Correlation Analysis Based on MIMO Channel Measurements in an Indoor Environment

Persefoni Kyritsi, *Member, IEEE*, Donald C. Cox, *Fellow, IEEE*, Reinaldo A. Valenzuela, *Fellow, IEEE*, and Peter W. Wolniansky

***Abstract*—Multiple-input–multiple-output (MIMO) systems have the potential to achieve very high capacities, depending on the propagation environment. Capacity increases as signal correlation decreases. We present the measurements of a MIMO system under strong and weak line-of-sight conditions. The system capacity decreases as the distance from the transmitter increases. Indeed the transmitter correlation increases as the distance increases. The receiver correlation is lower than the transmitter correlation under both propagation conditions.**

***Index Terms*—Arrays, correlation, diversity methods, polarization, propagation.**

I. INTRODUCTION

IN RECENT years, a lot of attention has been drawn to systems with multiple element transmitter and receiver arrays, because they can achieve very high spectral efficiencies [1]. As the user's needs for higher data rates grow and bandwidth is becoming an expensive commodity, multiple-input–multiple-output (MIMO) systems have become an especially attractive potential solution for wireless applications that are inherently power and complexity limited.

It has been shown theoretically that the capacity of a MIMO channel scales linearly with the number of transmitting/receiving elements in the case of uncorrelated channel gains [1], [2]. This is due to the decomposition of the channel into an equivalent set of spatial subchannels [3], and is a synergistic effect beyond the antenna and the diversity gain (the latter being logarithmically proportional to the number of elements).

The analysis of conventional diversity systems has shown that the benefit drawn from the use of diversity techniques diminishes in the presence of signal correlation independently of the combination method used (selection, equal gain/maximal ratio combining) or the domain to which diversity is applied (space, polarization, frequency, time, etc.). Similarly, it has also been demonstrated that signal correlation limits the achievable capacity of MIMO systems (theoretically in [4] among others). However, correlation analysis within the context of MIMO systems necessitates the investigation of additional characteristics of the wireless channel, such as its complex (amplitude and phase) and double directional (transmit and receive angular spectra) nature.

The purpose of this paper is to present the spatial signal correlation that was measured in an indoor environment with a real-life narrowband MIMO system.

II. NOTATION

Assume a system with M transmitters and N receivers. Each transmitter sends an independent data stream with power P_x, so that the total transmitted power is $P_{\text{total}} = MP_x$. Let $\underline{x}$, $\underline{y}$ be the transmitted and the received signal vectors, respectively. In the case of a flat-fading channel (no variation with frequency), the channel gain from transmitter j to receiver i is a scalar quantity, denoted H_{ij}. The transmitted and received vectors are related by the equation $\underline{y} = \mathbf{H}\underline{x} + \underline{n}$, where $\underline{n}$ is the receiver noise vector. The channel transfer matrix $\mathbf{H}$ incorporates the channel transfer gains from each transmitter to each receiver. The noise at the receivers is assumed to be Gaussian, of equal power σ^2 and its components are independent of each other, so that the noise auto-correlation matrix is $\mathbf{R}_{\text{nn}} = \sigma^2\mathbf{I}$ ($\mathbf{I}$: identity matrix).

The Shannon capacity for this static channel is [1]

$$C_{\text{static}} = \log_2\left(\det\left(\mathbf{I} + \frac{P_x}{\sigma^2}\mathbf{H}\mathbf{H}^H\right)\right) \tag{1}$$

where $\mathbf{H}^H$ is the Hermitian (complex conjugate transpose) of the matrix $\mathbf{H}$.

The signals used in our formulation are discrete-time complex baseband, so the vectors $\underline{x}$, $\underline{y}$, $\underline{n}$ and the elements of the channel transfer matrix $\mathbf{H}$ are complex. We also assume perfect down conversion, filtering, and sampling.

The measurements presented in this paper were taken in the Lucent Technologies Crawford Hill building in order to study the channel capacity in two different environments (strong/weak line-of-sight (LOS) conditions in the hallway/labs, respectively). Previous analysis [5] has shown that in the hallway the LOS component is significant, the channel is not rich in multipath and the achievable capacity is low. In the labs, the channel is richer in multipath but the common dominant propagation path (down the hallway and into the labs) limits the capacity. We expect to see these effects reflected in the signal correlation analysis.

Section III describes the measurement setup. Section IV defines signal correlation, and Section V summarizes the capacity measurements. Section VI presents the correlation results from the local statistics studies with respect to antenna polarization and element separation. Section VII includes the conclusions of this work.

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P. Kyritsi is with the Center for PersonKommunikation, Aalborg DK-9220, Denmark (e-mail: persa@ cpk.auc.dk).

D. C. Cox is with the Department of Electrical Engineering, Stanford University, Stanford, CA 94305–9515 USA (dcox@spark.stanford.edu).

R. A. Valenzuela and P. W. Wolniansky are with Bell Labs, Lucent Technologies, Holmdel, NJ 07733 USA (e-mail: rav@lucent.com; pww@lucent.com).

