SISO and SIMO Indoor Wireless Transmission Systems Simulations using the FDTD Method

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Abstract: - A SISO (Single Input Single Output) and a SIMO (Single Input Multiple Output) wireless transmission system operating in a Rayleigh distributed environment at the 434 MHz ISM band are investigated. The two systems are simulated using the Finite Difference Time Domain (FDTD) method, which enables the simultaneous characterization of the propagation channel and the immersed wire dipoles antennas. A novel procedure to evaluate the method's accuracy for this type of systems is introduced, through the convergence of the SISO system's Transfer Function (H). The results show that a numerical phase error of 1^o per wavelength is acceptable for accurate estimation of H for a propagation distance of about 12 wavelengths. Moreover, the instantaneous correlation coefficient and the received power ratio versus dipoles' separation distance are estimated and presented for the SIMO system.

Key-Words: - FDTD, numerical dispersion error, transfer function, dipoles, multipath, correlation coefficient.

1 Introduction

The 434 MHz ISM (Industrial Scientific Medical) band emerges as a good selection for operation of many applications, due to its advantages of low power consumption and large fractional coverage compared to the 2.45 GHz ISM band [1, 2]. Although applications such as wireless sensor networks, data transfer to medical record, data acquisition and smart appliances have already been proposed for the 434 MHz [3, 4], little work has been done in characterizing indoor wireless transmission systems at this band.

The most fundamental parameter to characterize wireless transmission systems is the Transfer Function H or its equivalent in the time domain, Impulse Response (IR). The estimation of H can be accomplished either by measurements or by computational methods. The major disadvantage of measurements is that they are time and cost consuming. Computational methods, on the other hand, demand large computer resources in order to obtain accurate results.

The most used computational methods are ray-tracing techniques [5], FDTD [6] and hybrid ones which combine both of them [7]. Ray tracing as an asymptotic method implies large errors for indoor environments due to the existence of objects with dimensions less than the wavelength. This fact is particularly true for the 434 MHz band, where the free space wavelength is in the order of 70 cm. On the other hand, FDTD may be very accurate in simulating environments with plenty of scatterers, provided that a sufficiently fine grid discretization is employed.

The two significant parameters for evaluation of the SIMO wireless transmission systems are the correlation coefficient (ρ) and the power ratio of the receiving antennas [8]. The evaluation of SIMO systems is accomplished almost exclusively by modeling separately the propagation environment and the transmitting and receiving antennas' configurations [9]. In this direction many researchers [10] have estimated the required parameters for the propagation environment models through measurements and statistical analysis. On the contrary, FDTD method provides the estimation of the SIMO evaluation parameters through the simultaneous characterization of the propagation channel and the antennas avoiding the time and cost consuming measurement procedure in real propagation environments [11] or in reverberation chambers [12].

In this paper the theoretical aspects of modeling wireless transmission systems using FDTD are presented. A SISO wireless transmission system comprised of two dipoles in a Rayleigh distributed environment is initially simulated. In order to validate the FDTD method's accuracy, a novel procedure through the convergence of H is proposed, which is a more informative indicator than the numerical dispersion error. Although the simulation results refer to the 434 MHz band, this procedure is applicable for any frequency band. Subsequently a SIMO system comprised of one transmitting and two receiving dipoles in a Rayleigh environment is simulated. The instantaneous cc and the power ratio of the receiving dipoles for five different separations distances are estimated via the H of the system.

2 FDTD modeling of wireless transmission systems

Wireless transmission systems can be characterized as static at movement's absence, and as dynamic at movement's presence. Static wireless transmission systems are linear and time-invariant (LTI) and as a consequence are modeled in the time domain by the following transmission equation:

$$y(t,\vec{r}) = \int_{-\infty}^{+\infty} h(\tau,\vec{r}) \cdot x(t-\tau)\, d\tau \tag{1}$$

where $x(t)$ is the excitation voltage, $y(t,\vec{r})$ is the voltage at the port of a receiving antenna inside the simulation environment, $h(\tau,\vec{r})$ is the Impulse Response (IR) of the wireless transmission system, τ is the delay domain and $\vec{r}$ is the receiver - transmitter separation distance.

