Detecting Personnel in Wooded Areas Using MIMO Radar

R.O. Lane*, S.D. Hayward†

QinetiQ Malvern, Malvern Technology Centre, St. Andrews Road, Malvern, Worcestershire, UK, WR14 3PS.
*Tel: +44 1684 896954, Email: rlane1@QinetiQ.com
†Tel: +44 1684 894532, Email: sdhayward@QinetiQ.com

Keywords: MIMO Radar, personnel detection, forest, woods, low-frequency radar.

Abstract

This paper discusses the problem of detecting personnel in wooded areas using radar. Radio wave propagation at high frequencies suffers severe attenuation in forests which means low-frequency radar is required. However, stand-alone compact low-frequency radars have a poor angular resolution, which suggests use of a distributed radar system. A proposed solution to the problem is the use of multiple-input multiple-output (MIMO) radar. This approach exploits the angular diversity of widely spaced transmit and receive antennas to combat dynamic range and multipath problems associated with the complex scattering environment present in the forest. We assess the feasibility of the concept through simulation of radio propagation in a forest using a simple point scatterer model and a more detailed radio frequency scattering approximation using a CAD model of a forest.

1 Introduction

A problem of interest to the military and border police is the surveillance of wooded areas for perimeter security. One element of the surveillance process is the detection and tracking of hostile personnel in the area. Currently available electro-optic systems and conventional high-frequency airborne radar systems are unable to penetrate the canopy and make measurements of ground-level targets in the forest. While airborne low-frequency foliage-penetration (FOPEN) radar systems can make measurements of ground targets, they are unable to provide persistent surveillance and lack the sensitivity to detect personnel.

It is well known that radio waves in the 30 MHz – 3 GHz frequency range propagate through foliage, but are subject to scattering from tree trunks. Wooded terrain creates a complex radio frequency (RF) channel which is affected by personnel moving through the area. Such effects have been observed in indoor wireless local area network (LAN) systems where the presence of people in a room alters the communications channel capacity [21]. The theory of modelling radio propagation through forests is quite mature, and predictions from numerical models of the attenuation levels of propagating signals have shown good agreement with measurements [13][14]. In particular, results indicate that there is good propagation (*i.e.* acceptable levels of attenuation) through forests at frequencies between 100MHz and 1GHz for ranges of up to 5 km. For frequencies above 200 MHz forest anisotropies become important; these can be modelled by considering a forest as an ensemble of discrete scatterers that are represented by an equivalent continuous stratified medium characterized by an effective dyadic permittivity [14]. Given such a model it should be possible firstly to determine the effect on the propagating field of a moving target within the forest, and secondly, based on coherent measurements of the field at some other point within the forest, invert the propagation model to determine the position and velocity of the target. The latter is a problem which is addressed in sonar under the topic of matched field processing. The present authors believe that sufficient sensitivity can be achieved to enable the detection of small bodies of personnel. Greater sensitivity would make the system susceptible to nuisance alarms caused by small animals.

The requirement to use low-frequency radar means that for reasonable angular location estimation the antenna size would be impractical for a single antenna system. This suggests a distributed radar system. However, if several conventional monostatic ground-based radars were used, individual radar units would face dynamic range problems due to clutter from nearby trees and fading problems related to multipath effects [13]. Therefore a multi-static distributed-sensor approach is proposed that uses a low-frequency radar system based on multiple-input multiple-output (MIMO) technology to detect and localize personnel in wooded areas, by making coherent measurements of changes in the complex RF channel.

The concept of MIMO radar is relatively new, therefore we first give a brief review of MIMO communications in Section 2 followed by a review of the MIMO radar literature in Section 3. Section 4 uses a simple point-scatterer simulation to demonstrate an algorithm for the detection and localization of moving targets. Section 5 demonstrates a more detailed simulation using CAD models of individual trees within a randomly constructed forest and the QinetiQ Spectre® ray-tracing code to compute the scattered field. Conclusions are drawn in Section 6.