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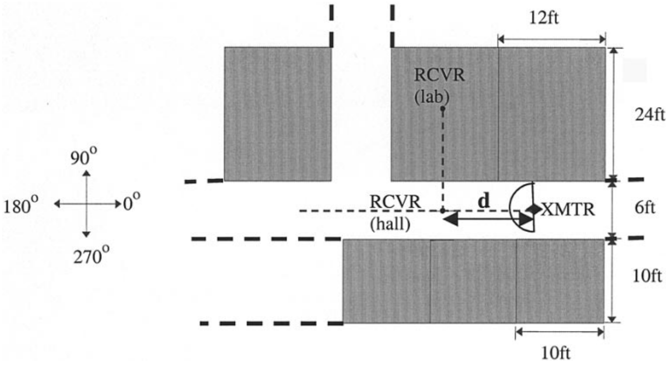

Fig. 1. Building layout.

III. MEASUREMENTS OF A MIMO SYSTEM

A. Measurement Location

The measurement campaign was conducted in the Lucent Bell Labs building in Crawford Hill, NJ. Fig. 1 shows a rough layout of the building, which in reality extends on both sides.

This is a two-story building that houses approximately 150 people and is built on the side of a hill. On the front side there is a parking area, and on the back side of the building, at a distance of approximately 100 ft, there is the hill slope.

The outside walls of the building are largely glass, whereas the inside walls are made of wood and wallboard. The ceilings and the floors are made of reinforced concrete over steel plates. The measurements were taken on the second floor of the building, in the main corridor and in the adjacent labs.

The main hallway is a straight corridor, 390 ft long, 6 ft wide, and 10 ft high. The hallway is lined with offices (typically 10 ft × 10 ft) on one side and laboratories (typically 12 ft × 24 ft) on the other. There is a second corridor that intersects the first one in a T shape. The second corridor is also lined with rooms, but no measurements were taken in that environment. The labs measurements were taken in the laboratories adjacent to the primary hallway. The offices face the parking lot and the labs face the side of the hill.

Fig. 1 also shows the angular coordinate system used in the following to describe both the antenna orientation and the array positioning.

B. Measuring Equipment

The measurements were taken with a system of 12 transmitters and 15 receivers at a frequency of 1.95 GHz, where the system bandwidth was 30 kHz.

The antennas used are flat arrays of folded cavity backed slot antenna elements mounted on 2 ft × 2 ft panels. They have a hemispherical gain pattern, so they pick up energy from the direction at which they are facing. The antenna elements were either vertically or horizontally polarized and arranged in alternate polarizations on 4×4 grids, separated by $\lambda/2$ ($\sim$ 8 cm). Fig. 2 shows how the arrays look from the front (V/H: vertically/horizontally polarized elements).

C. Measuring Process

The purpose of the experiment was to study the dependence of the channel transfer matrix $\mathbf{H}$ on the distance from the transmitter, the orientation of the receiver and the propagation environment (hallway versus labs).

TRANSMITTER SIDE

$\mathbf{V}_1$	$\mathbf{H}_6$	$\mathbf{V}_6$	$\mathbf{H}_5$
$\mathbf{H}_1$			$\mathbf{V}_5$
$\mathbf{V}_2$			$\mathbf{H}_4$
$\mathbf{H}_2$	$\mathbf{V}_3$	$\mathbf{H}_3$	$\mathbf{V}_4$

RECEIVER SIDE

$\mathbf{H}_5$	$\mathbf{V}_6$	$\mathbf{H}_6$	$\mathbf{V}_1$
$\mathbf{V}_5$	$\mathbf{H}_8$		$\mathbf{H}_1$
$\mathbf{H}_4$	$\mathbf{V}_7$	$\mathbf{H}_7$	$\mathbf{V}_2$
$\mathbf{V}_4$	$\mathbf{H}_3$	$\mathbf{V}_3$	$\mathbf{H}_2$

Fig. 2. Array layout.

For all our measurements the transmitter was placed 82.5 ft from the eastern end of the hallway (0° direction) and 2 ft from the northern wall of the hallway (90° direction), facing west (180° direction). This point is the origin (0,0) of our axis system. The receiver was wheeled to the desired position for each measurement and data were collected.

1) Single Measurement Process: The prototype used for the measurement campaign processes data in bursts. Each burst consists of 100 symbols. Out of these, 20 are training symbols and are used for the measurement of the channel transfer matrix. This is performed with orthogonal training sequences as described in [6]. The training sequences are the first 20 symbols of the burst and the last 80 symbols are data symbols that are decoded using the BLAST algorithm [7]. These 80 data symbols are not used in this analysis. We are interested in the channel characteristics so we concentrate on the recorded channel transfer matrices.

The transmit power during the signal measurements was set to 9.2 dBm for most locations. The measurements in the hallway at distances 3–18 ft from the transmitter were conducted with a lower transmitted power to prevent receiver saturation.

