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Implementable Wireless Access for B3G Networks — Part I: MIMO Channel Measurement, Analysis, and Modeling

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ABSTRACT

Within Mobile VCE, a team of several leading U.K. universities, in close association with major manufacturers and international telecom operators from the mobile industry, have been addressing the challenging task of designing transceiver structures for beyond 3G networks. Innovative approaches led to a plethora of cross-layer optimized technologies of low complexity and high robustness, allowing for the much promised multimedia-centric services over future wireless networks. This article presents a comprehensive overview of the research conducted within Mobile VCE's Core Wireless Access Research Programme,[1] a key focus of which has naturally been on MIMO transceivers. The series of articles offers a coherent view of how the work was structured and comprises a compilation of material that has been presented in detail elsewhere (see references within the article). In this article, the first of four, MIMO channel measurements, analysis, and modeling are presented, which were then utilized to develop compact and distributed antenna arrays. Parallel activities led to research into low-complexity MIMO single-user space-time coding techniques, as well as SISO and MIMO multi-user CDMA-based transceivers for B3G systems. As well as feeding into the industry's in-house research program, significant extensions of this work are now in hand, within Mobile VCE's own core activity, aimed at securing major improvements in delivery efficiency in future wireless systems through cross-layer operation.

AIMS

It was the aim of the Wireless Access work area to investigate and extend emerging technologies and techniques for providing wireless access for future networks. The Mobile VCE "Vision 2010" proposed the use of flexible software technologies to create autonomous radio networks, able to deliver ubiquitous mobile (and fixed) access supporting a wide range of convergent services. These services will be delivered to capitalize on the potential of diverse user devices, while complying with inherent constraints. A detailed understanding of the radio environment is required to create wireless bearer architectures necessary to support such desired services. Channel measurements and modeling therefore formed an important part of the research program. The research included technologies relevant to both base stations and user terminal devices, as well as the means whereby these devices are configured to cooperate to make the best use of their combined resources.

OBJECTIVES

The key research objectives of the conducted work program can be summarized as:
- To develop and generalize an understanding of new radio environments
- To invent and develop new technologies and techniques to support flexible wireless access
- To link new technologies and techniques to physical radio environments to create autonomous high-capacity wireless bearer architectures

Existing second-generation plus (2G+) and third-generation (3G) systems provided the baseline for the research described in this article, in conjunction with the work from Mobile VCE's own Core 1 research program, which provided a basis for information on the radio environment and base models for service types available in future networks.

RESEARCH AREAS

To facilitate an efficient realization of these aims and objectives, the scope of Wireless Access was condensed to the following areas of research:
- Evaluation of new radio environments

- Spectrally efficient but low-complexity transmitter/receiver architectures
- Space diversity methods for capacity enhancement
- Self planning and dynamically reconfigurable networks
- Indoor distributed antenna systems for high-bit-rate communications
- Radio resource metric estimation

These led to an interdependent set of research activities described in this series of articles.

STRUCTURE

The article structure reflects the objectives and interdependencies throughout the research activities to identify and extend practicable beyond 3G (B3G) techniques that would result in implementable transceivers. In this article, Part I, issues related to multiple-input multiple-output (MIMO) channel modeling and methods to exploit the MIMO nature of the communication system are reported. In the subsequent articles, Parts II–IV, the focus is more on the exploitation of MIMO, appropriate receiver architectures and resource management of such systems.

In this article dynamic MIMO channel measurements are described as well as analyzed; the measurements constitute direct input to the MIMO channel modeling presented in the article.

INDOOR DOUBLE-DIRECTIONAL DYNAMIC MIMO CHANNEL MEASUREMENT AND CHARACTERIZATION

INTRODUCTION

As MIMO technology plays an important role in future wireless local area networks (WLANs), considerable efforts are now focused on the indoor environment. In order to evaluate the performance of such systems, a realistic model for the indoor propagation channel is required. Clearly, the model must be able to account for the wideband characteristics as well as the spatial domain properties of typical indoor environments. The influence of the measurement equipment (bandwidth, antenna array type, heights of antennas, etc) must be excluded from the channel; thus, a physical model is preferred. Physical models consider the distributions of some crucial physical parameters that can be used to describe a realistic MIMO channel, such as direction of departure (DoD), direction of arrival (DoA), time delay of arrival (TDoA), and Doppler shift.

To date, several indoor channel models have been proposed. For example, Spencer's model [1] takes the spatial-temporal characteristics of the channel into account based on measurements conducted at 7 GHz. A stochastic radio channel model developed by Heddergott [2] was based on measurements at 24 GHz. Although the European COST 259 directional channel model has considered some indoor radio environments, it is based on a single directional configuration where the parameter's statistics were derived from a limited set of data.[2] In addition,

there is no extensive measurement that has been conducted to account for the dynamic features of the channel, that is, the distribution of channel parameters as the mobile terminal (MT) is in motion.

