Indoor Distributed Antenna Experiments

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***Abstract*—A MIMO channel sounder has been used to evaluate several transmission diversity schemes by simulating a distributed antenna system in an indoor environment. Using three fixed transmit antennas and one mobile receive antenna, three channel impulse responses (CIRs) have been measured simultaneously for many receiver locations throughout a hypothetical coverage area. Using the measured CIRs, three diversity schemes have been simulated: selective antenna diversity, multipath antenna diversity and co-phasing transmit antenna diversity. The performance of the diversity schemes are compared using two metrics: gross power and RMS delay spread. Co-phasing transmit diversity achieves the best diversity gain without increasing significantly the delay spread.**

***Index Terms*—Distributed antenna, channel sounding, antenna diversity, co-phasing transmit diversity**

I. INTRODUCTION

Optical fibre transmission has been proposed for use in the backhaul network of urban environment micro-cells [1]. This idea can be extended to distributed antennas, in which multiple antenna units deployed in different locations within a single cell are connected to the cell base-station using an optical fibre network. The space diversity afforded by a distributed antenna can dramatically improve coverage by combating shadowing and fast fading. A practical evaluation of such an antenna system in a real environment would have significant engineering utility. In [2], a distributed antenna with four directional antenna units (in the corners of the measurement area) and two omni-directional antennas (at the centre of the measurement area) are deployed in a 90ft × 300ft indoor environment. In [3], an experiment comprising four fibre-fed distributed antenna units is performed in two rooms, 30m × 30m and 15m × 15m at 900 MHz, 1.8 GHz and 1.9 GHz. In both of these experiments improved performance due to the distributed antenna is reported.

As signals from different antenna units have independent propagations path they will sum with random phase at the receiver and poor SNR due to destructive interference will not be uncommon. It is proposed in [4] that differential delay is intentionally introduced into the diversity branches resulting in the signals from each antenna unit arriving at the receiver well-separated in time. This allows each multipath component to be isolated and optimally combined with all others. We refer to this scheme as multipath antenna diversity. An experimental investigation of this scheme has been reported [5] for a 15m × 12m indoor environment using four corner reflector antennas. The distributed antenna achieves a 3 dB advantage in mean received signal strength.

When the phase and timing of each antenna unit can be controlled separately a more advanced diversity scheme, co-phasing transmission diversity, can be implemented. Signals from all antenna units are aligned in time and phase such that the complex impulse response (CIR) peaks would arrive simultaneously and in-phase thus providing increased diversity gain.

Here we present an indoor pico-cell distributed antenna experiment using a wideband MIMO channel sounder. As the CIRs from all antenna units have been measured at a grid of receiver locations in the pico-cell, different distributed antenna diversity schemes can be simulated, including selective diversity, multipath antenna diversity and co-phase transmission diversity. The coverage performance of different schemes can be evaluated and compared on the basis of total received power and RMS delay spread.

In the following, we first introduce the measurement equipment and campaign. We then briefly explain the diversity schemes to be simulated. Finally we present the simulation result, perform the comparison and draw conclusions.

II. MEASUREMENT EQUIPMENT

A. Channel sounder architecture

The channel sounder, specified by the University of Bath and developed by QinetiQ [6], can be divided into transmit and receive subsystems. Each subsystem comprises a primary transmit or receive unit, a 16-way antenna multiplexer (connected to the primary transmit/receive unit via 5 m of coaxial cable) and a laptop PC to provide a user control interface via Ethernet. In the receive subsystem, a JBOD Fast Data Storage Unit (FDSU), comprising fourteen 73-GB hard-drives, is used to store raw CIRs.

In order for data that is captured and stored by the receive subsystem to be post-processed for further analysis, an Ethernet interface allows stored data to be transferred from the FDSU to an auxiliary PC/network.

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B. *Operating principles and configuration*

The sounder employs pulse compression. The default sounding waveform is a single-sideband BPSK modulated maximal length PRBS with a maximum chip rate of 165 Mchip/s. Pulse shaping ensures that better than 50 dB peak-to-sidelobe ratio can be achieved following back-to-back calibration of the transmit and receive units. The PRBS sequences are chosen such that their length is broadly equal to the required measurement delay time range (5 or 10 µs). Since implementation is software controlled, any desired sounding waveform (including FM chirps) can be realized. Tetherless operation is possible using GPS disciplined rubidium frequency standards. The storage capacity allows approximately 50 minutes of data to be recorded at the maximum data acquisition speed.