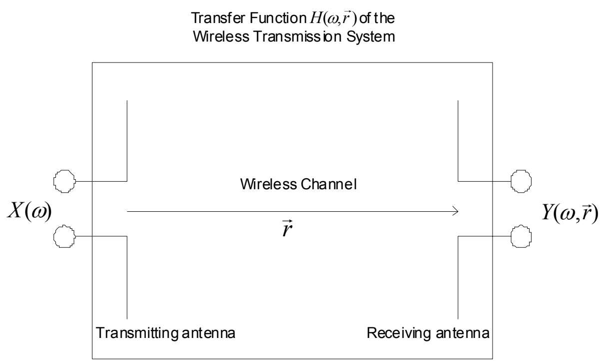

Fig. 1. Transfer function of a LTI Wireless Transmission System.

Since the system is LTI, its Transfer Function (Fig.1) is derived from equation (1) by simply applying the frequency domain duals of the voltages and is a function of only frequency and separation distance [13, 14]:

$$Y(\omega,\vec{r}) = H(\omega,\vec{r}) \cdot X(\omega) \tag{2}$$

Equation (2) provides a way to estimate the Transfer Function $H(\omega,\vec{r})$ of the wireless transmission system for any separation distance $\vec{r}$ inside the simulation environment, when the excitation and the received voltages are known.

In order to estimate the received signals accurately, the inherent in FDTD numerical dispersion error given by equation (3) must be controlled [15].

$$\varphi_{err} = 360^{o}\left(\frac{\tilde{k}}{k_{real}} - 1\right) \tag{3}$$

where k_{real} is the exact wavenumber and $\tilde{k} = \sqrt{\tilde{k}_x{}^2 + \tilde{k}_y{}^2 + \tilde{k}_z{}^2}$ is the numerical wavenumber given by the dispersion relation equation [16]:

$$\left[\frac{1}{c\cdot\Delta t}\cdot\sin\left(\frac{\omega\Delta t}{2}\right)\right]^2 = \left[\frac{1}{\Delta x}\cdot\sin\left(\frac{\tilde{k}_x\cdot\Delta x}{2}\right)\right]^2 + \left[\frac{1}{\Delta y}\cdot\sin\left(\frac{\tilde{k}_y\cdot\Delta y}{2}\right)\right]^2 + \left[\frac{1}{\Delta z}\cdot\sin\left(\frac{\tilde{k}_z\cdot\Delta z}{2}\right)\right]^2 \tag{4}$$

where Δx, Δy and Δz are the three cell dimensions, Δt is the timestep and c is the speed of light. For the case of cubic cells the error is minimum for propagation along the cell diagonal and maximum along the cell axes.

A solid way to evaluate the accuracy of FDTD when used for wireless transmission systems simulations is through the convergence of H. More precisely the convergence can be investigated through the ρ between the time domain duals of the frequency components of the simulated H for different discretization scenarios. This approach that will be shown in Section 3.1, provides a better view of the discretization requirements, since it measures the strength of the linear relationship between the frequency components of the simulated H for different discretization scenarios. This information cannot be obtained through the ρ of the time domain IRs, which cannot distinguish the different spectral components of H.

In order to characterize the worst operating case of a SIMO wireless transmission system the environment must be considered as static, since in this case the envelope of the signals is constant and not a random variable [17]. For these cases the instantaneous ρ between the received signals denotes the strength of their linear relationship and is purely deterministic. As a consequence FDTD method is a very effective way to characterize the worst case of a SIMO system, given that it provides static environments simulations.

3 Simulation Results

3.1 A SISO system simulation

The 3D environment with dimensions 8x0.96x0.96m^3 (Fig. 2) was simulated using the commercial FDTD tool Fidelity, which is based on the Yee's algorithm [18]. Two z-oriented dipoles were immersed with their terminal ports placed at (0.3m, 0.48m, 0.48m) and (7.8m, 0.48m, 0.48m) respectively. In order to create multipath conditions the receiving dipole was surrounded by two metallic scatterers ($\sigma = 5 \cdot 10^7$ S/m). The source used for the simulations was a sine modulated Gaussian pulse at 434 MHz with 160 MHz null-to-null bandwidth (354-514 MHz), which implies an electrical distance of 12.85 λ_{514} between the dipoles according to the maximum frequency component of the excitation.

