Link Performance Evaluation for mmWave Systems

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***Abstract*— This paper presents a link performance study for mmWave systems at 60 GHz. The study is based on mmWave wireless modem measurements. The system performance is characterized by means of common metrics such as packet delivery rate, Signal to Noise Ratio (SNR) and throughput. The effect of spatial and polarisation diversity/multiplexing is explored, considering various modulation and coding schemes (MCS). Based on our findings, spatial diversity mostly impacts the quasi/non-Line-of-Sight (LoS) locations, whereas the gain from polarization diversity is more significant for horizontal polarized transmitters. Finally, results are compared to results from a channel measurements campaigns, performed at the University of Bristol at the same time, showing similar SNR trends, and thus empowering the validity of our results.**

Keywords—mmWave; 60 GHz modem measurements; spatial diversity; polarisation diversity/multiplexing;depolarisation

I. Introduction

Future wireless networks will face the challenges of high mobile data traffic, and major requirement of increased spectral efficiency and Quality of Service (QoS). The current wireless spectrum (sub-6 GHz) will not be enough to meet those service demands. Thus, new technologies have been proposed, among which higher frequency bands, in particular millimetre (mmWave) frequencies (30-300GHz), to resolve the aforementioned issues. In addition, mmWave bands are expected to be exploited, apart for the access, for the fronthaul and backhaul of future Radio Access Networks (RANs).

The mmWave spectrum, mainly suitable for short distance communications (~ 200 m), can provide large continuous bandwidths, allowing data rates in the range of Gigabits per second. mmWave channels suffer from atmospheric absorption and sensitivity to blockage (i.e. high propagation loss) [1]. Therefore, highly directional beamforming should be employed together with a direct path in mmWave systems. The performance of mmWave systems is of major importance and undergoes major research. A modem measurements campaign has been performed, aimed at investigating the link performance of Single-Input-Multiple-Output (SIMO) and Multiple-Input-Multiple-Output (MIMO) systems at mmWave frequencies in downlink. Both Line-of-Sight (LoS) and non-LoS (NLoS) scenarios were considered, outdoors, under the investigation of the merits that receive and polarisation diversity can bring to a system.

Diversity combining techniques (switched/selection diversity, maximal ratio combining) provide improvement to the signal to noise statistics of the received signal in wireless communications [2]. Among the techniques required for diversity combining, space and polarization diversity have been implemented in our experiments. Space diversity involves reception over a number of antennas placed sufficiently far apart, usually selecting the branch (antenna) with the higher SNR or Received Signal Strength Indicator (RSSI) [3]. Polarisation diversity exploits the reception of the signal onto two orthogonal polarisations, since in a fading channel, it is highly improbable that both transmitted waves, with nearly the same transmit power, will be received on the polarized antennas in deep fades simultaneously [2].

This paper presents and compares the results of the modem measurement campaigns in mmWave systems at 60 GHz. It focuses on the performance of Single Input Multiple Output (SIMO) and Multiple Input Multiple Output (MIMO) mmWave systems, with fixed highly directional beams whilst investigating the impact of spatial and polarisation diversity. Performance is measured through metrics such as SNR, packet delivery rate and link rate.

The remainder of this paper is organized as follows: Section II provides a thorough description of the modem measurements campaign**.** Section III described the results of spatial/receive diversity looking at the SNR values. Moreover, Section IV presents a depolarization analysis based on our results related to polarisation diversity/multiplexing. Section V discussed the link level performance of our mmWave system. Finally, Section VI summarises the main outcomes of our work stating the most important conclusions drawn.

II. Measurements Set-Up

The modem measurement campaign aimed at investigating the gain, in terms of performance (packet delivery rate, SNR, data rate), that can be achieved with the application of receive and polarization diversity.

A. *Description of Kit and Measurement Plan*

The Modem Measurements campaign was carried out at Cantock's Close, Bristol. Overall, 17 location points were designated as testing points. As depicted in Fig. 1, points 1-10 lie on the north side of Cantock's Close, whilst 11-14 lie on the pavement on the south side, and points 15-17 are located on top of a 4m high wall/embankment overlooking Cantock's Close. Table 1 summarises the setting of the modem measurements campaign.

Fig. 1. Modem Measurements Plan (view from transmitter side)

Table 1. Modem Measurements Campaign.

