Experimental Investigation of Antenna Selection and Transmit Beamforming for Capacity Enhancement in 3×3 MIMO-enabled Radio-over-Fiber DAS

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***Abstract*—This paper examines the impact of two simple precoding schemes on the capacity of 3×3 MIMO-enabled radio-over-fiber (RoF) distributed antenna systems (DAS) with excess transmit antennas. Specifically, phase-shift-only transmit beamforming and antenna selection are compared. It is found that for two typical indoor propagation scenarios, both strategies offer double the capacity gain that non-precoding MIMO DAS offers over traditional MIMO collocated antenna systems (CAS), with capacity improvements of 3.2–4.2 bit/s/Hz. Further, antenna selection shows similar performance to phase-only beamforming, differing by $<0.5\%$ and offering median capacities of 94 bit/s/Hz and 82 bit/s/Hz in the two propagation scenarios respectively. Because optical DASs enable precise, centralized control of remote antennas, they are well suited for implementing these beamforming schemes. Antenna selection, in particular, is a simple and effective means of increasing MIMO DAS capacity.**

I. Introduction

Currently there are over 5.9 billion mobile subscriptions and 1.2 billion wireless-LAN enabled devices worldwide [1]. Further, mobile data usage is predicted to increase 18 fold from 2011 to 2016 [2]. To keep pace with this exploding demand from users, several important technologies have been widely adopted in recent years.

Distributed antenna systems (DAS) are a commonly used infrastructure technology designed to improve performance of wireless systems within buildings, tunnels etc., and it is estimated there are over 89,000 DAS installations worldwide [3]. In a DAS the antennas of a wireless transceiver or base station may be replicated and located remotely from the RF hardware, improving coverage and capacity of wireless systems [4]. This is in contrast to traditional co-located antenna systems (CAS) where antennas are located on the base station. In a DAS the antenna feeds of a wireless base station are transported via cabling, in this case optical fiber using *radio over fiber (RoF)* techniques, to *remote antenna units (RAU)* where they are amplified and re-transmitted. RoF is a popular choice for DAS because it enables broadband operation, and hence transparent multiservice support, over distances of several hundred metres [4]. Further, because of the flat frequency response and low-loss of optical fiber over a very large RF frequency bandwidth and the ease of sending low-rate digital data in parallel with RF streams, it is possible to precisely and coherently control RAUs from a centralized control hub.

Another recent wireless protocol technology aimed at improving the capacity is *multiple-input multiple-output (MIMO)* antenna technology, whereby individually fed arrays of antennas are used at the transmitter and receiver. The capacity

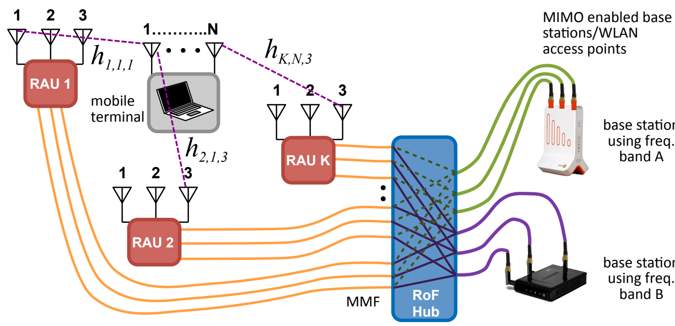


Fig. 1. Diagram showing an example of a clustered 3×3 MIMO DAS with K RAUs each having 3 transmitting antennas. The complex channel transfer coefficients are denoted as $h_{\mathrm{K,M,N}}$.

of these is maximized through *spatial multiplexing*, whcih exploits the spatial decorrelation of adjacent array elements due to multipath interference to transmit multiple parallel data streams that are later extracted using DSP [5].

It remains an important technological challenge to combine the benefits of both DAS and MIMO. One major question is whether there is any benefit to replicating multiple spatial streams at each RAU, a design termed *clustered MIMO DAS* here, or whether it is better simply to distribute the spatial streams amongst different RAUs. An example of a clustered 3×3 MIMO DAS is shown in figure 1. Theoretical work has shown there to be performance advantages of fully distributing spatial streams [6], [7], but other simulations have shown that in more realistic propagation environments the performance is similar [8]. Furthermore in emerging standards such as 802.11ac, which allows up to 8 spatial streams, fully distributing all spatial streams becomes impractical and increases the risk that many of the streams will be underutilized due to higher loss resulting from larger distances to the mobile [9]. Given this, it is likely that in some cases, it will be necessary to support multiple spatial streams at each RAU.