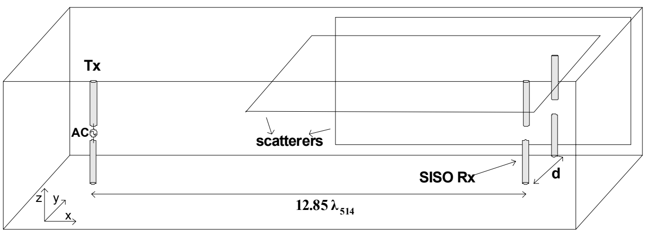

Fig. 2. The simulated SISO and SIMO systems.

The dipoles resonate at 434 MHz with a bandwidth of 64 MHz (Fig. 3). In order to get accurate results the dipoles were discretized with 54 cells ($\lambda_{514}/100$) in the Z direction and 4 cells ($\lambda_{514}/600$) in the X-Y plane.

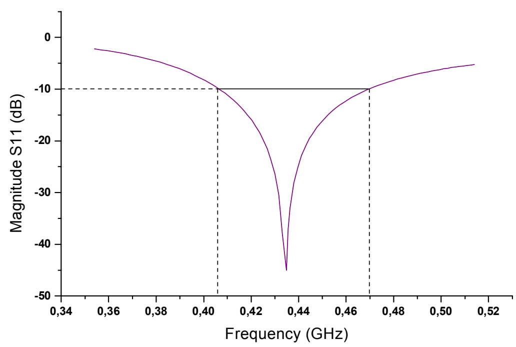

Fig. 3. S_{11} parameter of the transmitting and receiving dipoles.

The environment of Fig. 2 was simulated for three different discretization scenarios with cell dimension $\lambda_{514}/10$, $\lambda_{514}/20$ and $\lambda_{514}/30$. Table 1 demonstrates the calculated through equations (3) and (4) dispersion error implied by the FDTD method for the three different cases. The voltages at the port of the receiving dipole for these scenarios are illustrated in Fig. 4. Fig. 5 shows the magnitude and phase of the calculated via equation (2) H of the system for the three cases making apparent the resemblance between the $\lambda_{514}/20$ and $\lambda_{514}/30$ cases.

Phase error per wavelength (deg)			
Cell dimensions	$\lambda_{514}/10$	$\lambda_{514}/20$	$\lambda_{514}/30$
Minimum	2	0.5	0.2
Maximum	7	1.6	0.7
Mean	4.5	1.05	0.45

Table 1. Numerical dispersion error for three different discretization cases.

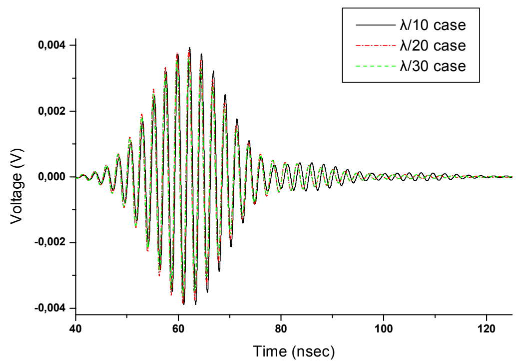

Fig. 4. Received voltage for the three discretization cases.