2 MIMO communications overview

The concept of a MIMO system for use in communications was first proposed around 10 years ago (see [11], for example), when it was shown that under certain fading conditions the capacity of a communications channel could be increased significantly through the use of multiple transmit

(Tx) and receive (Rx) antennas, with different waveforms transmitted on each antenna. Compared to a single-input-single-output (SISO) system where multipath signals interfere with the direct path signal and cause fading, a MIMO system is able to 'form beams' to resolve the multipath. If there are three distinct propagation paths, for example, then the same bandwidth can be reused for each path to increase the capacity of the link by a factor of three. In the communications literature the term MIMO is used to describe a system where the outputs of multiple receive antennas are combined coherently, as opposed to a diversity arrangement, where typically only the output from the antenna providing the highest SNR is processed. MIMO communications technology is most advanced for indoor wireless LANs, where an IEEE standard, 802.11n, is about to be ratified for use at 2.5 and 5 GHz. Wireless routers are available commercially conforming to the draft 802.11n standard. These devices typically incorporate 2 transmitting and 2 receiving antennas. In experiments with indoor wireless LANs of this nature it has been observed that the movement of people within buildings causes the MIMO channel to be perturbed [19]. This effect offers a way of detecting people remotely both indoors and outdoors, if the same principle applies in outdoor MIMO systems.

3 MIMO radar overview

Over the last few years researchers have begun to apply MIMO concepts originally developed for communications to radar systems. A common theme behind MIMO radar is the use of statistically independent looks at the scene of interest. However, there are a wide variety of methods for achieving this independence, such as spatial [7], frequency [17], or temporal diversity [3]. The term MIMO radar has been used by Fishler *et al.*, [7][8][9], to refer to a particular form of multiple channel radar processing, in which the outputs of particular Tx-Rx antenna pairs are combined incoherently. Fishler's approach exploits angular diversity by making measurements of a target at a set of different bistatic angles, and so is robust to the target cross section fluctuations that are a feature of monostatic measurements. In [7] Fishler identifies scenarios in which direction finding accuracy is improved through the incoherent combination of measurements made across a receive array due to different transmitting antennas. In [8] and [9] a related MIMO radar system for improving target detection is compared to a conventional phased array radar. Fishler describes his MIMO approach as statistical MIMO processing. Other authors have described MIMO radar systems in which the returns are combined coherently at the receive array [2][3][5][6][10]. In these works the key feature that makes a MIMO radar system distinct from a phased array radar system, is that unlike a phased array radar where a common waveform is transmitted from all transmitting elements, in a MIMO system different waveforms are transmitted. This allows the received signals to be post-processed in way which effectively modifies the transmit beam-pattern. Thus adaptive beamforming can be performed simultaneously on transmit and receive. The work of Donnet and Longstaff [6] is particularly interesting because they describe how a bistatic MIMO radar with transmit and receive antennas makes measurements of independent Tx-Rx paths, and can be used to synthesis a monostatic array with more antennas than are physically present. In general, most work to date on MIMO radar has been on theoretical developments but some measurements using a MIMO radar system situated in an anechoic chamber have been reported in the 1-2 GHz and 8-12 GHz bands [16] .

4 Detection and localization

The MIMO radar system considered for our personnel detection application is essentially a coherent change detection system based on spatial diversity. The transmitter and receiver consist of an array of M and N antennas, respectively. The difference between this system and conventional phased array radar is that the antenna elements are spaced more than one wavelength apart and each element in the transmitter uses separate orthogonal waveforms. Therefore a beam is not formed as occurs in phased array radar. The signal from each receiver is correlated with each transmitted waveform to obtain the response for MxN channels. Frequency dependent behaviour of scatterers could potentially distort the waveforms so they are no longer truly orthogonal. In this case, an alternative to orthogonal waveforms is to time multiplex pulses into MxN time slots at the expense of a lower effective pulse repetition frequency. At frequent intervals in the order of one second, the current state of the forest radio propagation environment is recorded for each Tx-Rx antenna pair. New measurements are then made and coherently subtracted from the previous measurement. If any target in the observed area has moved between measurements then this manifests itself as a change in the recorded data. The matched-filter difference signal for each antenna pair is mapped onto a plan-view representation of the scene, with the maximum of each filter output indicating the location of the target. For a single Tx-Rx antenna pair there is an ambiguity in the target location – the target is known to lie on an ellipse whose foci are located at the Tx and Rx locations. However, by incoherently combining the responses of all antennas it is possible to determine an unambiguous target location. We call this technique incoherent back-propagation. Output of the back-propagation method is illustrated in Figure 1 for four Tx antennas located near (0, 0) and four Rx antennas near (500, 500). The result is the summation of 16 ellipses with slightly different locations and orientation but which overlap at the target position (400, 240).