In the case where spatial streams are replicated at different RAUs, there is an additional degree of freedom introduced over conventional MIMO systems because in total there are many more transmit antennas than spatial streams. This offers the potential to use precoding schemes to improve capacity. Popular precoding schemes include *multiple eigenmode transmission*, which uses the singular value decomposition of the channel matrix to achieve full spatial multiplexing capacity, *antenna selection*, which selects only the optimal subset of antennas for use, and *transmit beamforming*, which changes the phase, amplitude and mixing between transmit elements to focus the transmitted power towards the receiver.

Previous theoretical work on *massive MIMO* systems or *large scale antenna systems (LSAS)* with a significant surplus of transmit antennas has found that linear precoding beamforming techniques such as conjugate beamforming provide significant capacity gains [10]. Coordinated beamforming between groups of distributed transmit antennas has also been demonstrated, both theoretically and experimentally, to mitigate intercell interference, as in *cooperative MIMO* or *coordinated multipoint (CoMP)* [11], and to improve capacity within a cell [12]. In the latter case, a key problem is synchronising all transmit antennas as they are assumed not to be linked to a central controller. Antenna selection has also been shown theoretically to enable significant improvements in capacity for MIMO DAS [13].

However, this work has been largely theoretical and if these advances are to be realized practically as incremental improvements to existing systems, some important technical challenges remain. One key issue is that many common spatial multiplexing algorithms, such as Bell Labs' V-BLAST used in 802.11n wireless, are only defined for systems with the same number of transmit and receive antennas (though 802.11n does allow limited beamforming as an optional feature). Therefore, the additional antennas must be 'transparent' to the protocol, meaning that in general precoding techniques must have implementations in analog hardware. Implementing full beamforming in this way is challenging as it requires the ability to send any arbitrary linear combination of spatial streams to any transmit antenna. A simplified version of beamforming would enable each spatial stream at each RAU to have its phase changed and could be implemented simply with a variable electronic delay in the central DAS hub, termed *phase-only transmit beamforming*. Antenna selection, too, can be implemented simply and transparently in hardware using RF or optical switches. Further, the ease with which RoF DAS can be centrally controlled means that these techniques can be implemented in the DAS hub, avoiding the need to synchronize independent transmitters. Information can be transferred between the hub and the RAUs via digital transmission over the fiber, making RoF DAS ideally suited for implementing coherently optimized MIMO transmission.

This paper then compares the effect of phase-only transmit beamforming and antenna selection for optimising capacity. The results presented are based on experimental channel measurements taken for two typical indoor 3×3 MIMO RoF DAS scenarios. It is found that using a simple antenna selection scheme offers almost the same improvement in capacity again as switching from MIMO CAS to MIMO DAS of the order of 3-4 bit/s/Hz. Further, the antenna selection scheme provides capacity comparable (within 0.5%) of phase-only transmit beamforming schemes.

II. THEORY

The performance of a MIMO system can be fully characterized from measurements of the complex channel transfer coefficients $h_{k,n,m}$ for every transmit and receive antenna pair, as shown in figure 1. In this case it is possible to represent the channel using K separate $M \times N$ matrices (one for each RAU), defined as:

$$\mathbf{H}_k = \begin{pmatrix} h_{k,1,1} & h_{k,1,2} & \cdots & h_{k,1,M} \\ h_{k,2,1} & h_{k,2,2} & \cdots & h_{k,2,M} \\ \vdots & \vdots & \ddots & \vdots \\ h_{k,N,1} & h_{k,N,2} & \cdots & h_{k,N,M} \end{pmatrix} \tag{1}$$

