Doubling wireless channel capacity using co-polarised, co-located electric and magnetic dipoles

D.D. Stancil, A. Berson, J.P. Van't Hof, R. Negi, S. Sheth and P. Patel

Experiments are described demonstrating the ability to realise independent information channels using co-located, co-polarised electric and magnetic dipoles in the presence of multipath propagation. The calculated information capacity is in good agreement with a random matrix channel model.

Introduction: It is well known that the two polarisation states of electromagnetic waves can be used to transmit separate channels of information. This property has been used in microwave transmission systems and as a diversity technique for wireless fading channels [1, 2]. It has also been shown that multipath propagation can be exploited with spatial diversity techniques to increase capacity [3]. Polarisation diversity in a multipath environment has recently been re-examined by Andrews *et al.* [4] with the surprising conclusion that there can be as many as six separate polarisation channels instead of two. This results from treating all three components of the electric field and all three components of the magnetic field as capable of transmitting independent information. To illustrate this point, a pair of tri-polarised electric dipole antennas was constructed and used to verify that three independent signals could be transmitted in a multipath environment. This demonstration left one key assertion unverified: the ability to convey independent information on the electric and magnetic fields. More specifically, to use all six degrees of freedom would require two coincident tri-polarised antennas: one composed of electric dipoles and one composed of magnetic dipoles. The second key concept to be verified, therefore, is whether co-located, co-polarised electric and magnetic dipoles can be used to realise independent channels. In this Letter we describe how such antennas can be realised, and present experimental results verifying the predicted increase in capacity.

Theory: Consider the geometry shown in Fig. 1. In this geometry, a coupling path exists between the two loop antennas, but no path exists between the electric dipoles in the absence of the reflector since the radiation pattern nulls are pointed at one another. However, the presence of a reflecting surface provides a path between the two electric dipoles as well as an additional path between the magnetic dipoles. With the geometry shown, these two signals will not couple, yielding two independent channels.

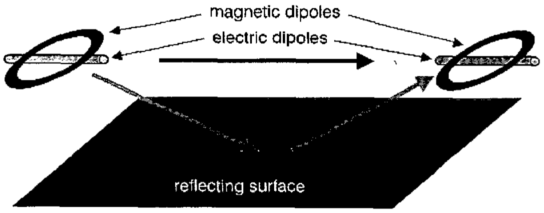

Fig. 1 *Co-located and co-polarised electric and magnetic dipoles in presence of reflecting surface*

In general, reflections can cause coupling between the signals, as well. Thus, in a rich multipath environment, the fundamental requirement for the existence of two channels is that the 2×2 matrix $\mathbf{H}$ coupling the two pairs of antennas must be full rank. Telatar [5] has presented a random matrix model for the capacity of multi-antenna systems in a fading environment. The capacity for a system with two transmit and two receive antennas is

$$C = E\left[\log_2 \det\left(\mathbf{I} + \left(\frac{P}{2}\right)\mathbf{H}\mathbf{H}^{\dagger}\right)\right] \qquad (1)$$

where $E[x]$ represents the expected value of x, P is the signal-to-noise ratio (SNR), $\mathbf{I}$ is the 2×2 identity matrix, and C is in bit/s/Hz. This equation assumes a narrowband signal so that $\mathbf{H}$ is constant over the bandwidth of the signal (flat fading), $\mathbf{H}$ is taken to have independent zero-mean Gaussian entries with independent real and imaginary parts, each having a variance of $1/2$. This is equivalent to a channel with uniform phase and Rayleigh distributed amplitude. One way to determine if the matrix $\mathbf{H}$ is full rank is to perform a singular value decomposition and test to see if there are two nonzero singular values. These singular values can be interpreted as indicating relative channel gains, so it is desirable for the values to be comparable in magnitude.

Antennas: A photograph of one of the antennas used in our experiments is shown in Fig. 2. The electric dipole is a conventional half-wave element fed from the centre. Since a pure dipole radiation pattern is desired, a Balun (balanced-to-unbalanced transition) was used to minimise currents radiating from the outer conductor of the feed line.