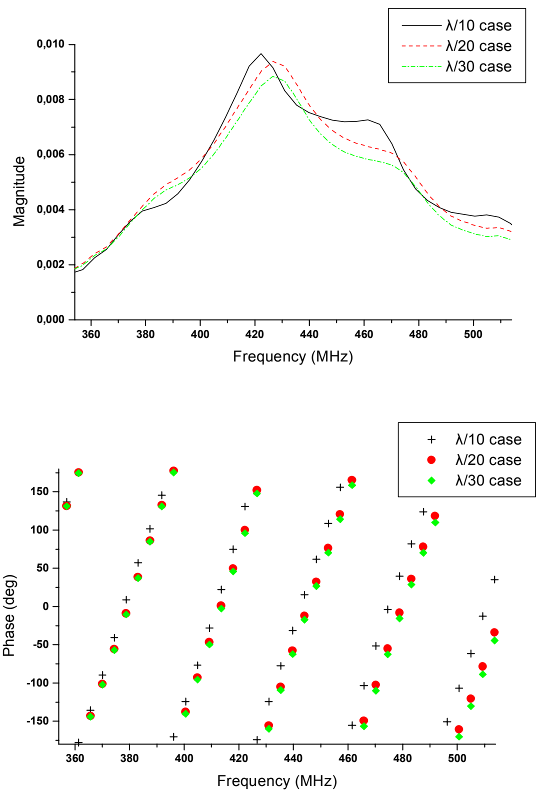

Fig. 5. Magnitude and phase of H for the SISO system for the three discretization cases.

An expected remark is that as the frequency increases, the phase difference between the frequency components of H for the three different discretization scenarios also increases.

Fig. 6 depicts the correlation coefficient ρ between the time domain duals of the frequency components of H for the three different discretization cases. Although ρ_{12} and ρ_{13} substantially decreases as the frequency increases, ρ_{23} remain at high levels even for the highest frequency component of the transmitting signal. The results of Fig.6 indicate that the $\lambda_{514}/20$ discretization scenario (mean phase error = 1.05^{o}) provides accurate results for separation distance of the order of 12 λ_{514} between the transmitting and the receiving dipole. As a consequence the results for the 434 MHz band will be even more accurate, since for the central frequency the discretization is finer ($\lambda_{434}/23$) and the separation distance smaller (10.85 λ_{434}).

The signals' Cumulative Distribution Function (CDF) for the 434 MHz frequency component of H inside the space enclosed by the scatterers is estimated through the procedure described in [19] and displayed in Fig. 7. It can be seen that it follows closely a Rayleigh distribution.

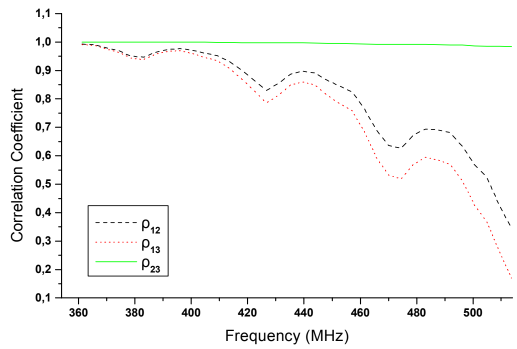

Fig. 6. Correlation coefficient between the time domain duals of the frequency components of H for the three different discretization scenarios.

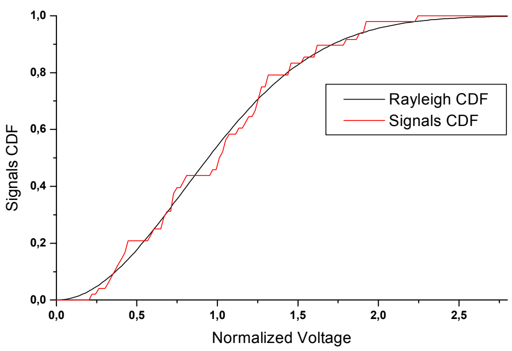

Fig. 7. Signals' Cumulative Distribution Function for the 434 MHz frequency component.

3.2 A SIMO system simulation

For the SIMO system simulation a second dipole was added near the receiving one of the SISO system at separation distances of d = 0.1, 0.13, 0.2, 0.4 and 0.5λ_{434} (Fig. 2). According to the previous results the adopted discretization was $\lambda_{514}/20$, while all the other simulation parameters were kept the same as for the SISO system.

The voltages at the ports of the two dipoles are quite similar but not identical as illustrated in Fig. 8 for the case of d = 0.2λ. In order to obtain a more detailed view of the relationship among the frequency components that comprise the signals, the H (magnitude and phase) for the two channels of the system is demonstrated in Fig. 9.