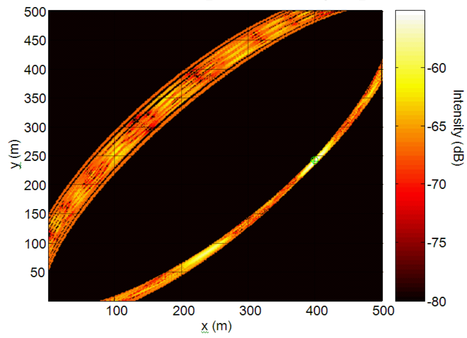

Figure 1: Summation of 16 Tx-Rx ellipses

A simulation to demonstrate operation of the proposed MIMO radar system in relation to a forest is now described. The system consists of four antennas at both the transmitter and receiver. Forest trees are modelled as 100 point scatterers in a 3 km square area each with a bistatic radar cross-section (RCS) of -10 dBsm. Free space propagation between the scatterers is assumed. A diagram showing the configuration of the antennas and tree locations is shown in Figure 2.

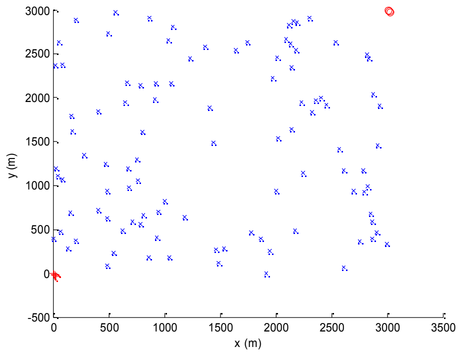

Figure 2: Tx/Rx antenna configuration in a simulated forest. Key: (+) Tx antenna (o) Rx antenna (x) Tree

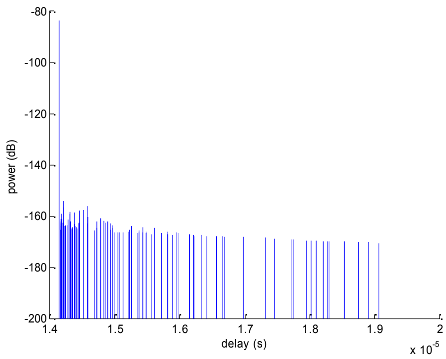

Figure 3: Single Tx-Rx antenna pair power-delay profile

Ray-tracing is used to compute the impulse response for the multipath channel corresponding to each Tx-Rx antenna pair. The power-delay profile of the forest scene for a single Tx-Rx antenna pair is shown in Figure 3. The first signal received is the direct-path signal, which is also the strongest. Subsequently received signals are due to multiple scattering between different combinations of trees and have a much lower power. Each Tx-Rx pair has a characteristic profile similar to that shown in Figure 3 but with variations due to the slightly different paths the radio wave takes between each Tx and Rx antenna location. The resolution of the channel impulse responses is determined by the bandwidth. In the examples about to be presented this has been taken to be 100 MHz corresponding to a path length difference of 3 m.

A target representing an intruder was placed at position (1500, 2400) in the scene and the before and after power delay profiles recorded. The output of the coherent change detection followed by incoherent back-propagation is shown in Figure 4 with a zoomed-in view of the target area in Figure 5. The true location of the target is marked with a "+" and the maximum of the filter output is marked with a "o". The difference between the true and estimated positions is only a few metres. This demonstrates that basic operation of the algorithm provides a useful estimate for target location.

