Demonstration of Radio-over-Fibre Transmission of Broadband MIMO over Multimode Fibre using Mode Division Multiplexing

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Abstract *A novel method for sending MIMO wireless signals to remote antenna units over a single multimode fibre is proposed. MIMO streams are sent via different fibre modes using mode division multiplexing. Combined channel measurements of 2km MMF and a typical indoor radio environment show in principle a 2x2 MIMO link at carrier frequencies up to 6GHz.*

Introduction

The demand for high-speed wireless services is increasing rapidly as mobile devices become increasingly ubiquitous and consume more data. Distributed antenna systems (DAS) using radio-over-fibre have been shown to improve both coverage and channel capacity (by improving SNR) for wireless services over a broad frequency range[1]. Another emerging technology that has been shown to improve capacity for wireless channels is multiple-input multiple-output (MIMO)[2]. MIMO makes use of spatial multiplexing to provide increased data rates without using additional bandwidth or transmit power. MIMO is rapidly being adopted with wireless LAN standard IEEE 802.11n and cellular standard 4G/LTE supporting up to 4 separate MIMO spatial RF-streams by using 4 transmit and 4 receive antennas (4x4 MIMO). Wireless LAN protocols presently in development, such as IEEE 802.11ac, allow for up to 8 spatial RF-streams (8x8 MIMO).

In order to meet future capacity demands it is necessary to combine the capacity benefits of MIMO with the coverage benefits of DAS technology. This raises a difficulty because in many DAS designs it will be necessary to send several MIMO spatial RF-streams to a remote antenna unit (RAU) and the installation of multiple fibres (one for each stream) is likely to be too costly. However, since MIMO spatial streams occupy the same frequency range, in order to send them over a single fibre a form of multiplexing is required, particularly as it is preferable for the distribution network to be broadband and support multiple services. Since around 85% of all pre-existing fibre installed in buildings is MMF the multiplexing scheme would benefit from working over MMF[3]. The multiplexing scheme should support frequencies up to at least 6GHz in order to support MIMO standards such as 802.11ac. An example MIMO enabled DAS is illustrated in Fig. 1.

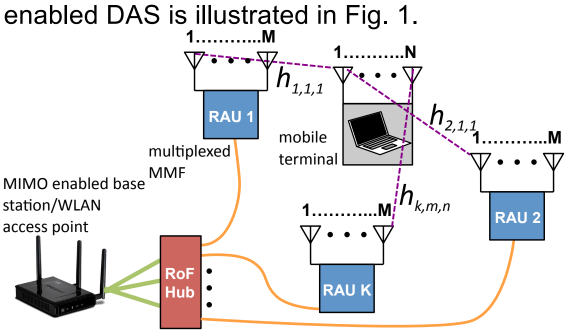


Fig. 1: Schematic of MIMO-enabled DAS

Previously, there have been a number of multiplexing techniques proposed for MIMO DAS[4-5]. Sub-carrier multiplexing and other RF frequency translation techniques have been demonstrated[4]. However there is a limit to reusing RF spectrum for a large number of MIMO streams, particularly if they are broadband. WDM has been proposed but requires complex and expensive equipment[5].

Mode Division Multiplexing (MDM) of MMF is a technique that allows different propagation modes in MMF to be individually excited, allowing parallel transmission of data streams[6-8]. Using this technique in the context of a DAS transforms the RF MIMO channels of different antennas into different spatial channels propagating on different fibre modes. This is an interesting transformation in its own right, but is of practical benefit as the principles of modal selectivity upon which MDM relies upon for operation, also heavily suppress the effect of intramodal dispersion, increasing the bandwidth-distance product of the fibre for each channel.

The authors have previously demonstrated mode multiplexing achieved with phase masks generated using LCOS spatial light modulator (SLMs) that that can transmit two separate 12.5Gbps data streams over 2km of OM2 fibre[7]. In this same set-up there are at least 20 non-degenerate modes, spanning 9 mode groups, that can be individually excited using separate phase masks and that have 3dB bandwidths of greater than 6GHz[8]. To provide 8 independent streams at 1550nm it would only be necessary to populate a single mode from each mode group, meaning low optical coupling between modes can be achieved. Previous MDM systems have been unable to provide more than 2-4 independent channels because of high coupling between modes at the transmitter and receiver resulting from, for example, the need to accommodate connector tolerances and fibre imperfections[9]. However, precise dynamically adjustable phase masks make it possible to independently excite a much greater number of modes. This has the potential to transmit large numbers of broadband MIMO RF-streams, which will be essential for future MIMO systems.