Parameter	Value (meters)
Antenna height (on pole)	2
Tx antenna height from ground	6.5
Rx antenna height from ground (Location Points 1-14)	2
Rx antenna height from ground (Location Points 15-17)	6.5
Distance of Tx from Location Point 1	29
Distance of Tx from Location Point 11	27
Distance of Tx from Location Point 15	48
Distance between Location Points	2

The main equipment comprised of four Blu Wireless Technology Lightning II modules (used as receivers/transmitters based on the IEEE 802.11ad standard), shown in Fig. 2, mounted on 2m poles. The modules operate in either transmitter (Tx) or receiver (Rx) mode and work with locally generated raw packets (neutral mode). Modules can also operate bidirectionally, but we did not use this mode of operation. In Tx mode, packets are continuously constructed and transmitted with an incrementing sequence number. The 16-bit sequence number wraps every 64K packets. The Effective Isotropic Radiated Power (EIRP) is fixed at 33 dBmi. The tapered antennas on the modules were operated with a fixed zero-phased beam and no beamforming was performed. In Rx mode, the unit listens and receives all complete packets heard from any source. Finally, the maximum throughput that can be achieved with these raw packet tools is around 400Mbit/s, significantly below the 1.1Gbit/s that can be reached with the full Medium Access Controller (MAC). The test configuration is given in Table 2.

Fig. 2. BWT Lightning II Module

Table 2. BWT Modules Test Configuration.

Parameter	Value
Packet size	65536 bytes
Packets received	10000
Type of antenna	Tapered patch antenna array
Modulation and Coding Scheme (MCS)	Mode 2 (BPSK code rate 1/2) Mode 5 (BPSK code rate 13/16) Mode 6 (QPSK code rate 1/2) Mode 9 (QPSK code rate 13/16)

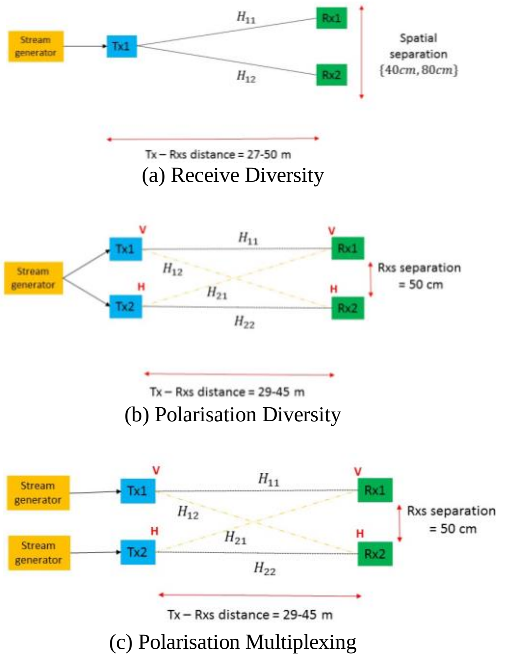

Fig. 3. Experiment Set-up.

Three scenarios, depicted in Fig. 3, were investigated: a) receive diversity (with two receivers and one transmitter – all in vertical polarisation), b) polarization diversity (with two receivers and two transmitters sending the same data stream in different polarisations), and c) polarization multiplexing (with two receivers and two transmitters sending different data streams in different polarisations). Lastly, the modules were manually tilted in elevation by eye to align transmitter and receiver, and manually rotated in azimuth, also for best alignment.

III. RECEIVE/SPATIAL DIVERSITY

In wireless telecommunications, in order to improve the signal to noise statistics of the received signal, several receive diversity combining techniques, such as switched diversity, selection/receive diversity, and maximal ratio combining, can be employed. For the modem measurements, the scenario of receive diversity, which selects the branch with the higher SNR, was designated.

A. Signal-to-Noise Ratio

One transmitter and two receivers, as depicted in Fig. 4, were considered in order to create a Single Input Multiple Output (SIMO) system. The experiment was carried out for two receive antenna separations: a) 40 cm, and b) 80 cm, and four MCS modes (as described in Table 2).

Fig. 4. Receive Diversity at Rx side (left: Point 2-LoS, right: Point 10-Foliage).

