system with larger one-dimensional and two-dimensional arrays, real time receiver data processing and additional system enhancements are presently underway.

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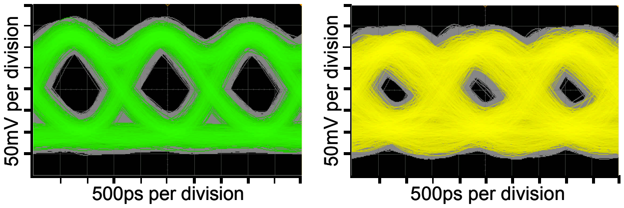
TABLE II

SUMMARY OF OUTDOOR MEASUREMENTS

	Channel Number	1	2
BER	Single Active Transmitter	<10^{-6}	<10^{-6}
	Two Active Transmitters	<10^{-6}	1.8x10^{-6}
Channel Suppression Ratio (dB)	10Mbps per Channel	27.8	28.8
	600Mbps per Channel	21.1	9.7



(a) (b)

Fig. 7 Receiver eye patterns at 600Mbps for (a) channel 1 and (b) channel 2.

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