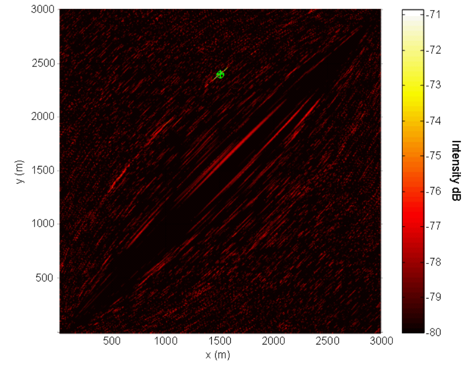

Figure 4: Image of scene using incoherent back-propagation

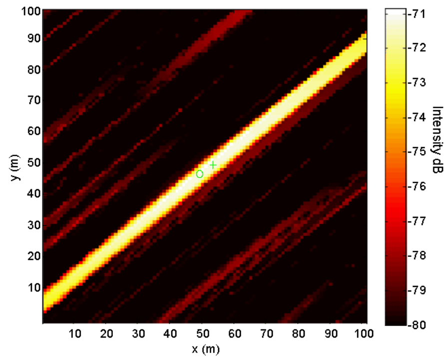

Figure 5: Scene image zoomed-in to target location

5 Three-dimensional scattering simulations

The model and simulation considered in Section 4 consisted of point scatterers only. A more advanced simulation based on a 3D computer aided design (CAD) model of a forest is now presented. An example forest CAD model is shown in Figure 6. Each tree is represented by a cylinder, with the circular cross-section approximated by a 12-sided polygon. At the low frequencies being considered here the radio wavelength is larger than small branches and leaves, so their effect on propagation is neglected. The forest is generated by first creating randomly-distributed tree locations with a density of 0.01 tree/m^2. Each tree is given a Gaussian distributed height (mean 5m, standard deviation 1m), and tilt (mean 0^o, standard deviation 5^o) and a uniformly distributed azimuthal orientation (0^o-360^o) and width (5cm-15cm). The complex dielectric constant of an object defines Fresnel reflection coefficients, which determine the amount of power reflected at the air-object boundary [12]. A typical dielectric constant for tree trunks at P-band is given by [4] as 20.7+10.2i, which was used in simulations. A human intruder is represented by a cylinder 1.8 m high and 30 cm wide with a dielectric constant $\varepsilon'_r = 50$ and conductivity $\sigma=10^{-3}$ S/m. The circular cross-section was approximated by an 1800-sided polygon. A more detailed body representation is unnecessary at this frequency – in fact this cylindrical human body model has been used at frequencies up to 2.45 GHz [20].

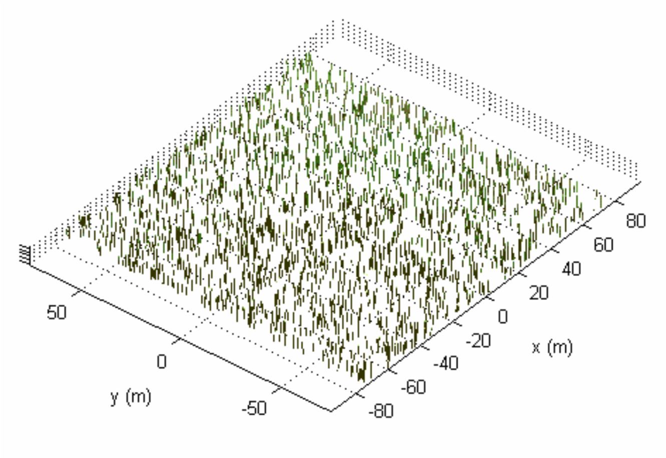

Figure 6: CAD model of a wooded area

Radio wave propagation simulations were carried out using the Spectre radar signature prediction tool [15] (formerly known as RESPECT [18]). The tool has been developed by QinetiQ to model the RCS of large, complex targets using CAD models. Reflections are modelled using a combination of physical optics for the last reflection and geometrical optics for any preceding bounces. Edge diffraction effects are represented by an equivalent-current extension of the physical theory of diffraction. The advantages of Spectre over the point-scatterer model are that it captures interactions between the propagating wave and the ground, includes the effects of obscuration, and does not necessarily assume the bistatic cross section of the trees is independent of angle. It also includes additional multipath effects between the target and trees not captured by the point-scatterer model. However, it does not include creeping or surface waves, corner diffraction, or resonance effects. Target-ground multipath effects for a complex target are analysed in detail using Spectre in [1].

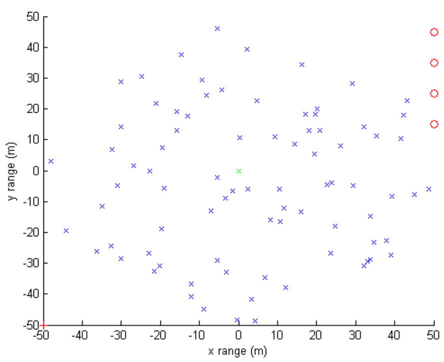

Figure 7: Tx/Rx antenna configuration in a simulated forest
Key: (+) Tx antenna (o) Rx antenna (x) Tree (x) Target

A 100 m x 100 m scene containing 81 trees and a human target placed at the centre of the scene was simulated in Spectre with a single transmitter at (-50,50) and four receive antennas. The configuration of the scene is shown in Figure 7. Horizontal polarisation was used on transmit and receive and up to two ray bounces were simulated. The simulation was run two times, one with and one without the human present, to obtain the coherent change detection signal. The combined incoherent back-propagation for all Tx-Rx antenna pairs is shown in Figure 8. The maximum of the combined response is very close to the true target position as was the case in the point scatterer simulation.

