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A dual polarisation MIMO broadcast TV system

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Abstract

Digital Terrestrial Television (DTT) in the UK has been a great success with high levels of viewer take up. But DTT is severely capacity constrained, limiting opportunities for the continued growth of the platform. However, the likely emergence of revised set top boxes to receive anticipated new services, such as High Definition (HD), allows modifications to be considered to the basic delivery system.

The experimental hardware described here demonstrates a DTT modulation system with much greater spectral efficiency and/or robustness. It employs dual polarised transmit and receive antennas to form a 2-by-2 Multiple Input, Multiple Output (MIMO) system offering up to twice the throughput of conventional DVB-T. To achieve this, two DVB-T like signals, each with independent data, are transmitted in a single 8MHz RF channel.

Results from laboratory testing are presented along with data from field trials that provide an insight into the viability of such a system.

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ABSTRACT

Digital Terrestrial Television (DTT) in the UK has been a great success with high levels of viewer take up. But DTT is severely capacity constrained, limiting opportunities for the continued growth of the platform. However, the likely emergence of revised set top boxes to receive anticipated new services, such as High Definition (HD), allows modifications to be considered to the basic delivery system.

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INTRODUCTION

A method of delivering terrestrial digital television is proposed which uses MIMO techniques to facilitate dual-polarisation transmission and reception. In the basic realisation outlined here there are two transmit and two receive antennas. Such a system can deliver up to twice the throughput of conventional DVB-T, whilst requiring no additional spectrum.

This paper is an overview of the system including the changes required to the standard DVB-T transmission specification.

The potential of the proposed solution was recognised many years ago. A digital transmission system employing dual-polarisation transmissions was suggested in a paper at IBC in 1992 by Monnier et.al.(1).

TECHNICAL OVERVIEW

A MIMO radio link employs at least two transmitters and two receivers. The basic assumption is that in a suitable environment the set of RF paths from the transmitters to the receivers can be decomposed into distinct usable channels. Figure 1 below illustrates a 2-by-2 MIMO system.

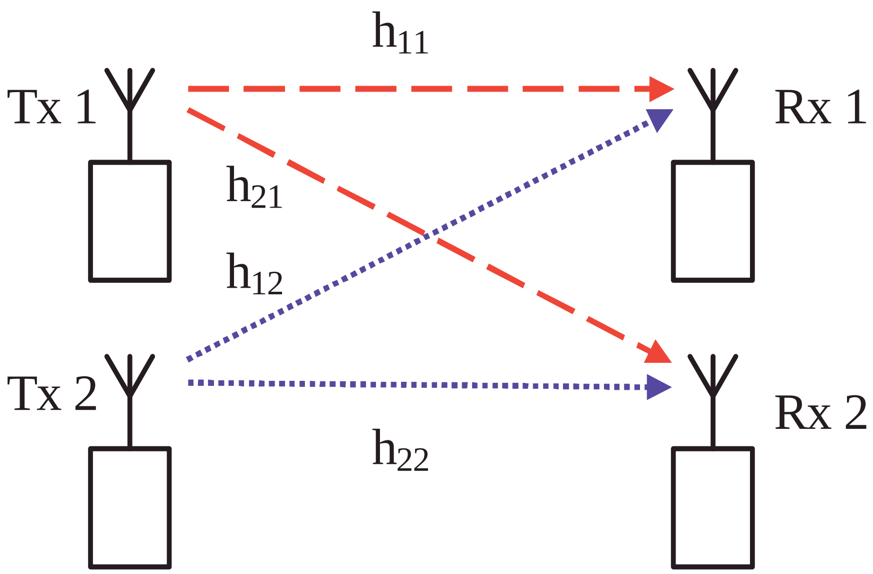

Figure 1 - A 2-by-2 MIMO system

Channel matrix

If the paths between the transmitters and receivers are not time varying, then the composite channel associated with Figure 1 can be described by a 2 x 2 matrix of complex coefficients thus:

$$\mathbf{H} = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where each coefficient h_{ij} is of the form below (with $i \equiv$ receiver index, $j \equiv$ transmitter index)

$$h_{ij} = A_{ij} \exp j\theta_{ij} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

The coefficients h_{ij} must be deduced by the receiver, at each carrier position. Once **H** is known, a number of techniques are available to 'invert' the channel, the simplest being the application of the inverse matrix to the received signal-plus-noise, and this technique was employed in the experimental hardware described below.