MEASUREMENT CAMPAIGN

In order to overcome these drawbacks, a total of four different indoor channel measurement campaigns were carefully planned and conducted within the overall program. These measurements were taken at 5 GHz (120 MHz bandwidth). The ultimate goal of this activity was to conduct extensive dynamic double-directional (MIMO) measurements using dual 16-element circular arrays, providing a full azimuth view at both ends. Dynamic measurements were conducted using a specialized measurement trolley, enabling the characterization (as a birth-death stochastic process) of the dynamic evolution of multipath components as the MT is in motion. Several typical indoor environments were chosen, including an open foyer, a corridor, an open plan office, a laboratory, and small home environments. In addition, measurements were conducted under different propagation conditions, including line of sight (LOS), non-LOS (NLOS), obstructed LOS (OLOS), populated (in terms of number of moving people), unpopulated, and different heights of array at both ends.

ANALYSIS AND RESULTS

In offline analysis the newly developed hybrid-space space alternating generalized expectation-maximization (HS-SAGE) algorithm was employed to extract multipath parameters of the channel (e.g., DoA, DoD, TDoA, and Doppler shift). Briefly, the HS-SAGE algorithm is a combination of element-space and beamspace processing. Despite being suitable for use with a circular array, it enhances the effective processing speed of the classical SAGE algorithm without sensibly sacrificing accuracy and resolution. This is achieved by reducing the overall size of the raw data by projecting the original element-space data into its beamspace counterpart via appropriate beamspace processing.

Figure 1 shows a sample of (instantaneous) estimated DoA, DoD, TDoA, and Doppler shift results in an LOS corridor environment, processed using the 4D HS-SAGE algorithm. The double-directional results give us better insight into the propagation mechanisms of the channel. While the channel is mostly dominated by LOS paths, several single-bounce reflection paths can be identified by inspecting their DoA, DoD, and TDoA (corresponding to propagation distance) values. Since the figures only display instantaneous results within a dynamic window of 30 dB, double-bounce reflection paths are not seen here since they are much weaker. This indicates that double-bounce reflections do not contribute significant power to the channel. At least two clusters can be identified here, corresponding to an LOS cluster and a single-bounce reflection cluster. In addition, the Doppler shift values also match well with the velocity (approximately 0.2 m/s) of the mobile trolley.

Figure 2a presents the joint distribution of DoA and DoD in an LOS corridor environment.
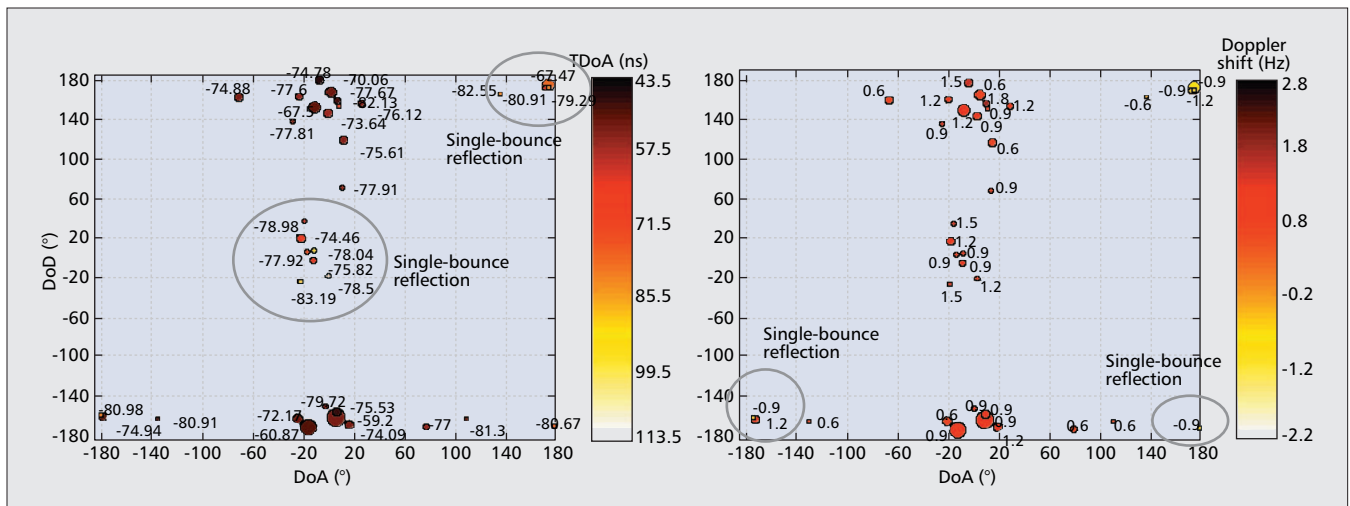
■ Figure 1. *Sample of estimated results in the corridor environment: a) estimated DoA, DoD, and TDoA results; path weight is size-coded; its value is shown; b) estimated DoA, DoD, and Doppler shift results; Doppler shift is color-coded; its value is shown.*