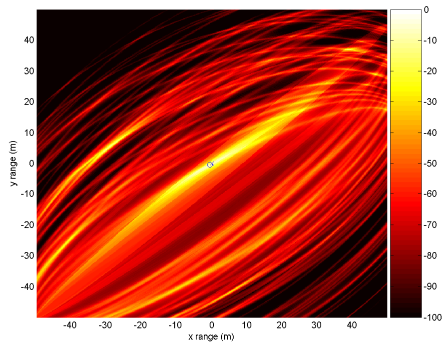

Figure 8: Image corresponding to the scene in Figure 7

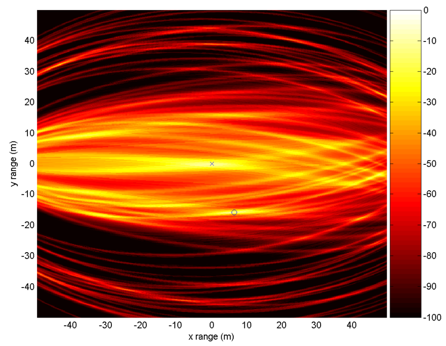

Figure 9: Image corresponding to the scene in Figure 7 with different antenna positions

A second simulation of the same scene using Spectre was carried out with different Tx and Rx antenna positions. With reference to Figure 7 the transmitter was placed at (-50, 0) and the receivers placed 10 m apart in a line and centered on (50, 0). The same processing as before was applied to the data and the combined response of the antennas is shown in Figure 9. It can be seen that while there is a significant local maximum near the correct target position, the global maximum appears at a different location. This is because different multipath events for each Tx-Rx antenna pair have by chance coincided at the same position. The chance of this happening is higher in scenarios like this one where the target is near the Tx-Rx line of sight, *i.e.* at a near-zero bistatic range, where bistatic range is defined as half the difference between the total Tx-Rx propagation path length via targets and the direct distance between Tx and Rx positions. This is because multipath events via the target always give rise to a response at a greater bistatic range than that of the target alone. When the responses of all antennas are combined there is more scope for separate multipath signals to coincide within the area of interest than if the target is at the edge of the scene. However, it should be noted that the difference in power for the target and multipath peaks is only 2 dB.

Tracking algorithms should be able to track the human position with several frames of data because as the human moves with respect to the trees any multipath peak will fade in and out in random positions, while the human position is more consistent along the track.

7 Conclusions

An algorithm for the detection of personnel in forests using MIMO radar has been introduced. Simulations based on a simple point-scatterer model for trees and targets showed that it is possible to estimate a target's location to within a few meters of its true location. A more advanced 3D CAD model and simulation was used to validate operation of the algorithm. The simulation did verify the algorithm but revealed the potential for multipath interference. Observation of multipath peaks for near-zero target bistatic ranges suggests that antennas should be as widely spaced as possible. This ensures that whatever the target position there is at least one Tx-Rx antenna pair with a large bistatic range-to-target, which pushes multipath interference out of the region of interest.

Acknowledgements

This work was carried out as part of the Electronic Systems Domain of the UK Ministry of Defence Research Programme. The authors thank Dr. Daniel Andre of QinetiQ Malvern for his help and advice on Spectre simulations. Spectre® is a registered trademark of QinetiQ Ltd.

References

[1] D. Andre, "Radar target-ground interaction", *IET International Conference on Radar Systems (Radar 2007)*, Edinburgh, UK, 15-18 October 2007.

[2] I. Bekkerman, J. Tabrikian, "Target Detection and Localization Using MIMO Radars and Sonars", *IEEE Trans. Sig. Proc.*, Vol. 54, No. 10, October 2006, pp 3873 - 3883

[3] D.W. Bliss, K. W. Forsythe, "Multiple-input multiple-output (MIMO) radar and imaging: degrees of freedom and resolution", *37th Asilomar Conference on Signals, Systems and Computers*, November 2003.