PROPOSED MIMO TRANSMISSION SCENARIO

Although the MIMO system may in principle be implemented in alternative forms, e.g. by using a single polarisation from two transmitter sites, the configuration described here relies on dual-polarisation transmission and reception to achieve double the throughput of the comparable mode of DVB-T (e.g. 48Mb/s at 64-QAM r=2/3 as opposed to 24Mb/s). The channel matrix is usually of the form:

$$\mathbf{H} = \mathbf{\Lambda\theta\Delta} = \begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} 1 & \delta \\ 0 & 1 \end{pmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

In this equation, the first term $\mathbf{\Lambda}$ represents an ideal cross-polar system if $\lambda_1 = \lambda_2$ and the second term is a rotation matrix accounting for antenna misalignment or polarisation rotation. The third term accounts for any small loss of orthogonality by introducing a term δ.

Although any loss of orthogonality results in some loss of performance, the effect of the rotation matrix is removed during channel equalisation without penalty. Hence it would not matter if an antenna installer rotated the whole assembly by 45 degrees about the main axis.

MODIFICATIONS TO THE STANDARD DVB-T TRANSMITTED PILOTS

It is fundamental to the MIMO system under discussion that the two-input receiver has knowledge of the 2-by-2 complex channel which characterises the transmission path. This type of information is encapsulated in a conventional DVB-T system by a complex vector of channel estimates. This vector is obtained by time and frequency interpolation of the DVB-T scattered pilots. Each element of the vector is a complex number representing the channel at a particular carrier position.

In the 2-by-2 MIMO case the channel estimate obtained by a given receiver of the pair would, however, correspond to the *sum* of the complex transmission paths to that receiver. What is actually needed is a way to estimate the paths from each transmitter individually. Now since we already have the sum, if we could find the difference then we could extract the individual terms by simple arithmetic. This is achieved by inverting the scattered[1] pilots on one of the two transmitters every other symbol. This causes the receiver to estimate the sum of the complex transmission paths during, say, even numbered symbols and the difference during the odd-numbered symbols.

Within the DVB-T standard (2), continual pilots are provided, in addition to scattered, in part to facilitate frequency lock of the receiver to the incoming signal. The modulation applied to both scattered and continual pilots is defined in (2) as +4/3 or -4/3 in accordance with a pseudorandom sequence in the carrier index.

A difficulty arises for the proposed technique during some DVB-T symbols because the scattered pilots are coincident in their carrier positions with the continual pilots (for instance, carrier index 0 is a continual pilot so, referring to Figure 2, it is coincident with a scattered pilot at time 0, 4, 8 etc.). If this happens to a symbol which is to have pilot inversion, the inversion takes priority and the continual pilot arriving at the receiver is effectively corrupted, being made up of an unknown proportion of the inverted pilot from one transmitter and the non-inverted pilot from the other. This necessitates some straightforward changes to the receiver automatic frequency control (AFC) which are outlined below.

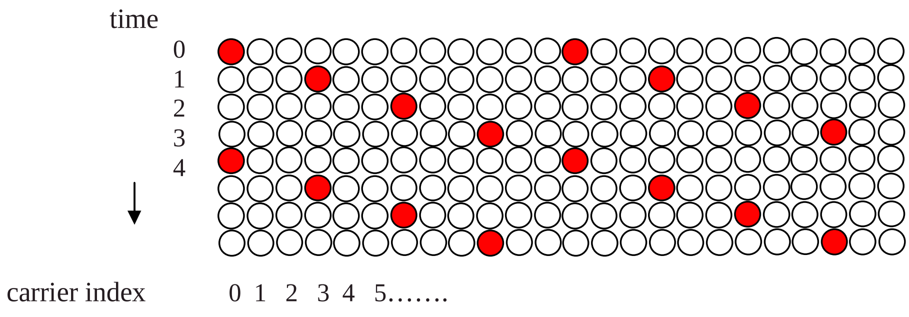

Figure 2 - Position of DVB-T scattered pilots

[1] See the DVB-T standard (2) for a full definition of scattered and continual pilots.