At each measurement location, about 100 bursts (100 temporal samples of the channel transfer matrix $\mathbf{H}$) were recorded in order to average over the small scale temporal variation (doors opening and closing, people walking through the hallway or in the labs, etc.). Also, the average signal-to-noise ratio at all locations was at least 15 dB. This was done in order to guarantee the accuracy of the capacity calculation [8].

2) Large-Scale Measurements: The purpose of the large-scale measurements was to study the dependence of the channel characteristics on the separation from the transmitter. These results have been presented in [9] and [22].

For the distance dependence study, the receiver was wheeled to the desired position at distances between 3 and 246 ft from the transmitter at 3-ft intervals along in the hallway. In the labs, the receiver was again wheeled to the desired position, which was 8 ft into the labs perpendicular to the 0°-180° line in the hall defined by the transmitter. Measurements were taken in 11 labs.

3) Small-Scale Measurements: The purpose of the small-scale measurements was to study the local statistics of the channel characteristics. For that, local area measurements of the channel characteristics had to be performed in grids of points surrounding nominal measurement locations. This process was repeated for three such nominal measurement locations in the hallway and the corresponding three labs. The distances of the nominal measurement locations from

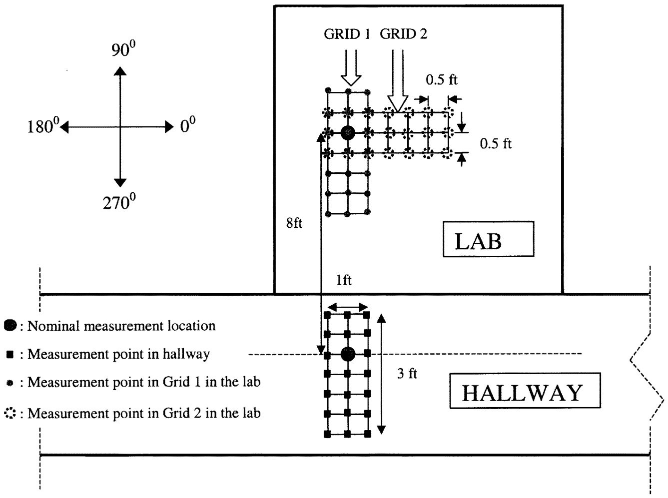

Fig. 3. Small-scale measurements.

the transmitter array were selected to be representative of the environment close to the transmitter, in the middle of the hallway, and far from the transmitter (21 ft, 117 ft, 240 ft).

Fig. 3 illustrates the relative arrangement of the grids with respect to the building layout. The grid cell size was 0.5 ft for all measurements.

In the hallway, measurements were performed on 3 × 7 points arranged on a regular rectangular grid as shown in Fig. 3. For these measurements the receiver array was oriented toward the transmitter, i.e., in the 0° direction.

In the case of the labs, two grids were studied: Grid 1 as shown in Fig. 3 was a 3 × 8 regular rectangular grid that spanned the lab in the 90°-270° direction. The measurements taken on this grid were for the 0° and the 180° orientation of the receiver array. Grid 2 as shown in Fig. 3 was a 3 × 8 regular rectangular grid that spanned the lab in the 0°-180° direction. The measurements taken on this grid were for the 90°–270° orientation of the receiver array.

IV. CORRELATION CALCULATION

A. Correlation Definition

Let v, u be two complex random variables.

The complex correlation coefficient ρ_{complex} of v and u is defined as

$$\rho_{\mathrm{complex}} = \frac{E\left[uv^*\right] - E[u]E[v^*]}{\sqrt{\left(E\left[|u|^2\right] - |E[u]|^2\right)\left(E\,|v|^2 - |E[v]|^2\right)}}. \tag{2}$$

where * denotes the complex conjugate operation.

Similarly, the power and the envelope correlation coefficients of u and v, ρ_{env} and ρ_{wpr} are defined as

$$\rho_{\mathrm{env}} = \frac{E\left[|u|\,|v|\right] - E\left[|u|\right]E\left[|v|\right]}{\sqrt{E\left[|u|^2 - \left(E\left[|u|\right]\right)^2\right]E\left[|v|^2 - \left(E\left[|v|\right]\right)^2\right]}} \tag{3}$$

$$\rho_{\mathrm{pwr}} = \frac{E\left[|u|^2\,|v|^2\right] - E\left[|u|^2\right]E\left[|v|^2\right]}{\sqrt{E\left[|u|^4 - \left(E\left[|u|^2\right]\right)^2\right]E\left[|v|^4 - \left(E\left[|v|^2\right]\right)^2\right]}}. \tag{4}$$

The denominators in (2)–(4) normalize the random variables, and, therefore, all correlation coefficients are upper bounded in absolute value by unity.