Here, the distributions of DoA and DoD are dependent on each other. Their distributions can be considered uniform across the azimuth range, but peaks are found around the region of LOS and single-bounce reflection. This indicates that most of the multipath in an LOS corridor environment propagates along the direction of the corridor axis. Nevertheless, the channel is still dominated by the LOS components, as shown by the power distribution in Fig. 2b. The power azimuth spectrum at both Tx and Rx exhibits Laplacian characteristics, where peak is detected at LOS direction.

## SPATIAL CHANNEL MODELING FOR MOBILE COMMUNICATIONS

MULTIPATH CHANNEL PARAMETER ESTIMATION AND DETECTION

The work described here focuses on the statistical characterization and modeling of the indoor propagation channel. The 2D frequency domain space alternating generalized expectation-maximization (FD-SAGE) algorithm was developed for data analysis in this work [3]. It was used to jointly estimate the times of arrival (ToAs), angles of arrival (AoAs), and complex amplitudes of the multipath components (MPCs). The formulation of SAGE in the FD is essential in order to provide an optimal way to post-process measurement data that is stored in FD form. Further improvement in FD-SAGE is achieved by replacing the parallel interference cancellation (PIC) technique in the standard time-domain SAGE with a serial interference cancellation (SIC) technique. It was shown that SIC outperforms PIC in a multipath-rich environment in terms of its accuracy, stability, and convergence rate. The SIC technique is also used as the detection technique to find the number of MPCs present prior to the estimation procedure. Thus, the number of MPCs detected was governed by the temporal and angular domain resolution of the measurement system, while not being limited by the number of antenna ele-

ments used during the measurements. Performance comparison of 2D FD-SAGE with 2D unitary ESPRIT verified its functionality. Figure 3 shows the power-delay-azimuth spectrum obtained by post-processing a sample measurement file using 2D FD-SAGE and 2D unitary ESPRIT algorithms, respectively. The leakage problem that occurred in the initial version of 2D FD-SAGE is overcome by employing FD windowing. Due to its high degree of flexibility and robustness in dealing with different array geometries, FD-SAGE proved to be a powerful tool for offline processing of raw channel measurement data prior to channel characterization and modeling.

Two models have been developed in order to characterize the spatial and temporal domain properties as well as the dynamic behavior of the indoor propagation channels. Since measurements for supporting the statistical analysis of the channels were conducted using a 5.2 GHz carrier frequency, these models are particularly important for 5 GHz band WLAN systems that employ SA architectures.