MODIFICATIONS TO THE RECEIVER

Receive antenna

A dual-polarised antenna can be compactly realised in a volume little larger than existing UHF products. Such a unit has been constructed for these trials. Furthermore, a practical domestic antenna could circumvent the need for a dual-core downlead by using an active 'head' unit, phantom powered from the set top box and multiplexing the two signal components onto a single coaxial cable.

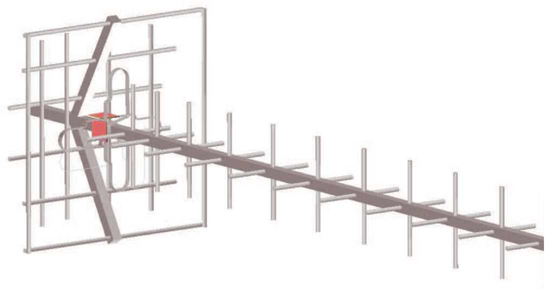

Figure 3 - Receive antenna

Channel equalisation

Clearly the receiver must be modified to carry out the necessary sum and difference operations on a pair of consecutive channel estimates in order to find the complex transmission paths associated with the vertical and horizontal transmissions. This process, and the subsequent matrix inversion to recover the transmitted data, is analogous to the zero-forcing equaliser found in a conventional DVB-T receiver.

Once each 'half' of the 2-by-2 receiver has determined its associated channel coefficients then matrix inversion can take place, followed by recovery of the transmitted data.

A distinct channel matrix exists for each carrier position, the nature of which determines the signal-to-noise ratio of each element of the recovered signal vector. It is desirable for the channel matrix to be near-orthogonal to maximise signal-to-noise ratio. Field tests reported below suggest this condition is largely satisfied.

AFC modifications

It is important now to take account of the effect of the continual pilot corruption mentioned above in respect of its impact on receiver automatic frequency control (AFC).

In a DVB-T receiver, the AFC works by determining the position of the continual pilots in a demodulated signal vector and then accumulating the phase of the pilots in such a way as to determine the sign and magnitude of any frequency error.

In the context of MIMO using scattered pilot inversion as described, the proposal is to determine which continual pilots have been corrupted by inversion of one or more of the transmitted sources and remove them from the AFC processing. Consider, for instance, the 2K mode of DVB-T which has 45 continual pilots. Let us suppose that symbol 0 in Figure 2 has no pilot inversion (on either transmitter), symbol 1 has pilot inversion (on one of the transmitters) etc. It follows that even-numbered symbols never have corrupted continual pilots, but odd numbered symbols do.

Of the 45 pilots, 11 are corrupted in symbol 1 and a different 11 in symbol 3. So, if we ignore all 22 potentially corrupted pilots during frequency acquisition (and just use the remaining 23) then the system will work as before, albeit with a slightly poorer AFC signal-to-noise ratio. Once full receiver synchronisation is obtained, and the scattered pilot sequence determined, then only 11 pilots need be ignored (on each of symbols 1 and 3), full use being made of all continual pilots on symbols 0 and 2. This gives improved bandwidth or signal-to-noise ratio within the AFC loop compared to just using 23 continual pilots all the time.

Although the examples given are for 2K-mode DVB-T, the extension to 8K is straightforward by considering the appropriate list of 177 continual pilots instead of 45.