It has been demonstrated in [19] that, under certain assumptions, these correlation coefficients are related by

$$\rho_{\mathrm{env}} \approx \rho_{\mathrm{pwr}} \tag{5}$$

$$\rho_{\mathrm{pwr}} \approx \left|\rho_{\mathrm{complex}}\right|^2. \tag{6}$$

B. Classification Process

Let us assume a system of M transmitters and N receivers. This means that there are MN complex variables, each one corresponding to the channel gain for a different transmitter–receiver pair. Cross correlating every combination of such variables would give rise to $O((MN)^2)$ correlation values. This can be a huge number for systems with several transmitters and receivers. For example in our case, where $M = 12$ and $N = 15$, we would have 12 038 correlation values (because of symmetry $\rho(u,v) = \rho^*(v,u)$ and $\rho(u,u) = 1$).

In order to come up with a meaningful grouping and interpretation of those, we classify the correlation coefficients according to the following.

- The polarization of the elements (vertical/horizontal): the polarization analysis of [20] has shown that the two polarizations have different propagation characteristics. Moreover, it is reasonable to correlate channel transfer gains where all the antennas have the same polarization in order to study the benefit of the spatial separation of the elements. Given the finite element separation in the fixed layout of the measurement array, we cannot compute the joint advantage of spatial and polarization decorrelation as in [15].
- The end of the communications link (transmitting/receiving): in any pair-wise correlation it makes sense to keep one end the same, i.e., calculate the correlation of the channel gains to two different receivers from the same transmitter (receiver correlation) or of the channel gains from two different transmitters to the same receiver (transmitter correlation).
- The separation of the elements (vertical/horizontal): in our study, the quantity of interest is the correlation as a function of the antenna separation d. Given the layout of our antenna arrays, the separation of the elements is along the horizontal direction or along the vertical direction, and is equal to 1λ.

Depending on the desired correlation value, we define the subset of all transmitter–receiver pairs that satisfy the polarization, communication end, and separation specifications. We calculate the correlation of each pair in this subset, and we average over the subset.

C. *Spatial Sample Selection*

In order to calculate the correlation between two random variables u and v, several independent measurements of the two variables are needed.

For every measurement at a given location, with a given antenna orientation, several bursts were recorded. However, the variation of the channel transfer matrix over these bursts illustrates the small-scale temporal variation of the channel and is very small. We cannot treat these temporal samples bursts as independent samples of the channel characteristics. Instead, we regard the average over the bursts as a single sample of the random variable.

The spatial samples of the random process correspond to different measurement locations, i.e., measurements at the points on the grids, as described in Section III-C. The measurement points were separated by one wavelength ($\approx$ 0.5 ft), which should, in the presence of rich scattering, guarantee the independence of the spatial samples [23]. In the laboratory environment, there is indeed lots of scattering, so the assumption of independent samples holds. The same is not true for the hallway environment. In the hallway, the angular spread is limited and the propagation is dominated by a deterministic effect (waveguide propagation). So although we perform the calculation for both environments, the hallway samples are more correlated and we have limited statistics.

Another provision that was taken in the laboratory environment to guarantee the independence of the samples was the relative orientation of the grids and the antenna gain pattern. The antenna gain pattern is a semicircle

$$G = \begin{cases} \text{constant}, & 0 < \varphi < \frac{\pi}{2} \\ 0, & \frac{\pi}{2} < \varphi < \frac{3\pi}{2} \\ \text{constant}, & \frac{3\pi}{2} < \varphi < 2\pi. \end{cases}$$

So a given displacement in the $\pi/2$–$3\pi/2$ direction gives fewer independent samples than the same displacement in the 0-π direction.

V. Capacity Results

Figs. 4 and 5 show the capacity for two symmetrical single polarization subsystems in the hallway and in the labs. The horizontal polarization subsystem contained the elements H1 through H6, and the vertical polarization subsystem contained the elements V1 through V6, on both the transmitting and the receiving sides.

The capacities have been calculated for a reference signal to noise ratio of 20 dB. This power normalization accounts for the power loss observed in the real measurements and isolates the effect of channel change with distance.

As a measure of comparison, we have plotted the median capacity of a 6×6 channel, where all the entries of the channel transfer matrix are independent and identically distributed complex Gaussian random variables. Neither subsystem achieves the capacity of a Gaussian channel.

The systems achieve higher capacities in the labs for all antenna orientations. Indeed the power analysis in [9] illustrated that power in the labs is uniformly distributed in angle of arrival, and that the furniture/equipment creates rich local scattering. However, the channel capacity falls off with distance, which indicates that the channel gains become more correlated for both the hallway and the labs. The same effect is observed for both polarizations. The thick vertical dashed lines in Figs. 4 and 5 indicate the distances where small-scale measurements were taken.