The models have several advantages, including the fact that they are relatively simple to use and yet provide accurate information. The first channel model developed incorporates both the spatio-temporal clustering phenomenon observed in the measurement data, as well as the correlation between these two domains [4]. Clustering of MPCs needs to be considered in the model if the MPCs are indeed clustered as non-clustered models tend to overestimate the capacity. Two joint probability density functions (pdfs) are introduced into the model that describes the cluster and MPC positions' spatio-temporal correlation properties. It was found that the a priori assumption made by most previous researchers concerning independence between the spatial and temporal domains is appropriate only for OLOS and NLOS scenarios. However, for the LOS scenario, this assumption fails to model the channel well due to the dependence that exists between the spatial and temporal domains. Figure 4 shows the joint pdf of cluster position for the LOS and OLOS scenarios, respectively. The
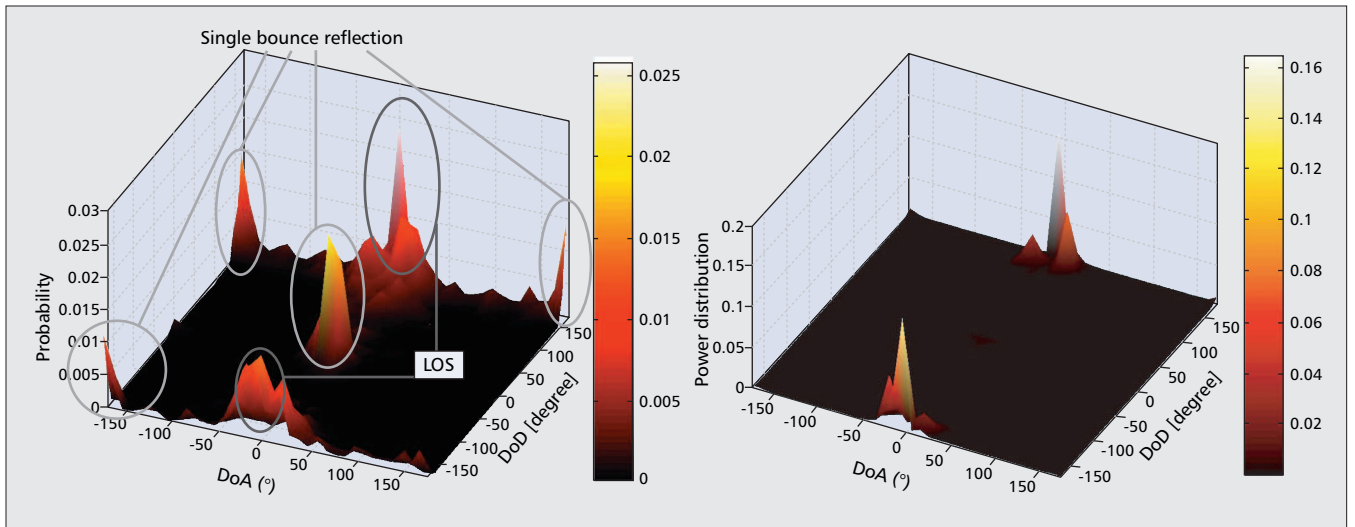
Figure 2. *2D distributions of DoA and DoD along dynamic path in a corridor environment: a) joint PDF of DoA and DoD; b) 2D power distribution of multipath.*
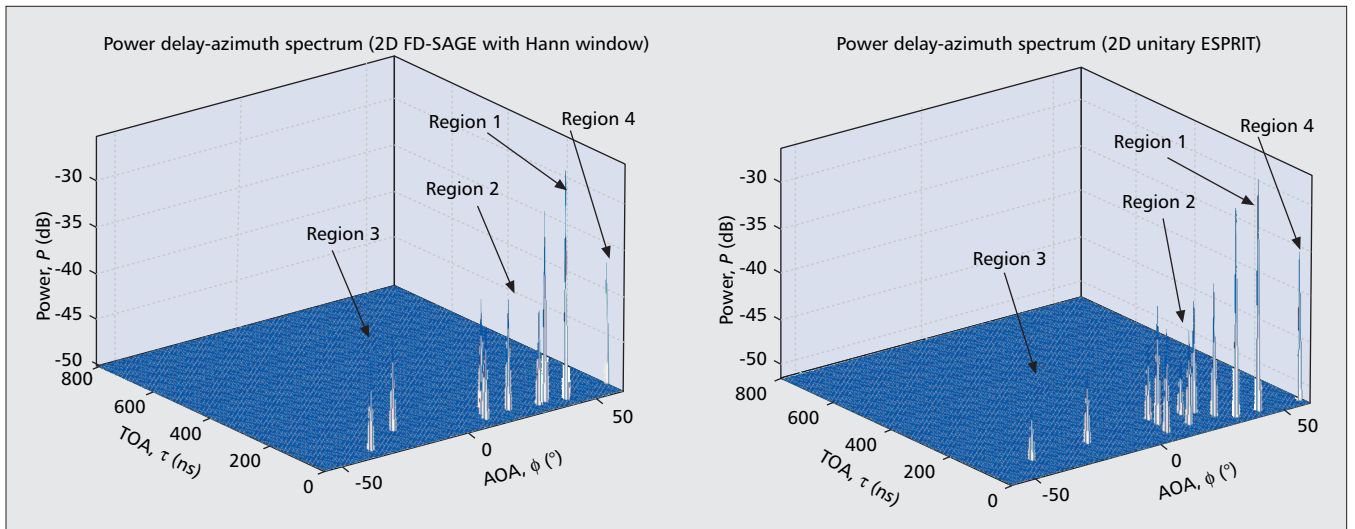

Figure 3. *a) Power delay-azimuth spectrum estimated by the 2D FD-SAGE algorithm; b) power delay-azimuth spectrum estimated by the 2D unitary ESPRIT algorithm.*

NLOS scenario is not shown here due to its similarity in shape to the OLOS case. Modeling the correlation between these two domains is essential as strong correlation could enhance the performance of space-time processing techniques. Thus, the finding reported here is important in providing more detailed insight on the spatio-temporal domain properties of the channel. The modeling approach proposed in this work combines the pdfs of the channel parameters with the channel power density spectra (PDS). All channel parameters and PDS are derived from measurement data. Thus, by having both of these, the channel can easily be reproduced by computer simulation.

