Performance of Diversity Combining Techniques for Antenna Arrays

Su K. Yong, J. S. Thompson and S. McLaughlin

Signals and Systems Group
Department of Electronics and Electrical Engineering
The University of Edinburgh

Abstract: This paper investigates the performance of compact antenna arrays for mobile communication systems. A number of diversity combining techniques are examined. The trade off between the system performance and computational complexity of these techniques is highlighted. Furthermore, the issues of channel modelling are described, which are a prerequisite for performance evaluation of antenna arrays.

1. Introduction

Over the past few years, mobile communications has experienced an exponential growth in the number of subscribers. This has driven the need for efficient use of bandwidth to support more users, higher data rates and better quality services. To be able to satisfy these demands, antenna arrays can be employed at both Base Station (BS) and Mobile Station (MS) for signal enhancement and interference cancellation to improve the overall system performance [1,3]. However, the application of smart antennas in MS faces a number of challenges mainly due to the physical sizes of the MS and selection of an appropriate signal-processing algorithm. This paper is organised as follows. In section 2, issues of channel models are presented to address propagation phenomena. In section 3, the implementation of various diversity combining techniques are described. Section 4 discusses the some simulation results using these combining techniques in terms of performance and complexity. Finally, in section 5 conclusions are drawn based on these results.

2. Channel Model

In the mobile radio channel, the signal from the transmitter arrives at the receiver with multiple copies due to multipath propagation. Hence, the dispersion of the channel in the temporal and angular domain is described by the time variant – directional vector channel impulse response (TV-DVCIR) given by

$$\boldsymbol{h}(t,t,\Omega) = \left[h_1(t,t,\Omega) \quad .... \quad h_M(t,t,\Omega)\right]^T . \tag{1}$$

Where $[.]^T$ denotes the transposition, M is number of receive antennas, t is the absolute time, τ is the time delay and Ω is the direction of arrival in azimuth and elevation angle. $h_m(t,t,W)$ is the TV-DCIR as "seen" at the m^{th} antenna and can be expressed as [1]

$$\begin{aligned} h_m(t,t,\Omega) &= \sum_{l=1}^{L} h_l(t,t,\Omega) \\ &= \sum_{c=1}^{C} \sum_{l\in C_m} h_l(t,t,\Omega) \\ &= \sum_{c=1}^{C} \sum_{l\in C_m} a_l d(t - t_l) d(\Omega - \Omega_l) \end{aligned} \tag{2}$$

This means that h_m comprises a large number of rays with amplitude a_l, delay t_l and angle W_l. Measurement results shown that multipath components are usually not uniformly distributed in delay and angular domain but typically arrive in cluster. Hence, (2) can be grouped into C disjoint clusters [1]. The CIR $\boldsymbol{h}(t,t)$ is obtained by integrating (1) weighted by antenna pattern over direction i.e. $\boldsymbol{h}(t,t) = \int_{\Omega} G(\Omega)\boldsymbol{h}(t,t,\Omega)d\Omega$. This can be used as the time variant coefficients of a multiple tap delay line model [4]. The effects that can be incorporated into this proposed channel model are 1) Channel effects that account for fading, delay spread, angular spread, and Doppler spread, 2) Antenna effects such as antenna pattern, antenna orientation, polarisation and mutual coupling. Useful parameters and probability distribution functions of these effects can be found in [1,2].

3. Diversity Combining Techniques

Having described the sources of fading, diversity combining techniques are now examined which use the antenna branches to develop information from several signals transmitted over independent flat Rayleigh fading paths. Among the available combining techniques, we only focus on Maximum Ratio Combining (MRC), Zero Forcing (ZF), Minimum Mean Square Error (MMSE) and Joint Detection (JD).

3.1 Maximum Ratio Combining.

In this technique, the received signals are adjusted both in magnitude and phase by the weights in the combining filter to maximise the Signal-to-Noise-Ratio (SNR) at the output of the combiner [5,6]. The weighting applied to each diversity branch is adjusted independently from other branches according to the SNR at that branch. The received signal at k^{th} branch, y_k, and the output of the MRC combiner, d, are given by

$$d = \sum_{k=1}^{M} w_k^H y_k \ , \tag{3}$$

$$y_k = h_k u + n \,, \tag{4}$$

$$w_k^H = h_k^H \,. \tag{5}$$

Where $[.]^H$ represents the Hermitian or complex conjugate. The transmitted signal, u is corrupted by the channel effects characterised by h_k, while w_k is the associated weight of the k^{th} antenna element.