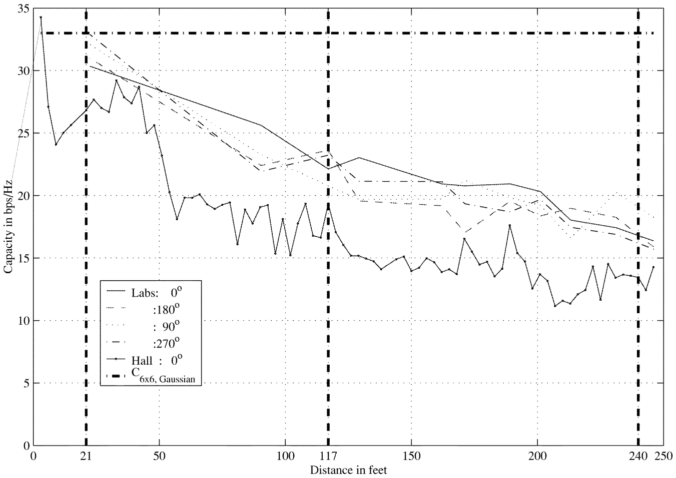

Fig. 4. Horizontal polarization subsystem.

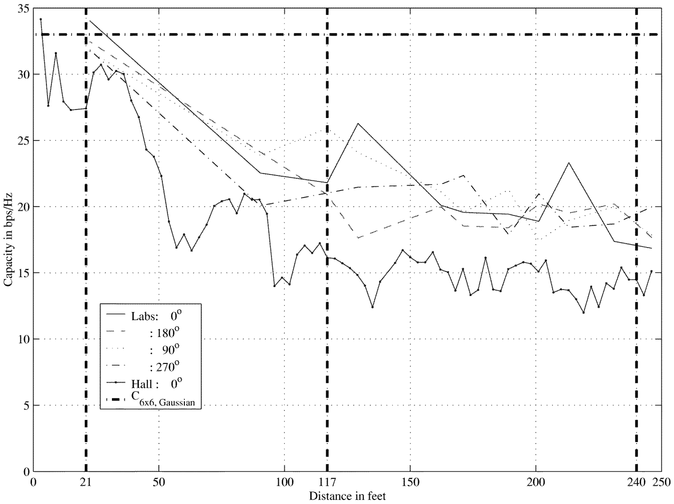

Fig. 5. Vertical polarization subsystem.

VI. Correlation Results

We compare the signal correlation for transmitters and receivers of the same polarization, but for spatially separated elements. Therefore, we study only the benefit due to spatial decorrelation under LOS versus nonline-of-sight (NLOS) conditions. We present the results in terms of the absolute value of the complex correlation.

A. *Transmitter Correlation*

We first look at transmitter correlation. Figs. 6 and 7 show the transmitter correlation for vertical and horizontal element separations assuming that the antennas at both ends have the same polarizations.

As expected, the transmitter correlation increases as the distance between the transmitter and the receiver arrays increases.

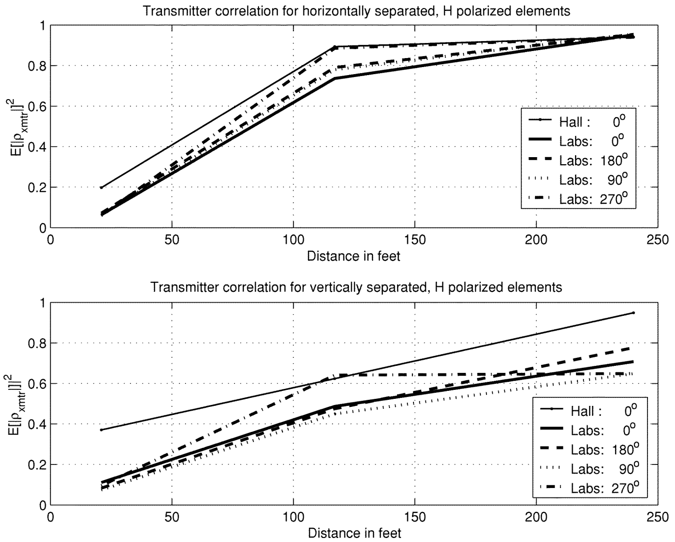

Fig. 6. Transmitter correlation for horizontally polarized elements.

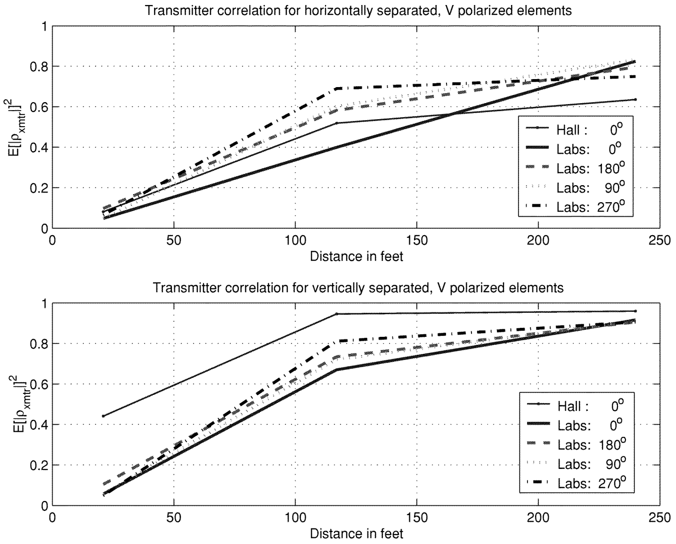

Fig. 7. Transmitter correlation for vertically polarized elements.