WIDEBAND DYNAMIC DIRECTIONAL MARKOV CHANNEL MODEL

The second channel model developed is an extension of the first channel model described previously to include the dynamic behavior of

the channel by adapting the concept of a Markov process [4]. Since statistical characteristics of the channel may change significantly with motion of the MT, modeling the dynamic evolution of paths is important to provide a more realistic simulation platform and for performance evaluation of tracking algorithms employing SA technologies. An *M*-step four-state Markov channel model (MCM) was proposed in order to account for the correlation between the number of births and deaths, and multiple births and deaths that can occur at any time instant observed in the measurement data. Figure 5 shows the distance-variant power-delay density spectrum for a sample measurement file, where with ongoing time paths appear and disappear. To date, most researchers have assumed that the channel is quasi-static, and the births and deaths are due to two separate stochastic processes. Thus, the dynamic model proposed in this work is important to provide better understanding of the time-varying channel and as a stepping stone toward a
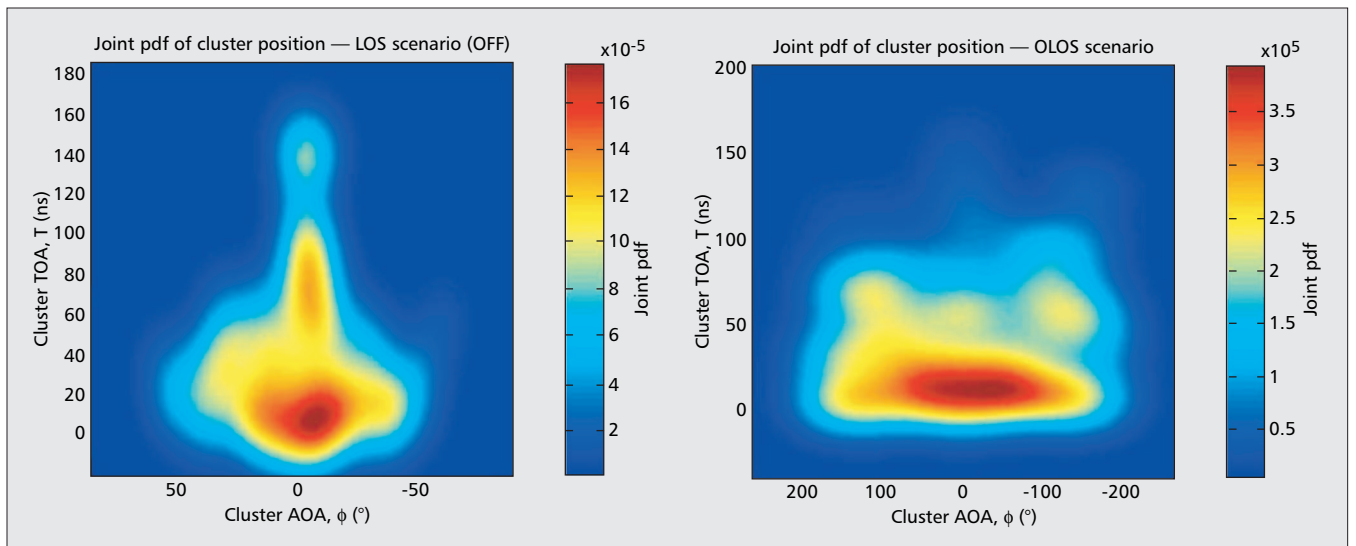
■ Figure 4. *a) Joint pdf of cluster position under the LOS scenario; b) joint pdf of cluster position under OLOS scenario.*

more realistic channel model for future wireless systems.

Both power and spatio-temporal variations of a path can occur within its lifespan due to the motion of the MT. It is found in this work that the power variation of each path within its life span can be modeled by a simple low-pass filter (LPF). Previous researchers have assumed that this variation is described by a sinusoidal function. Since this conjecture is not supported by any measurement results, the results obtained here are particularly significant for future research. On the other hand, the spatio-temporal variations of each path within its life span is found to be modeled by a Gaussian distributed spatio-temporal vector, which describes the changes in the temporal and angular domains of a particular path within its life span. Since no results are readily available in the open literature concerning this issue, more measurements and modeling work are required to verify this approach. Due to the distinction in the birth-death (B-D) statistics, and the spatio-temporal dispersion and correlation properties for LOS and NLOS scenarios, the model is generalized by classification of the measurement runs into segments that exhibit similar propagation mechanisms. Thus, the model can be completely parameterized by two sets of Markov parameters for LOS and NLOS scenarios, respectively.