In this paper we combine a 2-stream MDM system with MIMO RF channel measurements in a typical indoor DAS scenario to create a proof-of-principle demonstration of a broadband 2x2 MIMO-enabled DAS RAU fed by a single fibre. The system is shown to offer improved MIMO capacity over the test area for 2 spatial streams up to 6GHz over 2km of OM2 MMF.

Theory and experimental set-up

The capacity of a wireless MIMO link is determined by measuring the complex channel transfer coefficients $h_{k,m,n}$ as shown in Fig. 1, and combining them into a matrix, $\mathbf{H}$. The Shannon channel capacity is then given as[9]:

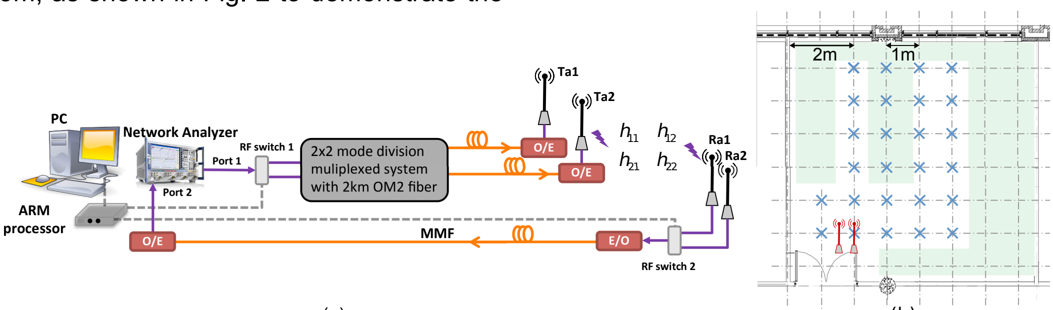
$$C_{MIMO} = \log_2 \det\left(\mathbf{I} + \frac{\rho}{N_T}\mathbf{H}\mathbf{H}^*\right) \qquad (1)$$

The entries of $\mathbf{H}$ vary randomly in different environments due to multipath interference. In order to simulate this and obtain a more generalised result, this experiment measures the radio propagation environment over a frequency range from 1.7GHz to 2.7GHz. This range is limited by the antennas and but is sufficiently broad to produce a representative range of multipath interference. The frequency responses of the antennas are accounted for so that the measurements accurately represent the broadband propagation environment. Measurements are repeated at 26 positions in the room, as shown in Fig. 2 to demonstrate the system performance over a coverage area in a typical indoor DAS situation.

The MDM system used is shown in Fig. 3. A single 1550nm tunable laser source is used to produce two separate optical streams, each of which is externally modulated with a Mach-Zehnder Modulator (MZM). This system uses lenses to excite the fundamental mode ($LP_{0,1}$) of the fibre and an SLM to excite a programmable choice of higher order mode, for transmission of two spatial channels. A binary-phase 256x256 SLM with a pixel pitch of 15μm is used to generate phase masks that allow the light to be launched into the fibre with a particular mode profile. This set-up can launch any mode of the fibre, or superpositions of these modes. In this experiment the $LP_{1,2}$ mode is used.

The fibre used is 2km of OM2 fibre, with a 3dB bandwidth of 940MHz for an overfilled launch condition. This bandwidth is greatly increased by the use of mode-multiplexing as modal dispersion is almost completely eliminated. At the receive end a 70/30 MMF coupler, made by *Go4Fiber*, is used to separate the $LP_{0,1}$ and $LP_{1,2}$ modes. After this a standard single mode fibre (SMF-28) is used to remove modes other than $LP_{0,1}$ from the first output. If more than two modes were to be multiplexed it would be necessary to use another SLM at the output of the fibre to provide full mode demultiplexing.

The complex transfer coefficients between each input (connected to the Mach-Zehnder modulators) and the photodiode receivers placed at the optical outputs are measured using a network analyser and power meter[7]. These are then used to produce additional transfer matrices, $\mathbf{H}_{mux}$, at 30 test frequencies from 40MHz to 6GHz. To obtain the response matrix of the combined system shown in Fig. 2, each matrix $\mathbf{H}_{mux}$ is multiplied by each normalised $\mathbf{H}$ representing a different fading scenario. Equation 1 is then used to calculate the capacity of the combined system for each fading realisation and frequency. These fading realisations are random variables so calculating capacity for each of them produces a statistical distribution.