The sounder's principal operating parameters are listed in the table.

Band centre frequencies	990 MHz, 2.442 GHz, 5.4375 GHz
Band tuning range	±200 MHz
Maximum sounding bandwidth	250 MHz
Delay resolution	7 ns (for 250 MHz bandwidth, equal amplitude paths)
	15 ns (for 250 MHz bandwidth, 0 dB and -40 dB adjacent paths)
Maximum unambiguous delay	5 µs or 10 µs
Maximum transmitter power	30 dBm
Data acquisition modes	free-run, triggered
Maximum free-run data acquisition rate	10,000 CIR/s in 5 µs mode
Maximum data storage	1 TB
MIMO capability	Any $n \times m$ ($n \leq 16$, $m \leq 16$)

Table 1 Operating parameters of channel sounder

C. *MIMO capability*

The sounder measures the wideband, time-varying, complex impulse response (CIR) of the equivalent baseband channels between 16 transmitter output ports and 16 receiver input ports. It has been designed, primarily, to allow Multiple Input Multiple Output (MIMO) characterization of the radio channels. The capability to measure MIMO channels is realized using a high-speed, digitally-controlled, 16-way antenna multiplexer at both the transmitter and receiver. Measurements are made on each receive antenna in turn before the transmit signal is switched to the next antenna in the series (to minimize RF switching transients). Power is not transmitted during the time that the antenna multiplexer is switched between channels. The multiplexer cycles between channels sufficiently quickly such that for practical engineering purposes the set of CIRs comprising a MIMO measurement can be assumed to be made simultaneously.

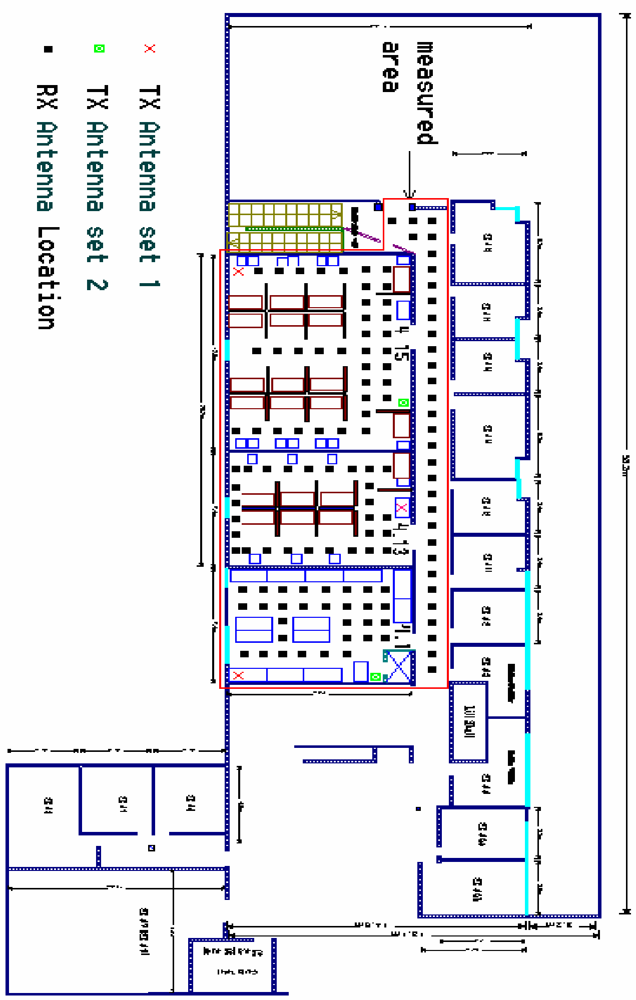

Figure 1 Measurement area floor plan

III. MEASUREMENT CAMPAIGN

A. *Environment*

The measurements were made on the fourth floor of the Department of Electronic and Electrical Engineering at the University of Bath. The measured area (approximately 27m × 11m, bounded by the solid line, shown in Figure 1) includes three laboratories and one corridor. The internal walls are constructed, principally, of plasterboard. In laboratory 4.15 and 4.13, there are desks separated by free-standing partitions. There are some small metal cabinets placed along the walls.