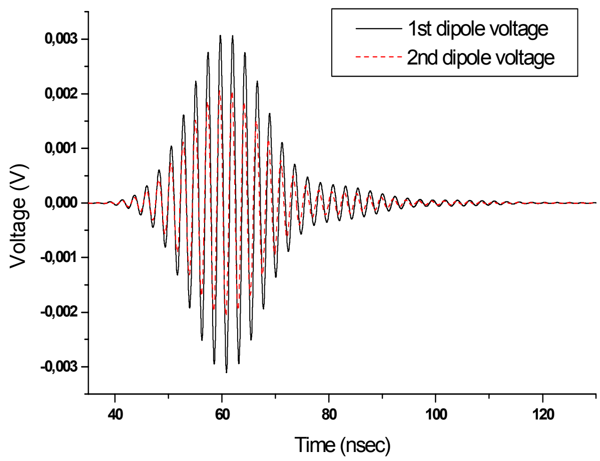

Fig. 8. Received voltages at the ports of the two dipoles when located at a distance d = 0.2λ apart.

The instantaneous correlation coefficient between the 434 MHz spectral components of the signals received by the two branches of the system versus dipoles' separation distance is illustrated in Fig. 10. It is remarkable that even for a separation distance of λ/2, ρ remains above 0.5. These values are close to those computed through measurements in [11] using a sliding window in order to show the variations of ρ in an electrically large area, but deviate a lot from the value of ρ estimated in [20] for electrically large areas without using the sliding window technique. This difference is attributed to the fact that the short-term means may differ greatly from the long-term means. The instantaneous ρ, as emerges from the deterministic solution via the FDTD method, is neither a short-term nor a long-term mean value. Nevertheless, the instantaneous ρ resembles the short-term ρ given that for electrically small areas the wireless channel is not that random.

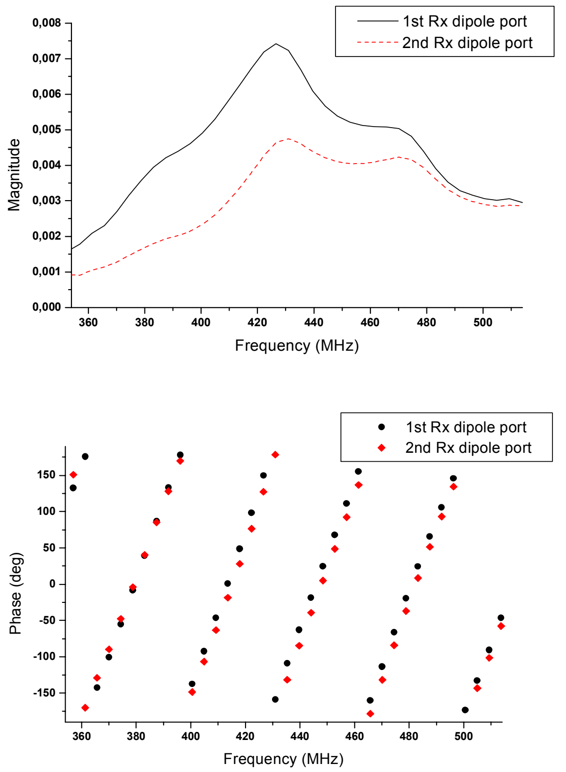

Fig. 9. Magnitude and phase of the Transfer Function H for the two channels of the SIMO system when the dipoles are located at a distance d = 0.2λ apart.

The ratio of the instantaneous powers received from the two dipoles of the system is given by:

$$\frac{P_1(\omega,\vec{r})}{P_2(\omega,\vec{r})} = \left|\frac{H_1(\omega,\vec{r})}{H_2(\omega,\vec{r})}\right|^2 \quad (5)$$

Fig. 11 illustrates the ratio of the instantaneous received power from the two ports of the system (in dB) for the 434 MHz spectral components versus dipoles' separation distance. It is obvious that as the dipoles' separation distance increases, this ratio also increases. These great differences between the received powers are in agreement with those that can be observed in Rayleigh distributed environments [21].