SPATIO-TEMPORAL DISPERSION AND CORRELATION PROPERTIES

In addition to the two models described above, issues concerning the spatio-temporal dispersion properties of the channel are characterized [5]. Measurement results showed that the main contributory factors in determining the value of spatio-temporal dispersion are the presence of an LOS path, the TX-RX separation, and the degree of clutter in the environment. A strong spatio-temporal correlation exists under the LOS scenario, and the correlation falls off when the LOS path is obstructed. Higher values of spatio-temporal dispersion are also found when TX-RX
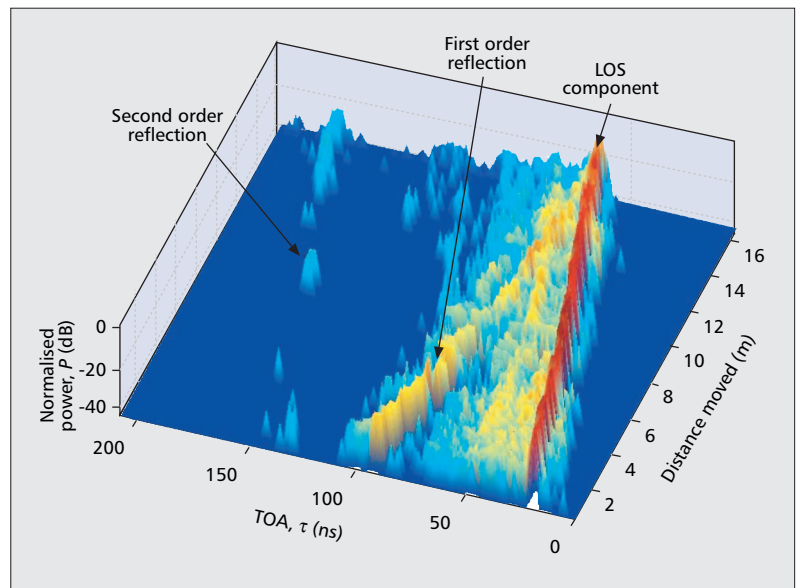
■ Figure 5. *Distance-variant power-delay density spectrum.*

separation is increased or in a more cluttered environment, particularly when the LOS path is obstructed. These results are particularly important in providing some insight for the generalization and parameterization of the dynamic model described above. Furthermore, the average values proposed in [5] can be employed to assist in the planning of WLANs.

SPATIAL FADING CORRELATION FROM CHANNEL MEASUREMENTS

In a MIMO communication system, both the transmitter and receiver have more than a single antenna element. In order for such a system to perform optimally, the time varying fading seen between pairs of transmit and receive elements must be independent and hence uncorrelated. However, in real systems spatial fading correlation (SFC) becomes an important limiting factor
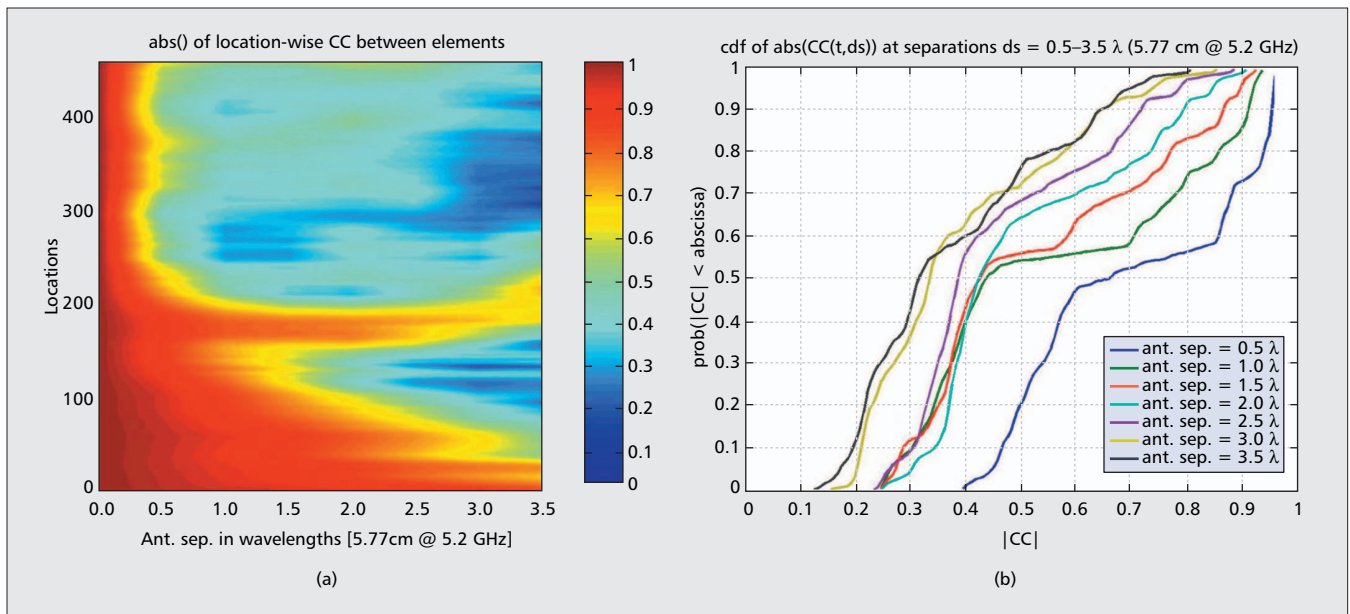
■ Figure 6. *Magnitude of SFC coefficient: a) SFC along the movement path; b) CDF.*