EXPERIMENTAL HARDWARE

Transmitter

A block diagram of the transmitter hardware implementation is shown in Figure 4. At the core of the transmitter is the MIMO modulator block. To speed up the development time for this prototype, the unit was realised using a commercially available field programmable gate array (FPGA) development platform, together with custom interfacing circuitry.

The modulator consists of two carefully synchronised DVB-T modulators, working in parallel. One of these is totally compliant with DVB-T. The other is also compliant, except that it inverts every scattered pilot contained in odd numbered OFDM symbols. Each modulator can be configured for any DVB-T operating mode. To allow direct performance comparison with DVB-T, MIMO functionality can be easily disabled. The input payload data is presented to the unit as a standard DVB transport stream. The data rate is exactly twice that required for a single DVB-T modulator operating in the same mode. This input stream is split between the inputs of the two modulators alternately, packet by packet.

Each modulator output is up-converted to exactly the same frequency for transmission. Amplification and filtering follow, prior to broadcast from a pair of spatially orthogonal transmit antennas. For our field trials these transmit antennas consisted of a quarter wave ground plane antenna to provide the vertical component and crossed half wave dipoles to provide the horizontal.

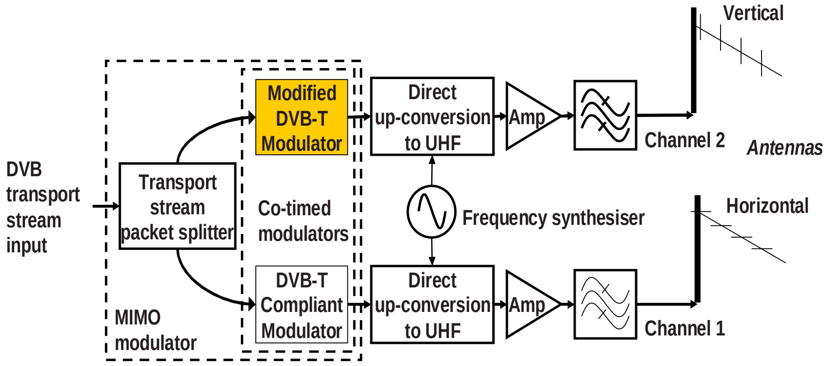

Figure 4 - Transmitter block diagram

Receiver

The receiver consists of a single antenna structure, two tuners, two analogue-to-digital converters, digital signal processing and an H.264 decoder. The receiving antenna is a modified Yagi capable of receiving both signal polarisations simultaneously. Each of the two polarisations is then fed independently into a separate ‘off-the-shelf’ digital television tuner to convert the signal from UHF to a low IF of 4.57 MHz. These signals are then fed into separate analogue-to-digital converters which sample the signal at 20.48 MHz.

The two resulting digital streams are then passed into an FPGA which implements the digital signal processing (DSP). The DSP is similar to that of a standard COFDM based

DVB-T receiver architecture as far as, but not including, the channel equaliser. Because there are two digital streams, special attention needs to be paid to the sample clock recovery, frequency recovery and the symbol start position. It is important that the two streams are aligned at the input to the channel equaliser. The channel equaliser forms an estimate of the **H** matrix for each carrier location on each symbol and from that calculates a suitable $\mathbf{H}^{-1}$ matrix which it uses to equalise the received data.

The two streams are then processed by two separate forward error correction (FEC) blocks. At the output of the two FEC blocks, the two corrected digital streams are then combined into a single transport stream in a complementary manner to the splitting process performed at the transmitter. The single transport stream is finally fed to an H.264 decoder and the service is recovered.