A SIMO system operates efficiently if the following two criteria are fulfilled: a) ρ < 0.5 and b) received power ratio ≤ ± 3 dB [8]. According to recently published works [9, 10, 22], these two parameters are estimated using propagation models based on large-term means. These estimations as well as those via measurements in electrically large areas [20] are fulfilling the above two criteria. On the other hand, the results presented in this paper and those obtained by measurements performed in [11] using the sliding window technique, do not fulfill these criteria even for antennas' separation distance as great as λ/2. Since the designers of SIMO transceivers want to know the worst-case operating conditions, the presented methodology when realized for many locations in an indoor environment provides a more detailed knowledge of the wireless transmission system.

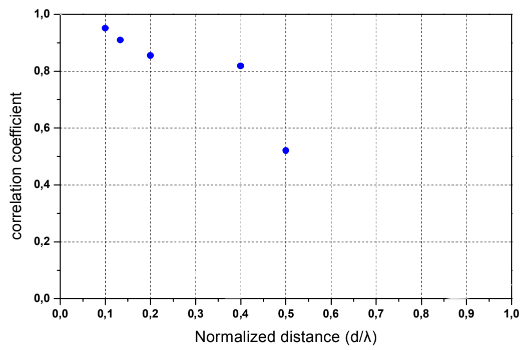

Fig. 10. Instantaneous correlation coefficient of the 434 MHz spectral components of the received signals versus dipoles' separation distance.

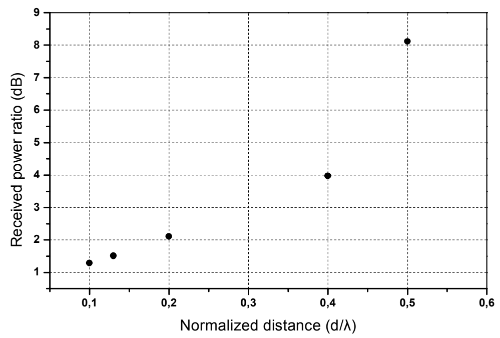

Fig. 11. Instantaneous received power ratio versus dipoles' separation distance for the 434 MHz spectral component.

4 Conclusion

A SISO and a SIMO wireless transmission system operating in the 434 MHz ISM band were simulated using FDTD. A novel procedure to evaluate the accuracy of the FDTD results, through the convergence of the Transfer Function was presented. The results show that a phase error of 1^o per wavelength of the higher frequency component of the signal is an accepted value for accurate results in a Rayleigh distributed environment for a propagation distance of about 12 λ. The instantaneous correlation coefficient and the received power ratio of the two channels of the system were estimated through the Transfer Function of the SIMO indicating the FDTD's potential in antenna diversity systems evaluation.

References:

[1] P. Ali-Rantala, L Sydanheimo, M Keskilammi and M. Kivikoski, Indoor Propagation Comparison Between 2.45GHz and 433MHz Transmissions, *2002 IEEE Antennas & Propagat. Soc. Int. Symposium*, pp. 240-243, San Antonio, Texas, June 16-21 2002.

[2] U. Buluku and A. Kavas, WLAN Propagation Path Loss Prediction at 2.4 GHz, *3rd WSEAS Int.Conf. on Electronics, Hardware, Wireless & Optical Communications*, Saltzburg, Austria, February 13-15 2004.

[3] K. Kobayashi, H. Nakae and J. Fujiwara, Proposal of Design Method for Fixed Wireless Telecommunication in 400-MHz Band and Measurements of Propagation Inside Office Buildings, *Electronics & Communications in Japan*, Part 1, Vol. 83, No. 8, pp. 42-52, 2000.

[4] L. J. W. van Loon, "Mobile In-Home UHF Radio Propagation for Short-Range Devices", *IEEE Antennas & Propagat. Magazine*, Vol. 41, No 2, pp .37-40, April 1999.

[5] P. Bernardi, R. Cicceti and Orlandino Testa, An Accurate UTD Model for the Analysis of Complex Indoor Radio Environments in Microwave WLAN Systems, *IEEE Trans. on Antennas & Propagat.*, Vol.52, No.6, pp. 1509-1520, June 2004.