demanding careful study. There are two main factors making it impossible to achieve the ideal independent fading scenario: the physical properties of the antenna arrays and the characteristics of the radio channel.

In this section we present the analysis conducted to extract the inherent SFC in the data collected through the extensive indoor channel measurement campaign. The focus here is on the levels of severity and the varying nature of spatial fading cross-correlation along the path of a mobile as it moves. The spatial fading correlations were calculated from the measurement data with extensive averaging to ensure a statistically representative result. Spatial fading correlation for indoor scenarios has previously been addressed in [6], where the average power correlation coefficient is reported for whole measurement runs. However, it does not help to gain insight into how the levels fluctuate along the path. The aim of our work is to identify trends in the variation of correlation against changes in the propagation environment due to the mobility of the array [7].

In order to enhance the statistical strength of the estimated correlation coefficients, it was calculated for all 24 sections of nonoverlapping 5 MHz bandwidths over the 120 MHz measurement, and the overall average was used to plot the location-wise SFC coefficient between impulse responses seen by the antennas (measurement details are mentioned earlier). For each selected 5 MHz bandwidth, as the first step, the data are complex averaged in the frequency domain such that the selected bandwidth is represented by one sample in the frequency domain. (It was noted that 5 MHz was within the coherence bandwidth for more than 80 percent of the time, making it valid to attach a single value of SFC over this bandwidth). In the next step all the snapshots taken at one specific location on the path were averaged into one snapshot, representing the complex gain at a point, d, on the path over the selected bandwidth. The correla-

tion coefficient between the Rx antennas was then estimated using these complex gains over a selected window of distance points $d = 1, \dots D$. The D distance points were chosen to cover at least 10 wavelengths along the measurement path to make sure the fading correlation is calculated over a corresponding number of Doppler fading cycles, while the channel within this window can still be considered wide sense sstationary (WSS).

A typical set of SFC results are plotted below in two types of graphs:

• Color-coded magnitudes of the correlation coefficients along the path plotted against the locations corresponding to the midpoint of the window D vs. antenna spacing from 0 to 3.5 λ (8-element ULA with 0.5 λ inter-element spacing provides a maximum of 3.5 λ).

• The cumulative distributed function (CDF) of the magnitude of the correlation coefficient for each possible antenna spacing

Figure 6 shows an interesting case where the single-antenna mobile starts in the broadside direction of the base station array (there is LOS for the first approximately 20–30 percent of the time), and moves across the view field in the endfire direction and disappears completely.

The plot shows that initially there is a strong LOS component leading to high correlations at all antenna separations. This corresponds to a location where the Tx-Rx separation is short, and the Tx is broadside to the array. As the Tx moves, the angle spread increases, leading to a drop in correlation, even though the Tx is moving away from broadside. At locations 180–200 the Tx bearing is close to endfire for the array, and at this point it appears that the angle spread is small, which again leads to high correlations for all antenna separations. Beyond that the Tx-Rx distance increases; scattering in the environment increases since the Tx becomes obstructed, so correlation is low across the range of antenna separations.

The CDF graph in Fig. 6b indicates that there were a number of incidents of lower correlation and a comparable number of incidents of high correlation values with a small number of values in the middle. The single antenna separation stands out, especially at lower values. This shows that the SFC will be considerable when there are strong dominating LOS paths or if the antenna array is used close to the endfire direction.