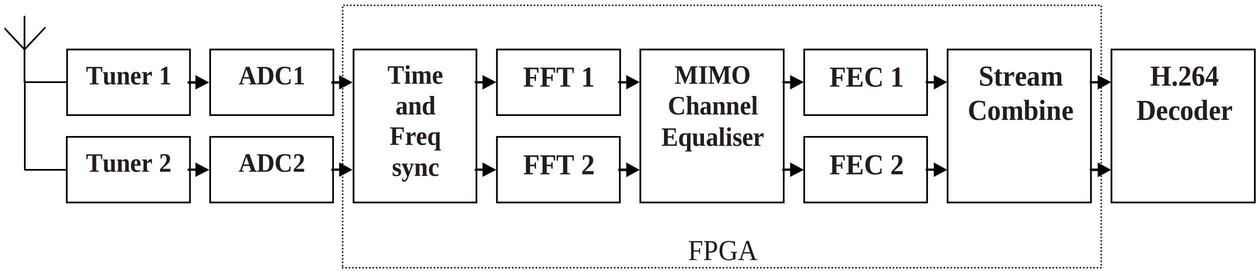

Figure 5 - Receiver block diagram

EXPERIMENTAL RESULTS

Laboratory tests

All of the laboratory measurements and field trials were performed with system parameters of 2K carriers, 1/32 guard interval, 64-QAM constellation and rate 2/3 convolutional coding for both polarisation channels, using UHF channel 51 (714MHz). The experimental hardware was subjected to a detailed performance evaluation in DVB-T mode as a benchmark prior to MIMO testing. A method to test receiver performance for a selection of static MIMO channels was devised as shown in Figure 6. This arrangement was inserted into the signal path of the receiver following down-conversion to baseband. Table 1 shows both the measured and theoretical loss of carrier-to-noise ratio (C/N) for a number of test channels. The hardware performed only marginally worse than theory predicted.

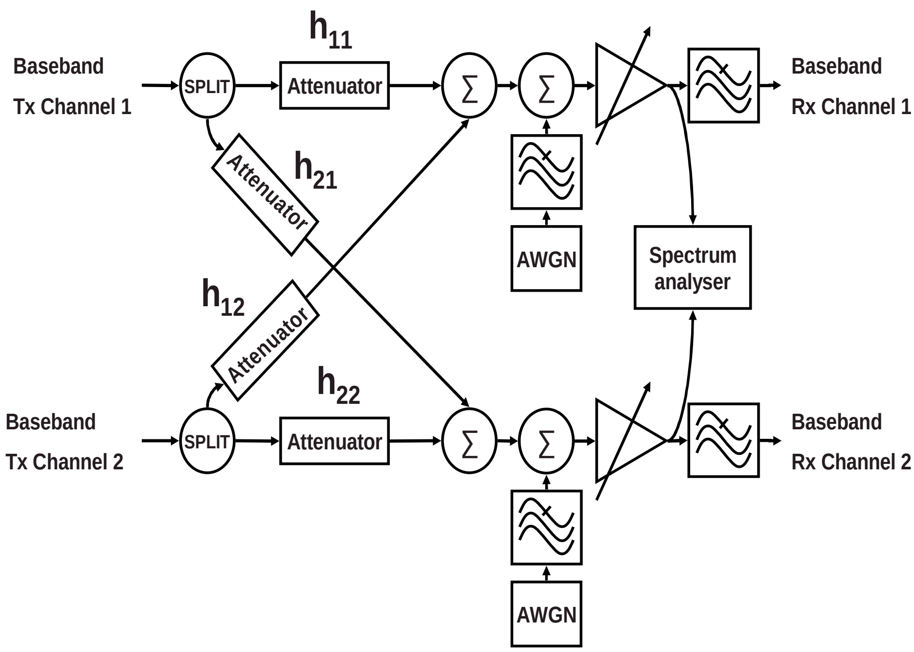

Figure 6 - Test arrangement

Test channel (**H**)	*C/N at failure channel 1* (dB)	*C/N at failure channel 2* (dB)	*C/N at failure both channels* (dB)	*Loss of Margin* (dB)	*Theoretical Loss of Margin* (dB)
$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$	18.1	17.1	18.1	0.1	0
$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$	18.8	18.1	18.8	0.8	0
$\begin{pmatrix} 1 & 0 \\ 0.891 & 0.4535 \end{pmatrix}$	20.1	26.9	26.9	9.8	9.4
$\begin{pmatrix} 1 & 0 \\ 0.707 & 0.707 \end{pmatrix}$	18.5	23.5	23.5	5.5	4.77
$\begin{pmatrix} 0.707 & -0.707 \\ 0.707 & 0.707 \end{pmatrix}$	19	19.7	19.7	1.7	0