The received signal from the k^{th} RAU is then:

$$\mathbf{y} = \mathbf{H}_k \mathbf{x} + \mathbf{n} \tag{2}$$

where $\mathbf{x}$ is the input signal vector from the base station, $\mathbf{y}$ is the signal vector received by the user and $\mathbf{n}$ is a complex random noise vector. To achieve maximum spatial multiplexing gain, the K matrices would be combined into a single $M \times KN$ matrix, $\mathbf{H}_k$. The singular value decomposition of $\mathbf{H}_{\text{full}}$ can then be used to devise optimal coding schemes at the transmitter and receiver (e.g. a multiple eigenmode implementation [14]) to achieve maximum channel capacity. This capacity is calculated from the singular values as:

$$\mathbf{C}_k = B \sum_{p=1}^{S} \log_2 \left(1 + \frac{\rho}{M} \sigma_{k,p}^2\right) \tag{3}$$

where B is the bandwidth of the channel, ρ is the total signal to noise ratio of the system and $\sigma_{k,p}$ is the p^{th} largest magnitude singular value of $\mathbf{H}_k$. This assumes that equal power is allocated to each eigenmode of the channel but it is known that the maximum theoretical capacity of a MIMO channel is achieved by allocating power using the *water filling* algorithm. Although this is not currently implemented in real MIMO systems, it is included in the results presented here for reference.

The implementation of a multiple eigenmode scheme is complex because, like conjugate beamforming, it requires the ability to arbitrarily distribute the M transmit streams amongst KN antennas. However, it is included here for reference. Antenna selection and phase-only beamforming offer much simpler implementations, requiring only variable phase delays and RF or optical switches respectively.

To examine antenna selection an equivalent channel matrix $\mathbf{H}_{\text{AS}}$ is formed using M columns picked from the $\mathbf{H}_k$ matrices so as to maximize channel capacity. This can be implemented practically by means of an RF or optical switch. Next, an equivalent phase-only beamforming channel matrix $\mathbf{H}_{\text{BF}}$ is formed by applying a phase shift, $\theta_{k,m}$, to each of the transmit antennas at each RAU and then summing the resultant channel matrices. The optimal values of $\theta_{k,m}$ are determined by an optimization algorithm, in this case an active-set algorithm using Lagrange multipliers. The target can either be to maximize capacity or to minimize condition number, which in this context is a measure of the decorrelation of spatial channels. Both methods are used in this paper for comparison. This search can make beamforming more complex to implement than antenna selection, which only requires a search through a predetermined number of configurations.

Also used in this paper for comparison are two popular diversity only (i.e. no spatial multiplexing) schemes – maximal ratio combining (MRC) and selection combining (SC). These represent the best possible performance that can be obtained using a traditional optical DAS that does not support MIMO.

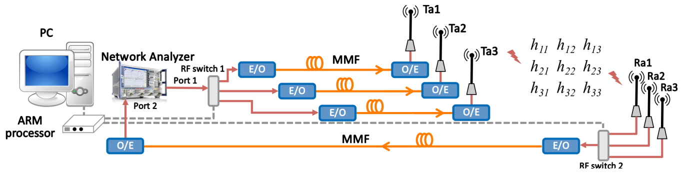


Fig. 2. Experimental setup of the 3×3 MIMO channel measurement system.

The Shannon channel capacity for both $\mathbf{H}_{\mathrm{BF}}$ and $\mathbf{H}_{\mathrm{AS}}$ is again determined using singular values as per equation 3. If the two matrices are square, which is very often the case, then many widely used spatial multiplexing algorithms such as V-BLAST may be used [14]. V-BLAST makes use of zero-forcing successive interference cancellation (ZF-SIC) and so is only defined for square channel matrices. Because in reality, channel matrices vary randomly due to multipath fading, the channel capacity, too, is a random variable and so is often characterized by its cumulative probability distribution (CDF). Experimental measurements of MIMO systems must then test performance under many different fading conditions and at many locations in the coverage area.

III. Experimental Setup

The experimental set-up used to take channel measurements is shown in figure 2. Measurements of the complex channel coefficients are taken by using a vector network analyser (VNA) to measure the amplitude and phase of the transfer coefficient between each input port on the DAS and the output port of each receive antenna. This is repeated at 1600 frequency channels over a range of 1.7GHz to 2.7GHz. Care is taken to compensate for the frequency dependent gain of the antennas and the RoF links so that only the broadband channel matrix is measured. In this way, many different multipath fading scenarios are tested giving a more generalized result. Measurements are taken in two different DAS scenarios, both of which are rich in multipath fading but one of which has a significant line-of-sight (LOS) propagation component, shown in figure 3.