3.2 Zero Forcing

In a zero-forcing combiner, the combiner coefficients W are chosen to remove undesired interference leaving only the desired signal. This technique assumes the channel characteristic is known or estimated from the pilot bits. Figure 4 shows a multi-user channel model with M antennas and N users. The output of the zero forcing combiner is given by [7]

$$\mathbf{y} = \boldsymbol{H}\, \boldsymbol{u} + \mathbf{n} \,, \tag{6}$$

$$\boldsymbol{d} = \boldsymbol{W}^H \boldsymbol{y} \,, \tag{7}$$

$$\boldsymbol{W}^H = (\boldsymbol{H}^H \boldsymbol{H})^{-1} \boldsymbol{a}^H \,. \tag{8}$$

Where $\boldsymbol{d}$ is an estimate of the users' signal vector, $\boldsymbol{y}$ is a received signal vector corrupted by the channel effects characterised by matrix $\boldsymbol{H}$ of size MxN as given in (4). $\boldsymbol{W}$ is a corresponding weight matrix of size NxM to the antenna elements and $[.]^{-1}$ is the inverse matrix.

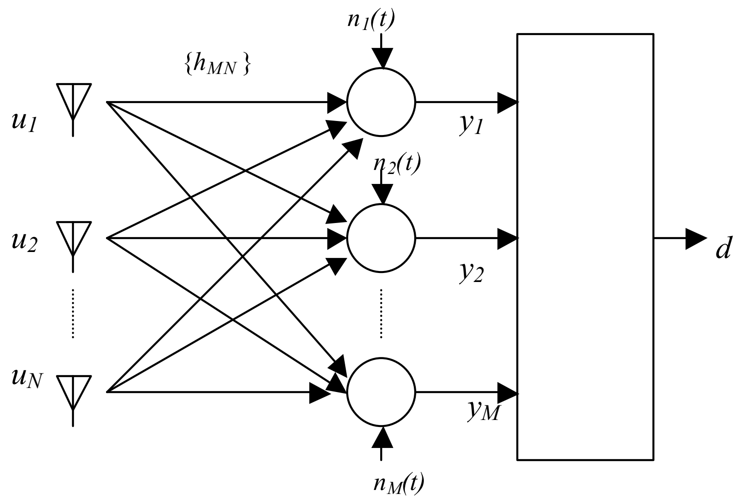

Figure 4 Multi-user scenario using smart antenna

3.3 MMSE

In this technique, the combiner implements the Wiener solution directly or some close approximation to it. Basically, the optimum combiner maximises the Signal-to-Interference plus Noise Ratio (SINR) instead of SNR in the MRC case [7,8,9]. The equation that governs the output of the MMSE combiner is given exactly by (7) but the corresponding weight matrix is modified by additional terms as given by

$$\boldsymbol{W}^H = (\boldsymbol{H}^H \boldsymbol{H} + \sigma\, \boldsymbol{I}\,)^{-1}\, \boldsymbol{H}^H\,. \tag{9}$$

Where σ and $\boldsymbol{I}$ are the noise variance and the identity matrix respectively.

3.4 Joint Detection / Maximum Likelihood Detector

This algorithm enables the detection and estimation of all the cochannel users' signals based on the channel differences between them [10]. These differences allow the receiver to make an accurate decision in extracting the desired user signal. The equation that governs the selection of the best sequence, based on maximum likelihood, is given by

$$J = \min_k \left\{ (\boldsymbol{y} - \boldsymbol{y}_k)^H\, (\boldsymbol{y} - \boldsymbol{y}_k) \right\}, \tag{10}$$

$$\boldsymbol{y}_k = \boldsymbol{H}\, \boldsymbol{u}_k\,. \tag{11}$$

Where $\boldsymbol{y}_k$ is the possible sequences of the transmitted signals and J is the kth sequence that gives the minimum difference between received signal and the possible sequences.