Table 1 - Measured and theoretical loss of C/N margin for a number of test channels

Field measurements

A small scale MIMO field trial radiating an omni-directional 1W ERP of signal on both horizontal and vertical polarisations was set up. In addition, DVB-T tests using 1W ERP on a single polarisation at a time were performed for comparison against the MIMO system. A van equipped with a dual polarisation receiving antenna was used to survey the locality, measurements being taken at a height of 10m above ground level. The MIMO receiver allowed detailed channel estimate data along with signal strength and quality indicators to be recorded at each location. Standard single polarisation DVB-T system measurements were taken first as a benchmark by which to assess the MIMO system. Figure 7 shows some results from this survey; 26 locations allowed quasi-error free (QEF) reception of both DVB-T and the MIMO system. A further 6 locations allowed reception of only one polarisation of the DVB-T transmission. Although a trial of limited scope, the results are encouraging, suggesting that such a MIMO system could deliver comparable coverage to a DVB-T service. A larger scale trial is now planned.

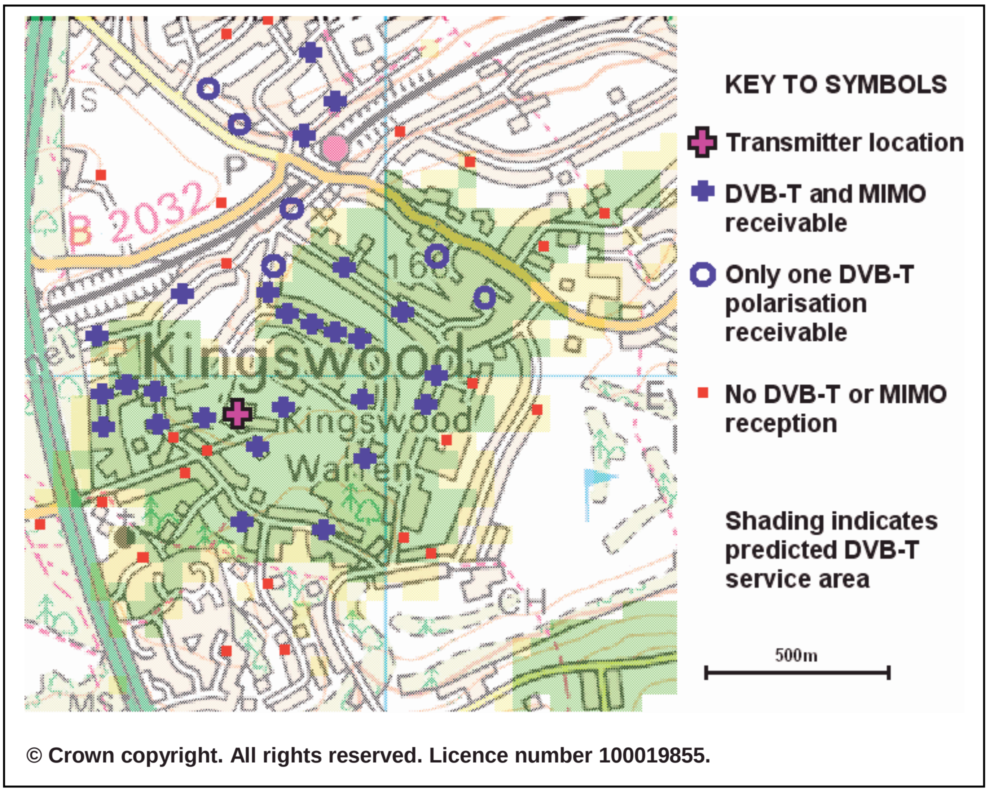

Figure 7 - Field survey results

An excess noise arises in matrix inversion if the channel matrix is not orthogonal. Figure 8 shows excess noise tabulated against locations having QEF MIMO reception. Positions 1 to 18 are close to the transmitter and mostly line of sight (LOS) to it. The predominately low excess noise values recorded indicate good channel orthogonality at the majority of these locations. Positions 14 to 18 show an unexpected