For each test, the greater of the metrics captured by the two receivers was taken. For the SNR, the metric is the mean of the per packet received SNR. The maximum average SNR for every location point is depicted in Fig. 5. We can observe how the average SNR degrades as receivers move further from the transmitter (points 1-9). The SNR value drops significantly at NLoS locations (points 10, 14, 23).

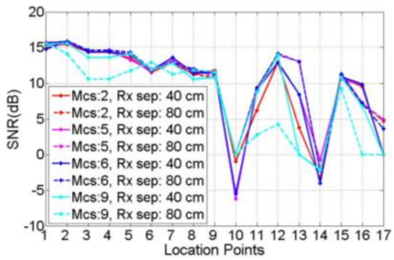

Fig. 5. Average SNR (maximum over the two receivers) for all location points tested.

Moreover, modulation and coding do not affect the SNR, apart from the case of QPSK 13/16, which could also have happened due to sudden misalignment or change in the environment. Overall, changing the spatial separation at the receivers does not affect the link performance in the LoS environment. On the contrary, at quasi-LoS and foliage environments (i.e. location points 10, 13, 14, 23), we observe different performance for the two cases of receiver separation, since a greater separation gives better visibility to one of the receivers.

B. Comparison with Channel Measurements Campaign

The SNR related results of the modem measurement campaign were compared to the results of the channel measurements campaign (performed at the same time in the University of Bristol) in order to investigate the correlation, in terms of SNR, at common location points (points 1-10). The transmit EIRP for the channel measurements was 40 dBmi, and for the modem measurements campaign 33 dBmi. Taking into consideration, only the difference in the transmit power, Fig. 6 depicts the maximum SNR for location points 1-10, where we can observe that the SNR follows the same trend. Other differences impacting SNR are the noise figure of the receiver and the receiver antenna gain.

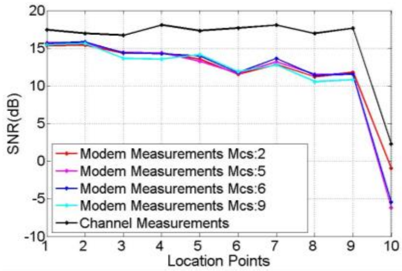

Fig. 6. Max SNR for location points 1-10 – Comparison between channel sounder and modem measurements.

IV. STUDY ON POLARISATION

After investigating the effects of receive diversity, the scenarios of polarisation diversity and multiplexing were examined in order to observe the potential diversity gains arising from cross-polarisation, and the potential losses that cross-polarisation can induce to a dual stream cross-polar transmission. Cross-polarisation is the capturing of power by a receiver that is orthogonally polarised to a transmitter. It arises because of depolarisation of the transmitted wave, imperfect alignment of Tx and Rx, and imperfections in the antenna performance.

Seven location points were tested (points 1-7 in Fig. 1) representing mainly a LoS environment. At both ends, antenna separation was set to 50 cm, with Tx 1/Rx 1 set to vertical polarization and Tx 2/Rx 2 to horizontal polarization.

Overall, for both scenarios, based on the results of the measurements, cross-polarisation was observed at Rx for all location points. In this context, cross-polarisation is manifested by the observation that: a) packets transmitted on horizontal polarisation are detected by the vertical polarised receiver, b) vertical polarised receiver performance is impacted by the transmission of packets from horizontal polarisation (whether the packet sequence is approximately aligned (diversity) or not (multiplexing)). On the contrary, hardly any cross-polarisation was observed at Rx 2.

In order to investigate depolarisation, an additional experiment was performed, with one transmitter (either in H or

V) and two receivers in different polarisations. Many location points were tested, but only at point 1 successful packet reception was recorded for a receiver orthogonal to the transmitter. Also, more azimuth settings (on boresite and +/- 10 degrees) of the receiver were used at location point 1, since it was observed that the azimuth orientation affects the behaviour.