(a) (b)

Fig. 2: a) Experimental set-up of 2x2 MIMO RF system b) DAS RF test environment showing test points.

This multiplication process accounts for the effects of mixing between modes in the fibre as well as between spatial streams in free space. MIMO systems periodically send pilot signals to determine the total channel matrix, in this case $\mathbf{H}_{sys}$, and in doing so detect the level of such mixing so this is automatically accounted for in the protocol meaning no additional DSP is required.

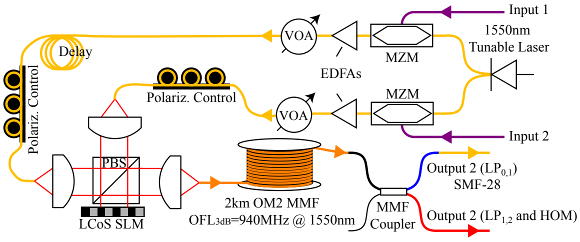


Fig. 3: Set-up of mode division multiplexing system[7]

Results

Fig. 4 shows a measurement of the coupling between the different inputs and outputs as shown in Fig. 3 indicating the mode-multiplexing system loss as well as the coupling between modes. It can be seen that for the fundamental and $LP_{1,2}$ modes the electrical link loss is about 20dB, mostly due to the insertion loss of the SLM which is not designed for operation at 1550nm. From Fig. 5 it is seen that the isolation between different modes as seen from the electrical inputs/outputs is more than 24dB over a frequency range of 18GHz. The standard deviations of the mode isolations over a 24-hour period are also shown. This indicates that the MDM link is well suited to sending separate MIMO streams with minimal cross-talk.

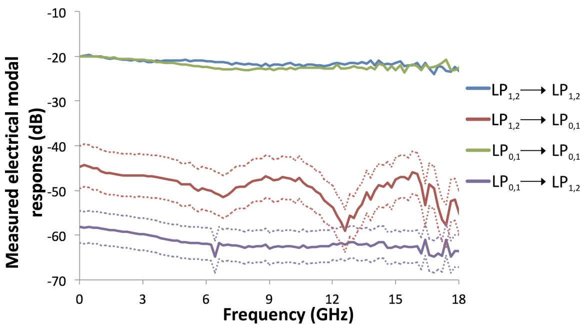


Fig. 4: Graph showing coupling between multiplexed modes at the output of the fibre vs frequency. Dashed lines represent the standard deviation over a 24-hour period.

Fig. 5 shows the 2x2 MIMO channel capacity measurements, each normalised to a 1Hz bandwidth, over a 6GHz frequency range. In 802.11n systems a 22MHz bandwidth is used with a typical transmit power of -5dBm and receiver noise floor of -60dBm. These values are used here to give a representative SNR for a 1Hz bandwidth. Shown for comparison is the case where there is 0dB cross-coupling between the fibre modes, i.e. no multiplexing can occur. Even with an electrical loss of 20dB from the mode-multiplexed link and an additional 12dB of electrical loss in other DAS components (antennas, electro-optic converters) the mode-multiplexed 2x2 MIMO link offers a 50% improvement in median capacity over the case where there is 0dB isolation between modes in the fibre with the same total transmit power.

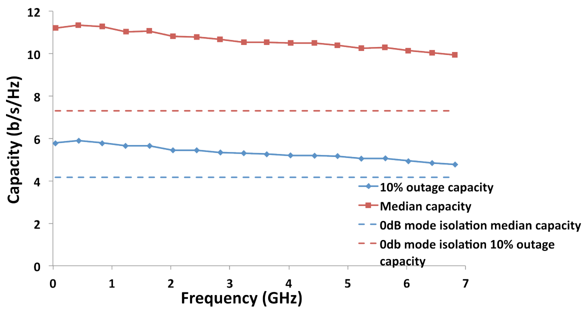


Fig. 5: Graph showing channel capacity of the 2x2 MIMO system detailed in Fig. 2 and Fig. 3vs frequency. Shown for reference is the case where there is 0dB of cross-coupling between modes in the fibre so that no multiplexing can occur.

Conclusions

It is shown for a typical indoor DAS scenario that a 2x2 MIMO system mode division multiplexed over 2km of OM2 MMF is able to provide sufficient SNR performance to support channel capacities of 10b/s/Hz over a bandwidth of 6GHz. The phase-masking system has the potential to multiplex a larger number of independent fibre modes, and hence MIMO RF-streams, than has previously been possible.

Acknowledgements

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