loss of orthogonality, a phenomenon which needs further investigation in future trials. Positions 19 to 26 are located further from the transmitter and are mostly non-LOS, these tend to suffer from a marked loss of orthogonality. The results suggest that a more sophisticated decoder implementation (eg. Maximum Likelihood) should be considered to improve performance under such conditions.

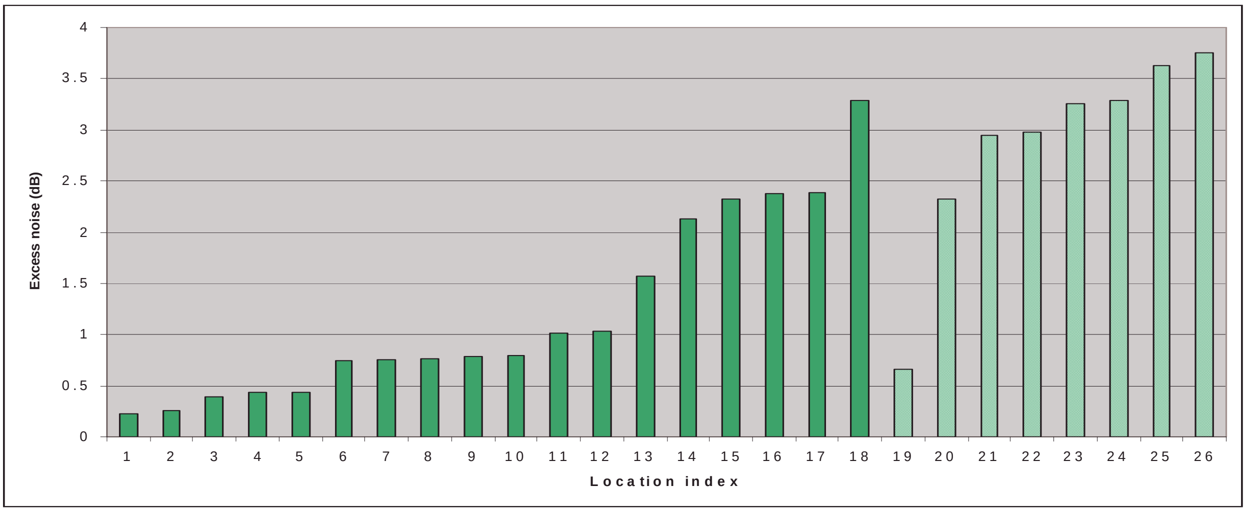

Figure 8 – Excess noise observed at various survey locations

CONCLUSIONS

A method of broadcasting high video data rates over a 2-by-2 MIMO channel based on dual polarisation transmission and reception has been presented. Experimental equipment has been built and has demonstrated practical data rates of 48Mb/s over an 8MHz channel. Initial test results have indicated a coverage area which is close to matching that for conventional DVB-T.

At the receiver a compact dual-polarised antenna has been demonstrated which, in a domestic setting, could incorporate an active ‘head’ unit to multiplex the two signal components onto a single coaxial cable.

In conclusion, the system as described could offer substantially greater capacity to digital terrestrial television, facilitating greater numbers of channels and/or high definition broadcasting.

REFERENCES

1. R. Monnier, JB Rault, and T. de Couasnon, 1992 “Digital television broadcasting with high spectral efficiency**”** Proceedings of the 1992 International Broadcasting Convention pp. 380-384.

2. ETSI EN 300 744 “Digital Video Broadcasting (DVB); Framing structure, channel coding and modulation for digital terrestrial television”

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