[4] N. S. Chauhan, R. H. Lang, K. J. Ranson, "Radar modeling of a boreal forest", *IEEE transactions on geoscience and remote sensing*, Vol. 29, No. 4, pp. 627-638, July, 1991.

[5] B. J. Donnet, I. D. Longstaff, "MIMO radar, techniques and opportunities", *Proc. of the 3rd European Radar Conference, Manchester, England*, September 2006.

[6] B. J. Donnet, I. D. Longstaff, "Combining MIMO Radar with OFDM Communications", *Proc. of the 3rd European Radar Conference*, Manchester, England, September 2006.

[7] E. Fishler, A. Haimovich, R. Blum, L. Cimini, D. Chizhik, R. Valenzuela, "MIMO radar: An idea whose time has come", *Proc. of the IEEE Radar Conference*, pp. 71-78, April 2004.

[8] E. Fishler, A. Haimovich, R. Blum, L. Cimini, D. Chizhik, R. Valenzuela, "Performance of MIMO Radar Systems: Advantages of Angular Diversity", *38th Asilomar Conf. Signals, Systems, Computers*, vol. 1, pp. 305–309, November 2004.

[9] E. Fishler, A. Haimovich, R. Blum, L. Cimini, D. Chizhik, R. Valenzuela, "Spatial Diversity in Radars—Models and Detection Performance", *IEEE Trans. Sig. Proc.*, Vol. 54, No. 3, pp 823 – 838, March 2006.

[10] K. W. Forsythe and D. W. Bliss, "Waveform Correlation and Optimization Issues for MIMO Radar", *39th Asilomar Conf. Signals, Systems, Computers*, vol. 1, pp. 1306 - 1310, October 2005.

[11] G. J. Foschini and R. A. Valenzuela, "Initial estimation of communication efficiency of indoor wireless channel", *Wireless Networks*, vol. 3, pp. 141–154, 1997.

[12] A. Ishimaru, *Electromagnetic Wave Propagation, Radiation and Scattering*, Prentice Hall, Englewood Cliffs, New Jersey, 1991.

[13] G. G. Joshi, C. B. Dietrich Jr., C. R. Anderson, W. G. Newhall, W. A. Davis, J. Isaacs, G. Barnet, "Near-ground channel measurements over line-of-sight and forested paths", *IEE Proc.-Microw. Antennas Propag.* 152(6), pp. 589-596, December 2005.

[14] L.-W. Li, C.-K. Lee, T.-S. Yeo, M.-S. Leong, "Wave mode and path characteristics in a four-layered anisotropic forest environment", *IEEE Transactions on Antennas and Propagation*, 52(9), pp. 2445-2455, September 2004.

[15] QinetiQ, "Spectre: radar cross section prediction tool", *QinetiQ software description*, 2001. Available at http://www.QinetiQ.com/home/defence/maritime/ marine_structures.html (Accessed 18th June 2007).

[16] F. C. Robey, S. Coutts, D. Weikle, J. C. McHarg, K. Cuomo, "MIMO radar theory and experimental results", *38th Asilomar Conference on Signals, Systems and Computers*, November 2004.

[17] P. F. Sammartino, C. J. Baker, H. D. Griffiths, "A comparison of algorithms for MIMO and netted radar systems", *International Waveform Diversity and Design Conference*, January 2006.

[18] S. D. Turner, "RESPECT: Rapid Electromagnetic Scattering Predictor for Extremely Complex Targets", *IEE Proceedings*, Vol. 137, Pt. F, No. 4, pp.214-220, August 1990.

[19] W. G. Scanlon and K. Ziri-Castro, "Modelling of MIMO channels for the populated indoor environment", *IEE Seminar on MIMO Communications Systems from Concept to Implementations*, pp. 1 – 6, December 2001.

[20] F. Villanese, W. G. Scanlon, N. E. Evans, E. Gambi, "Hybrid image/ray-shooting UHF radio propagation predictor for populated indoor environments", *Electronics Letters*, 35(21), pp.1804-1805, October 1999.

[21] K. I. Ziri-Castro, W. G. Scanlon, N. E. Evans, "Prediction of variation in MIMO channel capacity for the populated indoor environment using a radar cross-section-based pedestrian model", *IEEE Transactions on Wireless Communications*, 4(3), pp. 1186-1194, May 2005.