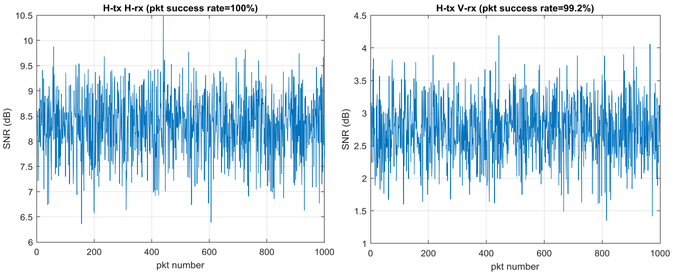

Fig. 7. SNR measurements with horizontal transmission

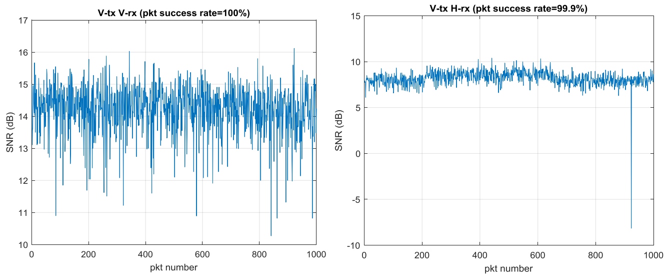

Fig. 8. SNR measurements with vertical transmission

With the horizontal transmission, it was found that the vertical polarised Rx picked up packets well when pointed about 10 degrees to the left of the transmitter. When pointing direct at the transmitter often no packets were received, although the performance was somewhat noisy, with some correct packets on the initial runs. Fig. 7 shows the SNR when the vertical receiver has a good orientation for reception. The SNR is lower than that of the horizontal transmitter but it is sufficient to decode MCS 2 packets. Stepping the MCS up to 5 or 6 gave no packets received on vertical, whilst approximately 100% packets were received on horizontal (SNR approximately 8dB).

Finally, when the transmitter was set to vertical polarisation, we recorded good pick up on the orthogonal receiver. SNR values were higher with the vertical transmission, as depicted in Fig. 8.

V. Link Level Performance

The link level performance of the SIMO/MIMO system, was investigated with regards to the packet delivery rate (pdr) and the data rate for both the receive diversity and polarisation diversity/multiplexing cases.

For the case of receive diversity, the packet delivery rate, depicted in Fig. 9, isn't affected by different receive separation. For LoS location points, the packet delivery rate is almost always 100% for all MCS modes. On the contrary, it drops significantly at locations that are quasi/NLoS. An interesting observation can be made for location points 12-13 and 15-16. Higher order MCS modes, i.e. Quadrature Phase Shift Keying (QPSK) 1/2, and QPSK 13/16, degrade the performance by 85%, mainly due to the fact that the points are located in partial foliage (points 12-13) and far from the transmitter (points 15-16).

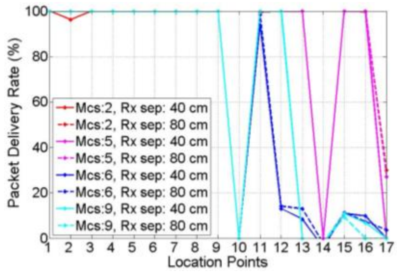

Fig. 9. Average Packet Delivery Rate for all location points tested (Receive Diversity)

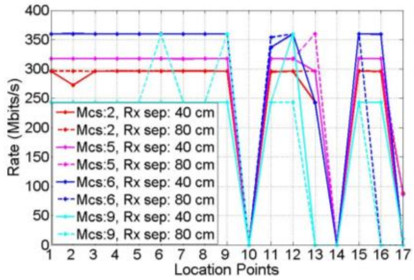

Fig. 10. Average Data Rate for all location points tested Receive Diversity)

The mean data rate, shown in Fig. 10, drops dramatically to 0 Mbits/s at NLoS location points following overall the same trend with the packet delivery rate. We can observe that receive separation does not affect the system performance, apart from the case of QPSK 13/16. Overall, the best performance (around 360 Mbits/s) is achieved by QPSK 1/2. Furthermore, at locations tested far from the transmitter (i.e. points 10, 13, 14-17) higher order of MCS modes (i.e. QPSK 1/2, QPSK 13/16) provide worse performance than lower order schemes, such as Binary Phase Shift Keying (BPSK) 1/2, BPSK 13/16.

For the scenario of polarisation multiplexing, Rx 1 was set at vertical polarisation, whereas Rx 2 at horizontal polarisation. Overall, both the packet delivery rate and the data rate, depicted in Fig. 11 and Fig. 12 respectively, are mostly higher for Rx 2, as expected, since during the campaign we have observed higher cross-talk from vertical to horizontal. As for MCS mode, BPSK 13/16 reaches the higher pdr on average, and QPSK 1/2 achieves the higher data rate (360 Mbits/s).