[6] Z. Yun, M. F. Iskander and Z. Zhang, Complex-Wall Effect on Propagation Characteristics and MIMO Capacities for an Indoor Wireless Communication Environment, *IEEE Trans. on Antennas & Propagat.,* Vol.52, No.4, pp. 914-922, April 2004.

[7] P. Bernardi et al. A UTD/FDTD Investigation on Procedures to Assess Compliance of Cellular Base-Station Antennas with Human-Exposure Limits in a Realistic Urban Environment, *IEEE Trans. on Microwave Theory & Techniques,* Vol.51, No. 12, pp. 2409-2417,December 2003.

[8] R. G. Vaughan and J. B. Andersen, Antenna Diversity in Mobile Communications, *IEEE Transactions on Vehicular Technology*, Vol. 36, pp.149-172, November 1987.

[9] K. Ogawa, T. Matsuyoshi and K. Monma, An analysis of the Performance of a Handset Diversity Antenna Influenced by Head, Hand, and Shoulder Effects at 900 MHz: Part II-Correlation Characteristics, *IEEE Trans. on Vehicular Technology*, Vol. 50, No. 3, pp. 845-853, May 2001.

[10] K. Kalliola et al., Angular power distribution and mean effective gain of mobile antenna in different propagation environments, *IEEE Transactions on Vehicular Technology*, Vol. 51, No. 5, pp. 823-838, Sept. 2002.

[11] R.S. Roberts, P. Sweeney, S.R. Saunders, Short-Term Fading Correlation Between Elements of Antenna Array in an Indoor Environment for 'MIMO' Communication Systems, *12th ICAP*, University of Exeter, UK, 31st March- 3rd April 2003.

[12] K. Rosengren, P. Bohlin, P. Kildal, Multipath characterization of antennas for mimo systems in reverberation chamber including effects of coupling and efficiency, *Antennas and Propagation Society Symposium*, Vol. 2, pp. 1712-1715,June 20-25 2004.

[13] G. D. Durgin, *Theory of Stochastic Local Area Channel Modeling for Wireless Communications*, PhD Thesis, Virginia Polytechnic Institute, December 2000.

[14] Y. Miyazaki, G. Rodriguez and N. Goto, Simulation Analysis of Radio Propagation in Big Areas using a Parallel FDTD Algorithm for Broadband Wireless Communication, *in Proc. PIERS 2004,* Pisa, Italy, March 28-31.

[15] K. L. Shlager and J. B. Schneider, Comparison of the Dispersion Properties of Several Low-Dispersion Finite-Difference Time-Domain Algorithms, *IEEE Trans. on Antennas & Propagat.,* Vol. 51, No. 3, pp. 642-653,March 2003.

[16] A. Taflove and S. C. Hagness, *Computational Electromagnetics: The Finite-Difference Time-Domain Method,* Artech House, 2000.

[17] W. C. Lee, *Mobile Communications Engineering*, 2nd edition, McGraw-Hill, New York, 1998.

[18] Fidelity User's Manual, Release 4, ZELAND Software Inc., 2004, www.zeland.com.

[19] V. Papamichael, C. Soras and V. Makios, FDTD Modeling and Characterization of the Indoor Radio Propagation Channel in the 434 MHz ISM band, *17th ICECom 2003*, Dubrovnik, Croatia, pp. 217-220,October 1-3.

[20] S.C.K. Ko and R. Murch, Compact Integrated Diversity Antenna for Wireless Communications, *IEEE Trans. on Antennas & Propagat.,* Vol.49, No.6, pp. 954-960, April 2001.

[21] L. B. Picasso, P. Jansson, *Simulation and Measurement of Radio Wave Propagation in the 400 MHz MICS Band*, MSc Thesis, Department of Electroscience, Lund Institute of Technology, Sweden, April 2004.

[22] P.S.H. Leather, D. Parsons, Antenna diversity for UHF handportable radio, ELECTRONICS LETTERS, Vol. 39, No. 13, 26th June 2003.