4. Simulation Results and Discussion

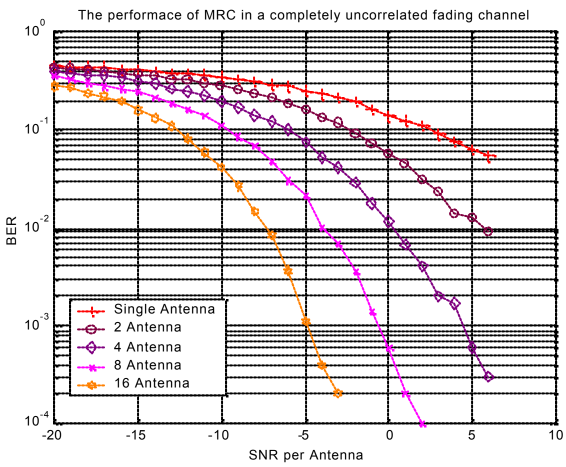

Figure 2 The performance of MRC in completely uncorrelated channel

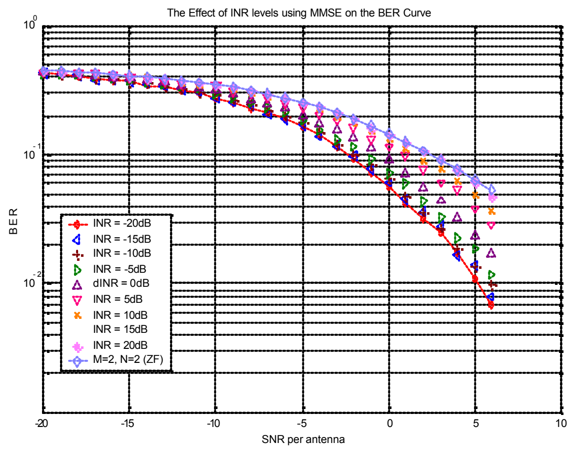

Figure 4 The effect of different INR levels using MMSE on system performance

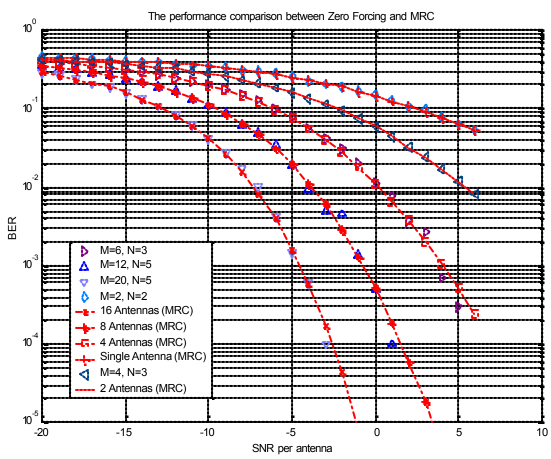

Figure 3 The performance comparison between Zero Forcing and MRC in flat Rayleigh fading

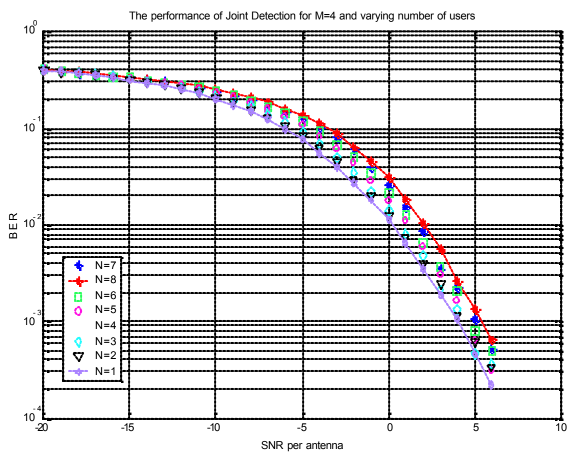

Figure 5 The performance of Joint Detection

Link level simulations have been developed for the combining methods discussed in section 3 to evaluate their performance. These simulations were based on Binary Phase Shift Keying (BPSK) modulation combined with flat Rayleigh fading channels and a receiver antenna array. In all cases, it was assumed that ideal estimates of all users' channel coefficients were available at the receiver. Different numbers of antenna elements in the receiver were also used to investigate the performance improvement over a single antenna receiver.