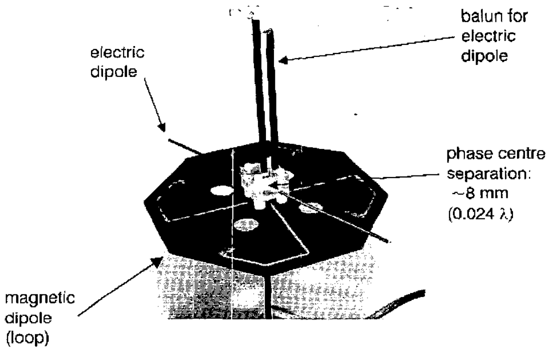

Fig. 2 *Dual dipole antenna used in experiments*

Feed lines for the two antennas enter from opposite sides of structure. Alternate segments of loop are on reverse side of printed circuit substrate

The magnetic dipole is a modified version of the Kandoian loop [6] and is fed at four symmetric points around the circumference. By feeding the loop in phase at four symmetric locations, the current is made approximately uniform even though the antenna is electrically large. Consequently, a favourable radiation resistance is obtained while maintaining a radiation pattern very close to that of a magnetic dipole. The experimental voltage standing wave ratio was measured to be <2:1 over the 902–928 MHz Instrumentation, Scientific, and Medical (ISM) band.

If independent currents are to be excited in the two antennas, the co-located antennas must be well isolated from each other. Surprisingly, even though the antennas are co-located and co-polarised, the geometry results in a high degree of isolation. To understand this, we note that the net magnetic flux through the loop from the electric dipole is zero. The experimental isolation between the two dipoles was measured to be 30 dB or more across the 902–928 MHz ISM band.

In addition to ensuring satisfactory isolation, it is also important to co-locate the dipoles to ensure that any measured capacity increase is the result of the polarisation effect rather than spatial diversity. The phase centres of both an electric dipole and a loop coincide with the geometric centres of the antennas. The centres were displaced by about 8 mm along the axis of the loop (Fig. 2). At 915 MHz, this is equivalent to a maximum relative retardation between the signals from the two antennas of about 8.6°, or 0.024 λ.

Results: Channel characterisation measurements were performed using a pair of dual dipoles mounted on tripods with the loop axes vertical. As a result, the waves from both the loops and the electric dipoles were horizontally polarised. Complex transmission coefficients between the antennas were measured over the 915 MHz ISM band with an Agilent E8358A PNA Series network analyser. Measurements were made for 21 different paths in an engineering laboratory in Roberts Hall, on the Carnegie Mellon campus. The line of sight was blocked for all locations. The orientation of the electric dipole of the receiving assembly was randomly varied from position to position. Four measurements were made in each location to obtain the four elements of $\mathbf{H}$. Each element of $\mathbf{H}$ was measured at 201 frequency points over the 902–928 MHz band. This process resulted in $21 \times 201 = 4221$ independent measurements of the channel matrix **H**. The four entries in **H** were normalised to unit variance for comparison with the random matrix theory. This normalisation corrects for the effects of different electronic and antenna gains associated with the four antennas.

Singular value decompositions of **H** were performed for the complete set of measurements (all positions and frequencies). Two nonzero singular values were consistently obtained, indicating that **H** is indeed of rank 2. The averages of the squared singular values obtained were 0.174 and 3.844. A Monte Carlo simulation with 10,000 random matrices yielded average squared singular values of 0.502 and 3.502. The cumulative distribution functions (CDF) for the measured and simulated singular values are shown in Fig. 3*a*. The higher slopes of the CDFs for the larger singular values indicate greater diversity for this channel.

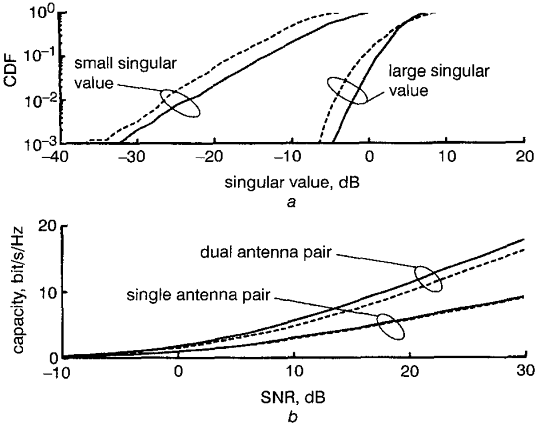

Fig. 3 *Comparison of experimental results with theory*

a Cumulative distribution functions for singular values of **H**
——— obtained from Monte Carlo simulation
- - - - - obtained from measurements
b Capacity of dual-dipole antenna compared with random matrix theory [5]
——— theoretical relations
- - - - - derived from experimental data
Data for one receive and transmit antenna obtained by averaging the elements of **H**

The capacity obtained from (1) averaged over the complete set of measurements is compared with the theoretical values in Fig. 3*b*. The agreement with theory is good, and the increase in capacity over the case of two single antennas is apparent. The experimental capacity for two channels was somewhat lower than the theoretical values however, owing to a nonzero correlation between the matrix elements. A more complex environment would reduce this correlation.