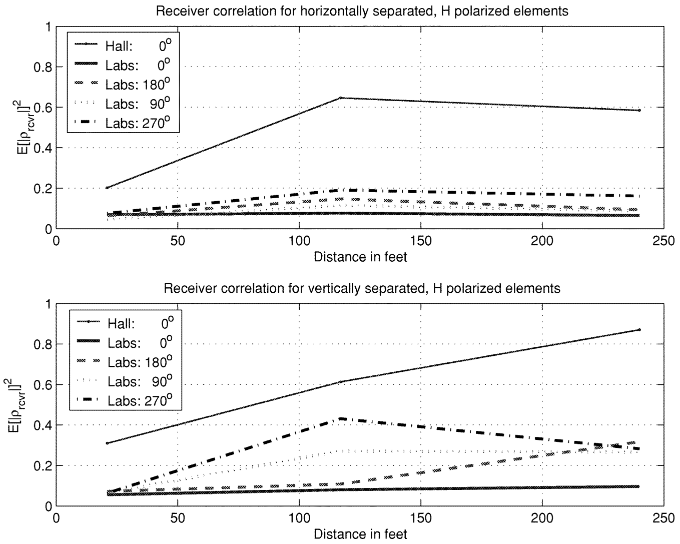

Fig. 8. Receiver correlation for horizontally polarized elements.

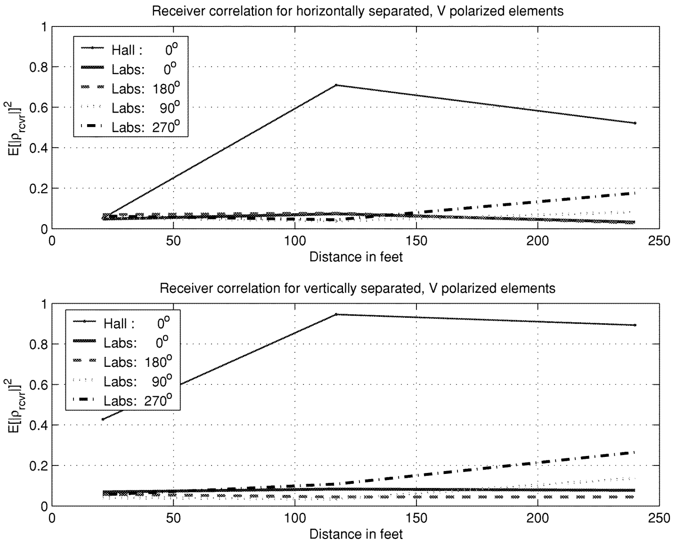

Fig. 9. Receiver correlation for vertically polarized elements.

Indeed at large distances it approaches unity in absolute value. Typically, the transmitter correlation is higher in the hallway than in the labs.

At small distances in the hallway, the phase differences between the different paths are significant and lower the transmitter correlation.

At larger distances in the hallway, the dominant signal component is the direct LOS component. Energy arriving from directions off the LOS has been multiply reflected off the hallway walls and has suffered serious attenuation relative to the LOS signal. Therefore, the angular spread is limited and the correlation for a given separation increases. Indeed the most drastic changes occur going from 21 to 117 ft. This indicates that by 117 ft the LOS component is the dominant mode of propagation.

Energy reaches the receivers in the labs by: 1) propagating down the hallway and into the labs or 2) propagating through the building walls. Obviously, the attenuation of the rays propagating through the walls is proportional to the number of walls they have to cross and, therefore, at large distances their contribution is negligible. Propagation along the hallway and into the labs is then the common dominant propagation path, hence, the high transmitter correlation in the labs. Nonetheless, this result is consistent with the uniform angle of arrival observation: energy can get scattered locally by the clutter in the labs.

Similar effects are observed for both the vertical and the horizontal polarizations, as well as both the vertical and the horizontal element separation.

B. Receiver Correlation

We now look at the receiver correlation. The results are shown in Figs. 8 and 9.

Receiver correlation is lower than transmitter correlation independently of antenna orientation polarization separation. The existence of local scatterers around the receivers accounts for the low correlation at all distances.

The antenna separation does not have a significant effect on receiver correlation and both polarizations behave in similar ways.

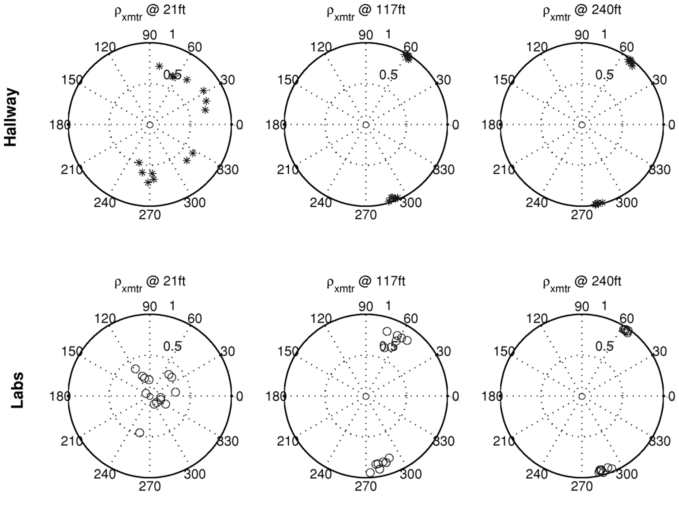

Fig. 10. Distribution of the transmitter complex correlation coefficient.