B. *Antennas*

Three transmit antennas and one receive antenna are used in the measurements. All are sleeve dipoles tuned to the measurement frequency of 2.4 GHz. The antennas are mounted on tripods at a height above the ground of 1.5 m.

One transmit antenna is located in each laboratory. The antenna in laboratory 4.13 is identified as 1, the antenna in 4.15 as 2 and the antenna in 4.1 as 3. All three transmit antennas are connected, via low loss coaxial cable (1.784 dB @ 2.4GHz for 2.24 m cable), to the channel sounder's transmit multiplexer. There are two sets of transmit antenna locations (although in room 4.13 the antenna location remains unchanged, see Figure 1). In set 1, the antenna units are placed in the far corner in the respective laboratory. In set 2 they are placed in the middle along the wall. The receive antenna locations form, as far as possible, a 1 m square grid (the black squares in Figure 1) within the measurement area.

C. Measurements

The CIRs of the three channels are measured sequentially at each receive location, in a period that is short enough to deem them simultaneous.

IV. DOWNLINK DIVERSITY SCHEMES

We consider three transmission diversity schemes in this paper. All the schemes target spread spectrum signaling systems, in which the RAKE receiver can resolve multipath components and make use of all the energy they contain.

A. Selection diversity

In this scheme, for each receiver location, only one antenna, which has the strongest signal strength (largest gross power of the CIR), is selected.

B. Multipath antenna diversity

Multipath antenna diversity pre-delays the transmission from each transmit antenna unit so that the CIRs occupy different time windows at the receive antenna, Figure 2. The gross power of the resulting (aggregated) CIR is approximately the sum of the powers in the individual CIRs. In the implementation, an x dB threshold measured down from the peak is used to determine the window of the effective signal delay profile. These window edges are defined by the points at which the power delay profile has fallen to the selected fraction ($-x$ dB) of its peak. The simulations have been carried out with $x = 20$. Delays are introduced at the transmitter such that all windows arising from all transmit antennas are disjoint at the receiver.

Destructive interference between CIR components (which can, in principle, arise between out-of-window energy) is therefore limited to a relatively small proportion of total transmitted power. After alignment of the windows, the CIRs involved in the diversity are summed phasor-wise, the phase of each individual CIR remaining unchanged during the process.

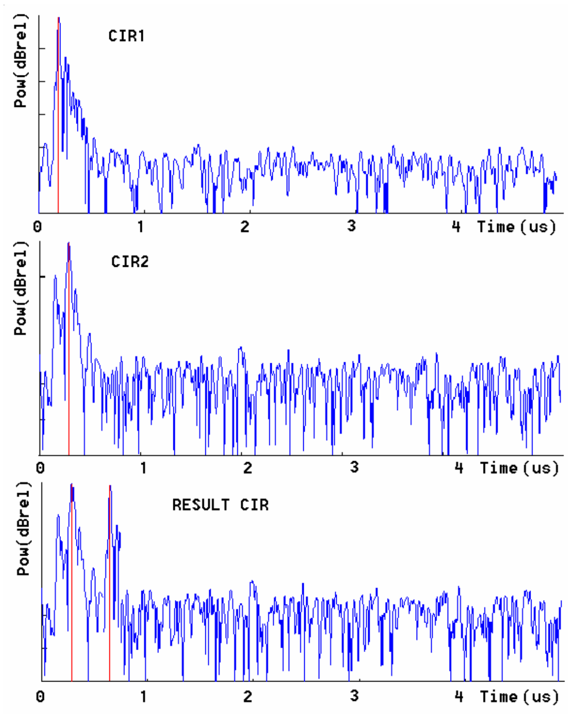

Figure 2 Example CIRs illustrating multipath antenna diversity

C. Co-phasing transmission diversity

In co-phasing transmission diversity, it is assumed that the base-station has knowledge of the downlink channels for every antenna unit.