Figure 2 shows the performance improvement of fully uncorrelated channel over fully correlated one (which only achieves 3dB improvement per doubling the number of antennas used). This suggests the importance of uncorrelated fading signal at the antenna elements in the implementation of combining technique. In the presence of noise only, the performance of an MRC array is optimal. However, when multipath or interference is taken into consideration, the performance of MRC degrades significantly. This is because MRC does not have the capability to reject interference.

Figure 3 shows the performance comparison between MRC and ZF in a multi user scenario with M antennas and N users where $M>N$. In addition, the power of all the interferers is assumed to be equal and hence the INR associated with each interferer is the same. With these assumptions, it can be seen in figure 3 that the performance of the zero forcing for M antennas and N users is equivalent to MRC with M-N+1 antennas and no interferers as suggested by [7].

Figure 4 shows the effect of different power levels of the interferers on the MMSE methods for N=2 users and M=2 received antennas. The desired user has a power level different from the interferer and the power level of the interferer is varied. Comparison is made with the zero forcing. Clearly from figure 4, zero forcing serves as an upper bound which represents infinity INR in dB. As the INR level drops, system performance improves gradually. The ability of optimum combining to trade-off interference and noise makes it more robust in mobile environments.

Figure 5 shows the performance of JD. This detection algorithm generates all possible sequences of the users' signals. Thus, for BPSK modulation and with N users, a total of 2^N possible sequences are needed. The sequence which yields the minimum error function is selected and this sequence is an estimate of the desired signal. From figure 5 it is obvious that this method outperforms MMSE combining for any array sizes and number of users [10]. Even when the number of interferers is greater than the number of antennas, joint detection is still capable of producing acceptable performance to a certain extent depending on the number of users and the severity of the channel effects. Obviously, this technique greatly improves system capacity. Nevertheless, the computational complexity will increase exponentially with the number of users.

5. Conclusions

A number of combining techniques were compared on flat Rayleigh fading channels. We find that the JD performs well but at the expense of higher computational complexity; while the performance MMSE processing is sub-optimal but easier to implement than JD. In order to obtain more accurate results, realistic channel models as described in section 2 must be developed for further investigations.

6. Acknowledgement

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7. References

[1] L. M. Correia, "Wireless Flexible Personalised Communications," John Wiley and Son, 2001.

[2] L. Schumacher, J. P. Kermoal, F Frederiksen, K. I. Pedersen, A. Algans and P. E. Mogensen, "MIMO Channel Characterisation," *IST Report 1999-11729/AAU-WP2-D2-V1.1*, 1999. www.ist-metra.org

[3] J. C. Liberti & T. S. Rappaport, "Smart Antennas for Wireless Communications: IS-95 and Third Generation CDMA Applications," Prentice Hall, 1999.

[4] J. S. Hammerschmidt & A. A. Hutter, " Spatio-Temporal Channel Models for Mobile Station: Concept, Parameters and Canonical Implementation," *Proc. IEEE VTC2000*, Tokyo, pp. 1641-1645, May 2000.

[5] J. S. Thompson, P. M. Grant & B. Mulgrew, "Smart Antenna Arrays for CDMA systems," IEEE Personal Communications pp.16-25, October 1996.

[6] H. Sano, M. Miyake & T. Fujino, " Performance of Diversity Combining Scheme Using Simplified Weighting Factor," IEICE Trans. Communications, vol. E80-B, no. 8, PP. 1160-1165, August 1997.

[7] J. H. Winters, "The Impact of Antenna Diversity on the Capacity of Wireless Communication System," IEEE Transactions on Communications, vol. 42 no. 2/3/4, pp. 1740-1751, Feb/Mar/Apr 1994.

[8] R. G. Vaughan, "On Optimum Combining at the Mobile," IEEE Trans. on Vehicular Technology vol. 37 no. 4, pp. 181-188, November 1988.

[9] J. H. Winters, "Optimum Combining in Digital Mobile Radio with Cochannel Interference," IEEE Journal on Selected Areas in Communications, vol. 2, no. 4, July 1984.

[10] S. J. Grant & J. K. Cavers, "Performance Enhancement Through Joint Detection of Cochannel Signals Using Diversity Arrays," IEEE Trans. on Communications vol. 46 no. 8, pp. 1038-1049, August 1998.