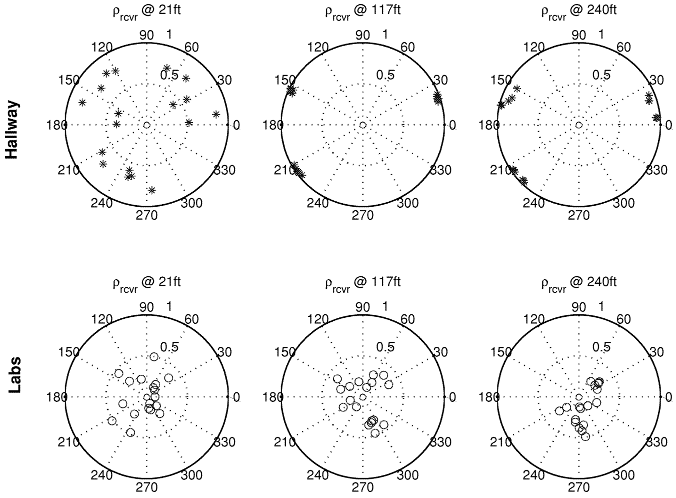

Fig. 11. Distribution of the receiver complex correlation coefficient.

C. Distribution of the Complex Correlation

Figs. 6–9 show the mean of the absolute value of the complex correlation coefficient that has been calculated for the transmit receive pairs. For each one of these instantiations (5) and (6) approximately hold. Figs. 10 and 11 show how the complex correlation coefficient is distributed in terms of both amplitude and phase. For simplicity, the results are presented only for vertically separated, vertically polarized elements, and only for the 0° orientation in the labs, but similar behavior is observed for the horizontal polarization, horizontal separation, and for all other receiver orientations.

We observe in Fig. 10 that at short distances, the complex correlation coefficients are low in amplitude and uniformly distributed in phase. As the distance from the transmitter increases, the amplitude is approximately constant for all the correlation instances, but a clustering effect is observed in angle in the transmitter correlation. Indeed each cluster corresponds to a pair of transmitters, whereas the different points within a cluster are the correlation coefficients as observed by different receivers. This can be explained as follows: the deterministic nature of propagation down a hallway (waveguide effect) introduces a constant phase term that relates to 1) the location of the transmitters in the cross section of the hallway, and 2) the distance from the transmitter array along the hallway. This in turn causes the clustering effect in the phase of the complex correlation coefficient.

As seen in Fig. 11, due to the symmetry of the structure, a similar clustering effect is observed for the receiver correlation in the hallway. However, the local area scattering from the clutter in the labs randomizes the phase of the signal and removes the clustering effect, hence, the uniformly distributed in angle and low in amplitude receiver correlation in the labs.

VII. CONCLUSION

In this paper, we presented the signal correlation results that were derived from measurements taken with a MIMO system under strong and weak LOS conditions in an indoor environment. The capacity analysis showed that capacity decreases as the distance from the transmitter increases. The correlation measurements showed that the transmitter correlation increases as separation increases. This result is intuitive under LOS conditions. In the NLOS situation, the existence of a single dominant propagation path accounts for the lower capacity. The receiver correlation is lower than the transmitter correlation in both the hallway and the labs, because the local scattering is richer around the receivers. The degree to which similar behavior would be observed in different indoor scenarios depends on the environment similarity in terms of building layout and construction materials. However, the conclusions drawn from this study describe intuitively expected phenomena and provide useful guidelines for the potential deployment of MIMO systems.

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Persefoni Kyritsi (S'98–M'02) received the B.S. degree in electrical engineering from the National Technical University of Athens, Athens, Greece, in 1996, and the M.S. and Ph.D. degrees in electrical engineering from Stanford University, Stanford, CA, in 1998 and 2002, respectively.

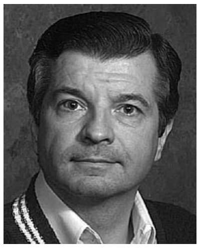
She has worked in several aspects of wireless communications for Lucent Technologies Bell Labs, in wireline communications for Deutsche Telekom, Frankfurt, Germany, and in circuit design for Intel Corporation and the Nokia Research Center, Helsinki, Finland. She currently holds the position of Assistant Professor at the Center for PersonKommunikation, Aalborg University, Aalborg, Denmark. Her research interests include radio channel measurements, channel modeling, multiple antenna systems, radio propagation, and information theory for multiple input-multiple output systems.

Dr. Kyritsi is a Member of Sigma Xi.