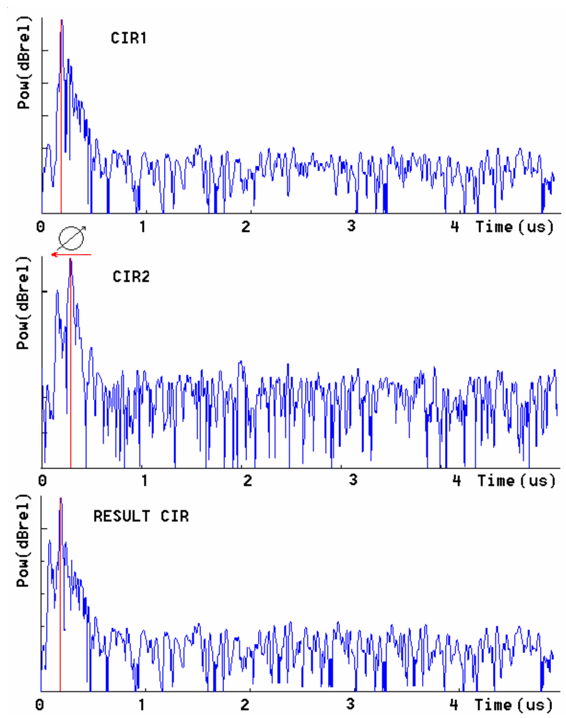

Figure 3 Example CIRs illustrating co-phasing transmission diversity

The transmissions from all antenna units are pre-delayed so that the peak values of all CIRs arrive at the receive antenna at the same time. The phase difference between the peak components is calculated. Every sample in each CIR is rotated by a common angle so that the peak components from all CIRs sum in-phase. This is equivalent to introducing appropriate phase shifts at the transmit antenna units. All CIRs are then summed phasor-wise, Figure 3.

Since, with large probability, the adjacent CIR components have small phase angle variation with respect to the peak (this is shown in a separate study [7]), the phasor sum of all CIRs gives a gain close to the optimum obtained when all CIR components in all CIRs are added in-phase. In contrast to the power-wise summation of multipath antenna diversity, this scheme results in amplitude-wise summation of the peak components. Since the delay profile typically follows an exponential decay, the loss due to phase differences between parts of the CIRs with long delays will be small.

V. PERFORMANCE SIMULATION

A. Method

The CIRs from all antenna units measured at the same receive location can be used as the diversity branches to simulate virtually any diversity schemes. Here, we use these CIRs to simulate the three diversity schemes introduced above.

For each scheme, diversity order of two and three are all simulated. For diversity order two, antennas 2 and 3 are used. As a reference, the CIR measured using antenna 1, located in 2E 4.13, is used to represent the single antenna performance.

B. Coverage performance evaluation

After processing the measured CIRs in accordance with a particular diversity technique we obtain a new spatial distribution of CIRs. Based on this 'simulated diversity' data, we evaluate the coverage performance. Here, we use the generic metrics of gross power and delay spread to summarize the performance of each technique simulated. These two metrics are indicative of channel quality. Gross power mean and variance and mean delay spread are then calculated for the entire measurement area.

C. Gross power comparison

Gross power is a good metric of channel quality, particularly for the case of spread spectrum systems. Due to the frequency diversity property of the RAKE receiver, the signal power it collects is, theoretically, equal to the gross power. We use the mean gross power of combined CIRs averaged over the whole measurement area as a coverage metric, which reflects the channel quality over a service area. To compare the various diversity schemes, we calculate the ratio between the mean gross powers of each diversity scheme and the single antenna scheme. These ratios are shown, along with the variance of received gross power, in Table 2 and Table 3.

It is observed that multipath antenna diversity and co-phase transmission diversity have the largest mean gross powers. This is because these two schemes make use of signals from all antenna units. The co-phasing transmission scheme has the best coverage. It achieves an approximate 3 dB advantage over multipath antenna diversity with the same number of antenna units.

When comparing the results from the two data sets, it is found that the ratio for different schemes varies. This is due to the changing of the transmit antenna positions and also the sampled receiver locations. In both data sets, however, the advantage trend of different antenna diversities can be observed, co-phasing transmission having the best performance and multipath antenna diversity having less performance advantage. Selective antenna diversity appears to be more sensitive to antenna position than co-phasing transmission diversity at least in the case of these limited measurements.