Finally, in order to investigate the higher than expected cross-talk between orthogonal polarisation channels the modems were mounted in the Communications, Systems & Networks group Anechoic chamber, and the modem firmware was used to setup one modem in `beacon' mode sending packets in either vertical or horizontal orientation, and a second modem on a (θ,ϕ) rotator mount was used to capture the packets for different values of azimuth and elevation, the recovered packet SNR was then used as a proxy for array pattern, to characterise the modem array performance. This method allowed a measure of the co polar and cross polar performance, and this can be seen in Fig. 13 and 14. Fig. 14 exhibits strong cross polar response at (±10), which provides a strong explanation for the observed cross-talk.

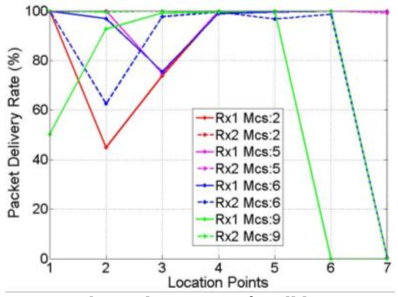

Fig.11. Average Packet Delivery Rate for all location points tested (Polarisation Multiplexing)

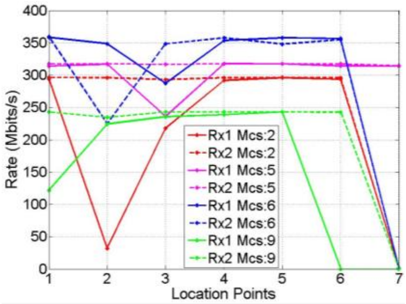

Fig. 12. Average Data Rate for all location points tested (Polarisation Multiplexing)

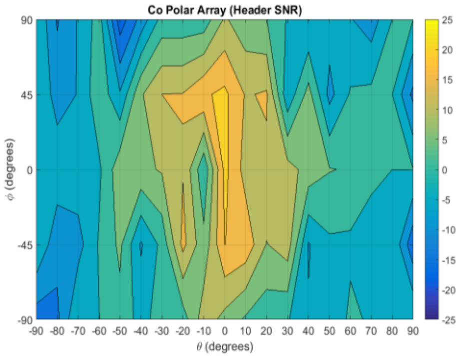

Fig 13. Co Polar SNR (Equivalent to VV for ϕ=0).

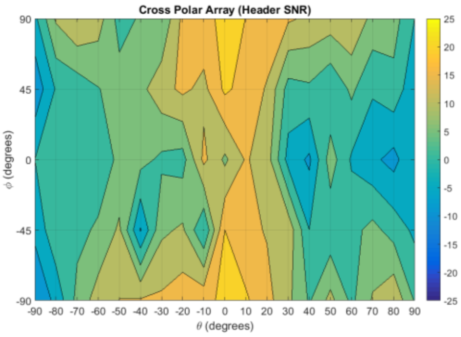

Fig. 14. Cross Polar SNR (Equivalent to HV for ϕ=0).

VI. CONCLUSIONS

This paper presents results drawn from a modem measurements campaign, investigating signal transmission in mmWave frequencies (60 GHz). Both LoS and NLoS scenarios were considered, exploring the merits of spatial and polarization diversity.

Regarding polarization diversity, based on the outcomes of the two campaigns, co-polarised signals have similar performance for vertical and horizontal polarised transmitted signals. Moreover, we have observed that cross-polarised received signals in horizontal polarisation achieve a better performance than in vertical polarisation. Furthermore, in LoS scenarios, a signal transmitted in vertical polarisation suffers stronger depolarization than it would in the case of being transmitted in horizontal polarisation.

As far as receive/spatial diversity is concerned, we have observed that no significant difference in performance is achieved if the antenna spacing changes in LoS environments, whereas in NLoS scenarios, increasing the spacing between the antennas results in higher packet delivery rate and data rate, mainly because at least one of the receivers has a better visibility to the transmitters.

Overall, the 60 GHz modem measurements campaign has given useful insights into the link performance of a mmWave SIMO/MIMO system. The fact that our results were in accordance with results (i.e. common SNR trends and observations regarding depolarisation), given by a channel measurements campaign (performed simultaneously at our site), strengthens the validity of our results and encourage further practical and analytical work on these grounds.

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