CONCLUDING REMARKS

This article, (the first of four) has presented the technical activities within Mobile VCE's Wireless Access research area. Since the research was defined and driven by the leading companies in mobile communications, the research naturally focused on the provision of wireless access in future networks. The research outcome clearly demonstrates that an extension from SISO to MIMO transceivers facilitates the high data rates required for media-centric applications and that such efficient implementations are feasible. This has been corroborated by means of an extensive MIMO measurement campaign that led to new MIMO channel models, also incorporating spatial and temporal correlation. As a source of material on subsequent work in this area, readers are referred to [8], which discusses related work in the IST WINNER project.

Further information regarding the work of Mobile VCE can be found at http://www.mobilevce.com.

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BIOGRAPHIES

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STEPHEN MCLAUGHLIN [SM] (Steve.McLaughlin@ee.ed.ac.uk) received a B.Sc. degree in electronics and electrical engineering from the University of Glasgow, United Kingdom, in 1981 and a Ph.D. degree from the University of Edinburgh, United Kingdom, in 1989. From 1981 to 1984 he was a development engineer with Barr & Stroud Ltd., Glasgow, involved in the design and simulation of integrated thermal imaging and fire control systems. From 1984 to 1986 he worked on the design and development of high-frequency data communication systems with MEL Ltd. In 1986 he joined the Department of Electronics and Electrical Engineering at the University of Edinburgh as a research fellow, where he studied the performance of linear adaptive algorithms in high-noise and nonstationary environments. In 1988 he joined the academic staff at Edinburgh, and from 1991 until 2001 he held a Royal Society University Research Fellowship to study nonlinear signal processing techniques. In 2002 he was awarded a personal Chair in electronic communication systems at the University of Edinburgh. His research interests lie in the fields of adaptive signal processing and nonlinear dynamical systems theory, and their applications to biomedical and communication systems. He is a Fellow of the Institute of Engineering and Technology and a Fellow of the Royal Society of Edinburgh.

MARK BEACH (M.A.Beach@bristol.ac.uk) received his Ph.D. for research addressing the application of smart antennas to GPS from the University of Bristol, United Kingdom, in 1989, which he subsequently joined as a member of academic staff. His interest in smart antenna techniques has continued with the application of dual array techniques or MIMO architectures to high-performance wireless networks. In particular, he has conducted research in the area of double-directional channel measurements and analysis as well the practical characterization channel of MIMO

> The research outcome clearly demonstrated that an extension from SISO to MIMO transceivers facilitates the high data rates required for media-centric applications and that such efficient implementations are feasible. This has been corroborated by means of an extensive MIMO measurement campaign.

using realistic user devices. He also has an active interest in analog RF technologies for cognitive radio and spectrum sharing, and leads this theme within the MobileVCE Delivery Efficiency research programme. He is also the U.K. National Representative to the EU COST 2100 action, and in August 2006 he was appointed head of the Department of Electrical and Electronic Engineering at the University of Bristol.

CHOR MIN TAN (chormin.tan@bt.com) received his M.Eng. (1st Hons) degree in electrical and electronic engineering and his Ph.D. in wireless and signal processing from the University of Bristol in 2000 and 2004, respectively. During his studies in the Centre for Communications Research at the university, he contributed to various research projects in the Mobile VCE and European COST 273 programs. His research interests lie in the areas of multidimensional array signal processing techniques, indoor and outdoor high-resolution propagation measurements, MIMO channel characterization and modeling, as well as emerging radio technologies of mobile broadband access. He is currently attached to British Telecom as a research professional, where he has been looking into QoS enhancement techniques, and technological and market trends of various converging technologies and standards.

HAMID AGHVAMI [F] (hamid.aghvami@kcl.ac.uk) joined the academic staff at King's College London in 1984. In 1989 he was promoted to reader and in 1993 to professor in telecommunications engineering. He is presently the director of the Centre for Telecommunications Research at King's. He carries out consulting work on digital radio communications systems for both British and international companies. He has published over 400 technical papers and given invited talks all over the world on various aspects of personal and mobile radio communications as well as courses on the subject worldwide. He was a visiting professor at NTT Radio Communication Systems Laboratories in 1990 and a senior research fellow at BT Laboratories in 1998–1999. He was an executive advisor to Wireless Facilities Inc., USA, in 1996–2002. He is the managing director of Wireless Multimedia Communications Ltd (his own consultancy company). He leads an active research team working on numerous mobile and personal communications projects for 3G and 4G systems; these projects are supported by both the government and industry. He was a member of the Board of Governors of the IEEE Communications Society in 2001–2003. He is a distinguished lecturer of the IEEE Communications Society, and has been member, chair, and vice-chairman of the technical program and organizing committees of a large number of international conferences. He is also founder of the International Conference on Personal Indoor and Mobile Radio Communications. He is a Fellow of the Royal Academy of Engineering and the IEE.