The DAS used in both cases is a Zinwave 2700 RoF system, operating at 1310nm and providing 30m links over OM1 MMF. This is a broadband system and is specified to provide services from 300MHz to 3GHz. The system is able to increase the available bandwidth-distance product of the MMF through use of offset launch techniques.

In order to determine the Shannon channel capacity for the different precoding schemes, the measured channel matrices are adjusted as described in section II. The transit power used is 15dBm and the noise floor is -90dBm in a 1Hz bandwidth, typical values for 802.11n compliant access points [15]. The total transmit power is kept constant across all schemes tested.

IV. Results

Figure 4 shows the median capacity of the different precoding schemes for the LOS propagation scenario as transmit power is increased. As SNR increases it is seen that there is a 3.7 bit/s/Hz capacity gain from using MIMO DAS instead of MIMO CAS, which represents the maximum possible non-DAS MIMO performance. The maximal ratio combining curve

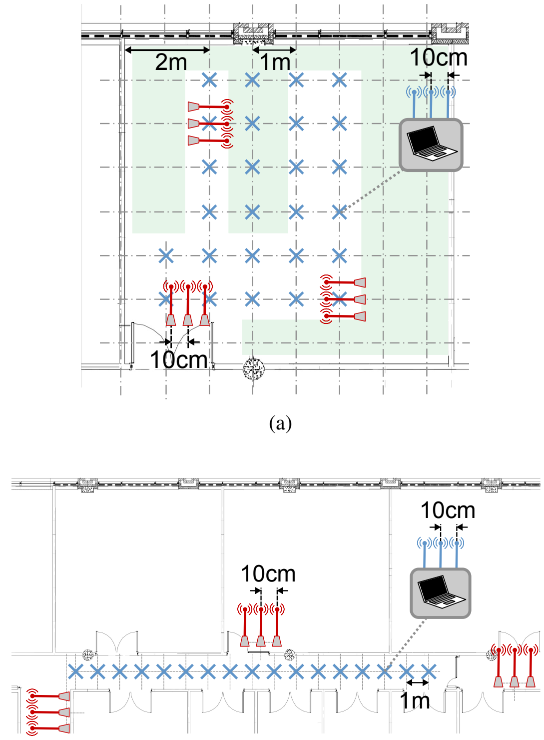


Fig. 3. The two test propagation environments (a) line-of-sight (LOS) scenario and (b) non-line-of-sight (NLOS) scenario, indicating location of transmit antennas and receiver test points.

represents the maximum possible non-MIMO DAS performance and the 9×3 MIMO curve represents the best possible MIMO DAS performance.

Antenna selection and phase-only beamforming optimized for capacity are seen to provide improvements of 3.9 and 4.2 bit/s/Hz over the case with no precoding. Thus, the DAS capacity advantage is almost doubled by using these schemes. It is also worth noting that there is less than 0.5% difference between antenna selection and phase-only beam forming optimized for capacity, both of which provide a median capacity of $\sim$94 bit/s/Hz.

Figure 5 shows the capacity CDFs measured for a range of locations and fading realizations in the LOS and NLOS scenarios. It should be noted that figure 4 in fact shows the median capacities of the LOS CDF (figure 5a) at different transmit powers. Similar results are observed for the LOS scenario and in the NLOS scenario phase-only beamforming optimized for capacity and antenna selection give improvements in median capacity over the non-precoding case of 3.4 and and 3.2 bit/s/Hz respectively, compared to the 4.3 bit/s/Hz gain of MIMO DAS over MIMO CAS – again, almost a doubling of this improvement. Further, it is again seen that the difference in capacities offered by antenna selection and phase-only beamforming is <0.5%, both of which provide a median capacity of $\sim$82 bit/s/Hz.