Donald C. Cox (S'58–M'61–SM'72–F'79) received his B.S. and M.S. degrees in electrical engineering from the University of Nebraska, Lincoln, NE, in 1959 and 1960, respectively, and the Ph.D. degree in electrical engineering from Stanford University, Stanford, CA, in 1968.

From 1960 to 1963, he worked on microwave communications systems design at Wright-Patterson AFB, OH. From 1963 to 1968, he was at Stanford University working on tunnel diode amplifier design and research in microwave propagation in the troposphere. From 1968 to 1973, his research at Bell Laboratories, Holmdel, NJ, in radio propagation and on high-capacity radio systems provided important input to early cellular mobile radio system development and is continuing to contribute to the evolution of digital cellular radio, wireless personal communication systems, and cordless telephones. From 1973 to 1983, he was Supervisor of a group at Bell Laboratories, that performed innovative propagation and system research for millimeter-wave satellite communications. In 1978, he pioneered radio system and propagation research for low-power wireless personal communications systems. At Bell Laboratories, in 1983, he organized and became Head of the Radio and Satellite Systems Research Department that became a Division in Bell Communications Research (Bellcore) with the breakup of the Bell System on January 1, 1984. He was Division Manager of the Radio Research Division until it again became a department in 1991. He continued as Executive Director of the Radio Research Department, where he led research on all aspects of low-power wireless personal communications. He was instrumental in evolving the extensive research results into specifications that became the U.S. standard for the Wireless or Personal Access Communications System (WACS or PACS). In September 1993, he became a Professor of Electrical Engineering and Director of the Center for Telecommunications, Stanford University, where he continues to pursue research and teaching of wireless mobile and personal communications. He was appointed Harald Trap Friis Professor of Engineering in 1994. He is the author or coauthor of many papers and conference presentations, including many invited and several keynote addresses and books. He has been granted 15 patents.

Dr. Cox received an Honorary Doctor of Science from the University of Nebraska in 1983. He was a Member of the Administrative Committee of the IEEE Antennas and Propagation Society (1986–1988), an Associate Editor of the IEEE Transactions on Antennas and Propagation (1983–1986). He is a Member of the National Academy of Engineering, is a Member of Commissions B, C, and F of USNC/URSI, and was a Member of the URSI Intercommission Group on Time Domain Waveform Measurements (1982–1984). He was awarded the IEEE 1983 Alexander Graham Bell Medal "For pioneering and leadership in personal portable communications" and was a corecipient of the 1983 International Marconi Prize in Electromagnetic Wave Propagation (Italy). He also received the IEEE 1985 Morris E. Leeds Award, the 1983 IEEE Vehicular Society Paper of the Year Award, the 1990 Communications Magazine Prize Paper Award, the Bellcore Fellow Award in 1991, the IEEE Communications Society L.G. Abraham Prize Paper Award in 1992, and the IEEE Third Millennium Medal in 2000. He is a Fellow of AAAS and the Radio Club of America. He is a Member of Sigma Xi, Sigma Tau, Eta Kappa Nu and Phi Mu Epsilon, and is a Registered Professional Engineer in Ohio and Nebraska.



Reinaldo A. Valenzuela (M'85–SM'89–F'99) received the B.S. degree from the University of Chile, Santiago, and the Ph.D. degree from the Imperial College of Science and Technology, University of London, London, U.K.

His doctoral work introduced novel digital filters for transmultiplexers. At Bell Laboratories, Holmdel, NJ, he studied indoor microwave propagation and modeling, packet reservation multiple access for wireless systems and optical wavelength division multiplexing (WDM) networks. He was Manager of the Voice Research Department, Motorola Codex, Boston, MA, where he was involved in the implementation of integrated voice and packet data systems. On returning to Bell Laboratories, he led a multidisciplinary team to create a software tool for wireless system engineering (WiSE), now in widespread use in Lucent Technologies. He is now Head of the Wireless Communications Research Department, Lucent Technologies, Bell Labs Innovations, Holmdel, NJ. He is interested in microwave propagation measurements and models, third-generation wireless systems, and achieving high capacities employing transmit and receive antenna arrays. He has published over 80 papers and has 12 patents.

Dr. Valenzuela is the Editor for the IEEE Transactions on Communications and the IEEE Transactions on Wireless Communications. He received the Distinguished Member of Technical Staff Award from Lucent Technologies, Bell Labs Innovations.

Peter W. Wolniansky received the B.S.E.E. and M.S.E.E. degrees from Boston University, Boston, MA, in 1983 and 1986, respectively.

He performed system tests on the HAWK missile system for Raytheon Corporation, Bedford, MA, from 1983 to 1984 and studied optical data storage for Sony Corporation, Tokyo, Japan, from 1986 to 1987. Since 1988, he has been with Lucent Technologies, Bell Labs Innovations, Holmdel, NJ, as a Member of Technical Staff. His duties have included system engineering of modem networks, millimeter radio design, and propagation studies. His recent activities include multichannel radio design and field studies using antenna arrays.