To further demonstrate the existence of two independent channels, an experimental communication system was constructed to generate and detect two FSK channels ($\Delta f = 2205$ Hz). The raw bit rate in each channel was 2.2 kbit/s and was limited by the hardware rather than any considerations of channel bandwidth. Although the sensitivity of the simple RF system was limited, with proper orientation of the antennas it was possible to repeatedly transmit simultaneous, short error-free messages over line of sight distances of 1 to 2 m in the laboratory. At a separation of 2 m and optimum orientation, an 8 h test resulted in no bit errors, corresponding to a bit error rate $< 10^{-6}$ per channel.

Conclusions: We have presented experiments confirming the assertion that co-located, co-polarised electric and magnetic dipoles can be used to realise separate information channels. Combined with the electric tripole antenna measurements reported by Andrews *et al.* [4], the ability to obtain up to six independent polarisation channels in the presence of multipath has been confirmed. Since antennas using multiple polarisations can be co-located, the composite antenna array could be smaller than similar arrays based on spatial diversity, making the use of such arrays on handsets worthy of consideration.

© IEE 2002 *6 February 2002*
Electronics Letters Online No: 20020442
DOI: 10.1049/el:20020442

D.D. Stancil, A. Berson, J.P. Van't Hof, R. Negi, S. Sheth and P. Patel (*Centre for Wireless and Broadband Networking, Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA, 15213, USA*)

E-mail: stancil@cmu.edu

References

1 JOHNSON, R.C. (Ed.): 'Antenna Engineering Handbook' (McGraw-Hill, New York, 1993, 3rd edn.)
2 LEE, W.C.Y., and YEH, YU.S.: 'Polarisation diversity system for mobile radio', *IEEE Trans. Commun.*, 1971, **COM-20**, (5), pp. 912–923
3 FOSCHINI, G.J., and GANS, M.J.: 'On the limits of wireless communications in a fading environment when using multiple antennas', *Wirel. Pers. Commun.*, 1998, **6**, (3), pp. 311–335
4 ANDREWS, M.R., MITRA, P.P., and DECARVALHO, R.: 'Tripling the capacity of wireless communications using electromagnetic polarization', *Nature*, 18 January 2001, **409**, pp. 316–318
5 TELATAR, E.: 'Capacity of multi-antenna Gaussian channels', *Eur. Trans. Telecommun.*, 1999, **10**, (6), pp. 585–595
6 KANDOIAN, A.G.: 'Three new antenna types and their applications', *Waves and Electrons*, February 1946, pp. 70W–74W

Effect of carrier frequency offset on performance of BLAST-OFDM systems

Liang Wang, Yong Ren and Xiuming Shan

The effect of carrier frequency offset on the performance of BLAST-OFDM systems is presented. Analysis shows that system performance degrades as frequency offset and channel state information estimation interval increase. Numerical simulations confirm this conclusion. A pilot channel is recommended for synchronisation and phase-shift adjustment.

Introduction: The vertical-Bell Laboratory layered space time (V-BLAST) has attracted much interest recently since it can achieve high spectral efficiency in a rich-scattering environment using multiple antennas [1]. It has been shown [2] that using antenna arrays at both the transmitter and the receiver, the spectral efficiency of V-BLAST increases almost proportionally to the number of transmitting antennas. Since it is highly spectral-efficient and can deal with non-line of sight (NLOS) problems, it has been proposed as a promising technology for use in high data rate wireless LAN and fix broadband wireless access.

One constraint of V-BLAST is that it requires the channel to be stable while decoding. To avoid inter-symbol interference (ISI), the bandwidth of V-BLAST has to be sufficiently narrow. This limits its usage in broadband wireless links. One way to break the limitation is to combine V-BLAST with orthogonal frequency division multiplexing (OFDM) [3] (see Fig. 1), since OFDM can break the whole frequency band into many parallel subbands. In each subband, the requirement of V-BLAST is satisfied. It has been proved [4] that a BLAST-OFDM system is equal to several V-BLAST subsystems transmitting in parallel.

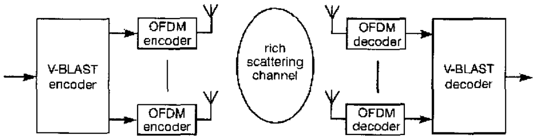

Fig. 1 *Architecture of BLAST-OFDM systems*

However, OFDM systems are sensitive to carrier frequency offset (CFO). This also influences the performance of BLAST-OFDM systems. In this Letter, we study, via analysis and simulations, how CFO affects BLAST-OFDM systems.