However, in the NLOS case it is seen than that the 10% outage capacity, i.e. the capacity below which the lowest 10% of fading realizations occur, only sees an improvement of 1.3 bit/s/Hz for antenna selection, compared to 3.4 bit/s/Hz for phase-only beamforming optimized for capacity. Thus, the

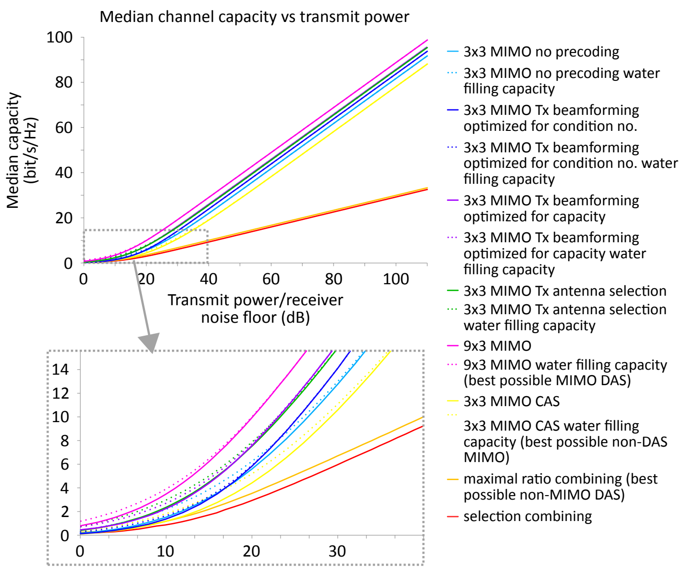
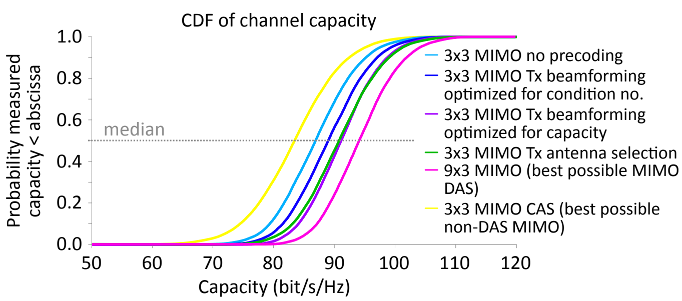
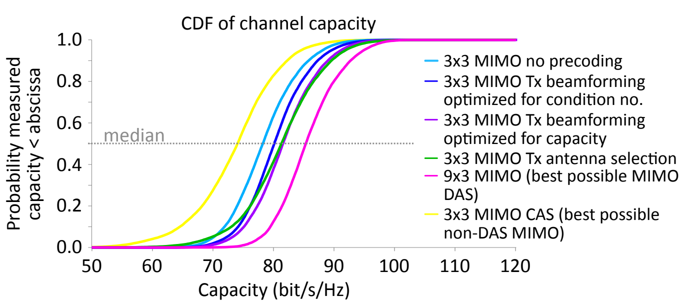


Fig. 4. Graph showing median capacity of different precoding schemes in the LOS scenario as transmit power is increased with noise floor -90dBm.



(a)



(b)

Fig. 5. Cumulative distribution functions of capacity across a range of fading environments comparing precoding schemes in (a) LOS and (b) NLOS scenarios. Transmit power is 15dBm and receiver noise floor is -90dBm.

capacity gain of antenna selection decreases for the worst-case fading scenarios.

Overall, the capacity gain of MIMO DAS over MIMO CAS can almost be doubled by using a simple precoding scheme. Antenna selection has the simplest implementation yet offers performance within 0.5% of that achieved by phase-only beamforming optimized for capacity.

V. Conclusion

This paper compares several simplified precoding schemes, namely phase-only transmit beamforming and antenna selection, for improving capacity in MIMO-enabled RoF DAS. Such precoding schemes are possible in RoF DAS designs where spatial streams are replicated at multiple remote locations, meaning there are many more transmit antennas than spatial streams. Using experimentally measured channel matrices from two typical indoor MIMO DAS scenarios, it is shown that the use of phase-only beamforming and antenna selection in such cases can provide can almost double the capacity advantage offered by switching from MIMO CAS to MIMO DAS. In the two propagation scenarios examined, capacity gains of 3.4 and 4.3 bit/s/Hz were achieved respectively, compared with the 4.2 and 3.7 bit/s/Hz gains of MIMO CAS over MIMO DAS.

Further, it is shown that antenna selection schemes offer similar capacities to phase-only beamforming, differing by <0.5% and providing capacities of 94 bit/s/Hz and 82 bit/s/Hz for the two propagation scenarios tested. Because antenna selection is simpler to implement, requiring only an RF or optical switch to test a predetermined number of possibilities, this presents an attractive means of further improving the data capacity of MIMO DAS in order to keep pace with demand from new generations of users.

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