Key for Tables 2-5: *n* SEL = Selective diversity order *n*; *n* MPA = multipath antenna diversity order *n*; *n* CPT = co-phasing transmit diversity order *n*

Diversity Scheme	Mean power ratio w.r.t no diversity (dB)	Variance of the received power (dB)
None	0	42.4
2 SEL	0.7	42.5
3 SEL	1.9	43.5
2 MPA	2.5	44.5
3 MPA	4.7	46.2
2 CPT	4.8	47.0
3 CPT	8.2	50.0

Table 2 Gross power statistics of measurement set 1

Diversity Scheme	Mean power ratio w.r.t no diversity (dB)	Variance of received power (dB)
None	0	38.4
2 SEL	3.7	40.7
3 SEL	4.6	41.0
2 MPA	4.4	41.0
3 MPA	5.9	41.7
2 CPT	5.2	41.3
3 CPT	8.1	44.1

Table 3 Gross power statistics of measurement set 2

D. *Delay spread comparison*

In addition to gross power, RMS delay spread is an influential metric for channel quality. Even in CDMA system, which can isolate multipath components, a small delay spread means that fewer taps are required in the RAKE receiver. The statistics of RMS delay spread are shown in Table 4 and Table 5.

Compared to selective diversity, multipath antenna diversity suffers longer delay spread. This is due to the delay artificially introduced at the transmitter. Co-phasing transmit diversity has a similar delay spread to selective diversity. Because all CIRs are time aligned at the receiver, in contrast to multipath antenna diversity (in which delay spread increases with increasing number of antenna units), each additional signal in co-phasing transmit diversity does not necessarily result in extra delay spread. It is worth noting particularly that order 3 co-phasing transmit diversity achieves reduced delay spread. It is thought that this is because the order 2 scheme employs antenna units located at the extreme ends of the measurement area**.** The order 3 scheme adds an antenna near the centre of the measurement area. This central antenna results in less delay spread because the propagation paths to it are more similar in length than is the case for the antenna units at more extreme locations.

Diversity Scheme	Mean RMS delay spread (ns)	Variance of RMS delay spread (ns)
None	25.0	7.5
2 SEL	41.7	21.4
3 SEL	29.6	12.2
2 MPA	92.8	36.5
3 MPA	128.9	38.8
2 CPT	42.2	18.4
3 CPT	30.0	9.5

Table 4 RMS delay spread statistics of measurement set 1

Diversity Scheme	Mean RMS delay spread (ns)	Variance of RMS delay spread (ns)
None	25.0	7.9
2 SEL	40.4	38.2
3 SEL	28.4	35.4
2 MPA	77.6	40.4
3 MPA	109.7	49.0
2 CPT	38.4	18.3
3 CPT	28.1	10.9

Table 5 RMS delay spread statistics of measurement set 2

VI. CONCLUSIONS

A selection of downlink diversities have been simulated using single input multiple output channel measurements. In terms of the mean gross power distributed antennas perform better than single antennas. Multipath antenna diversity and co-phase transmit antenna diversity achieves better performance than selective diversity because it makes use of all signals. Multipath antenna diversity, however, incurs a penalty in terms of delay spread. Co-phase transmit diversity achieves the best diversity gain without degrading delay spread.

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REFERENCES

[1] Chu, T. S. and Gans, M. J., Fiber optic microcellular radio, Vehicular Technology, IEEE Transactions on, vol. 40, no. 3, pp. 599-606, 1991

[2] Chow, P., Karim, A., Fung, V., and Dietrich, C., Performance advantages of distributed antennas in indoor wireless communication systems, 1522-1526, 1994

[3] Arredondo, A., Cutrer, D. M., Georges, J. B., and Lau, K. Y., Techniques for improving in-building radio coverage using fiber-fed distributed antenna networks, 3, 1540-1543, 1996

[4] Yanikomeroglu, H. and Sousa, E. S., CDMA distributed antenna system for indoor wireless communications, 2, 990-994, 1993

[5] Grundmann, L. and Nichols, S., An empirical comparison of a distributed antenna microcell system versus a single antenna microcell system for indoor spread spectrum communications at 1.8 GHz, 1, 59-63, 1993

[6] Glover, I. A., Davies, N. C., Shepherd, P. R. and Pennock, S. R., An advanced MIMO channel sounder for characterisation of WLAN channels, UK National URSI Meeting, Bath, UK, 7 2004

[7] Tong F., Glover I. A., Pennock S. R. and Shepherd P. R., Co-phase Transmission Diversity for Distributed Antenna, submitted to IEEE International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting