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Research Article

Investigations in Satellite MIMO Channel Modeling: Accent on Polarization

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Due to the much different environment in satellite and terrestrial links, possibilities in and design of MIMO systems are rather different as well. After pointing out these differences and problems arising from them, two MIMO designs are shown rather well adapted to satellite link characteristics. Cooperative diversity seems to be applicable; its concept is briefly presented without a detailed discussion, leaving solving particular satellite problems to later work. On the other hand, a detailed discussion of polarization time-coded diversity (PTC) is given. A physical-statistical model for dual-polarized satellite links is presented together with measuring results validating the model. The concept of 3D polarization is presented as well as briefly describing compact 3D-polarized antennas known from the literature and applicable in satellite links. A synthetic satellite-to-indoor link is constructed and its electromagnetic behavior is simulated via the FDTD (finite-difference time-domain) method. Previous result of the authors states that in 3D-PTC situations, MIMO capacity can be about two times higher than SIMO (single-input multiple-output) capacity while a diversity gain of nearly 2×3 is further verified via extensive FDTD computer simulation.

1. INTRODUCTION

It is more or less a commonplace statement that in the wireless technology of recent years, systems applying multiple-transmit and multiple-receive antennas (MIMO, multiple-input multiple-output) have become one of the few methods of real innovation. Space-time processing, in particular space-time coding (STC) techniques as applied to MIMO systems in a multipath environment, results in significant improvement both in transmission capacity and reliability. It turns out that there are significant differences between terrestrial and satellite multipath channels; these result in significant differences in MIMO applications as well. In this paper, we deal with some special problems raised by special characteristics of satellite links.

In terrestrial applications of MIMO, the basic method to diversify channels is with the additional *dimension* of *space*, that is, antennas are displaced spatially from each other, resulting in space-time processing. In addition, multipath channels and relevant fading characteristics—Rayleigh, Rice, Suzuki, and so forth—are assumed. A similar situation is present in satellite-to-mobile or satellite-to-indoor links. Among others, in [1] it is experimentally verified that the LEO satellite-to-indoor channel has nearly exactly Rayleigh character at any fixed indoor spot. More precise models are available (Loo, Corrazza, etc.) well describing the multipath behavior and not differing much from the terrestrial case. Consequently, similar-to-terrestrial results can be foreseen in satellite links of appropriate design. However, due to the very huge length of the radio path, transmit and/or receive antennas must be placed at significant distances from each other in order to ensure that the various paths are really *diverse*. To achieve this in principle generalization of *satellite diversity* and *site diversity* would be candidates in forming MIMO channels. (Note that in satellite diversity, there are two or more satellites transmitting/receiving the same signal; in site diversity there are two or more Earth stations.) These would make original space time processing possible: both ground and satellite terminals are in this case remote from each other and so are their antennas. Of course the original concept of site diversity can be excluded in the present—mostly hand-held mobile/indoor—situations.

In one class of cases, the ground terminals are located onboard large objects, such as trains, ships, or aircrafts. Large-antenna distances are possible then, realizing diverse routes. Multipath, on the other hand, is nonexistent or very sparse. Difference of LOS route lengths must be in such a case at least $\lambda/16 \cdots \lambda/4$. Site diversity might be applicable then, if as a rough estimate, terminal antennas can be placed at a distance of $b = 35$ m from each other. (For that figure, an LEO satellite and 30 GHz carrier frequency were assumed; note that b is proportional to the square root of satellite distance × wavelength.)

Satellite diversity for space-time processing would fulfill the requirement of uncorrelated channels and so it would be applicable. There is a few papers dealing with this topic; for example, [2] gives a physical-statistical model for satellite-to-urban and satellite-to-highway channel and computes capacity of a 2×2 MIMO system. In [3], a satellite-diversity MIMO system and its system aspects are investigated. Further papers on satellite MIMO are, among others, [4, 5].

There exists, however, at least one problem not present in terrestrial systems, that is, that of synchronization. In terrestrial MIMO systems, both the group of transmit antennas and that of receive antennas are at distances from each other in the order of a wavelength. Consequently, the path lengths of the diversity routes are very closely identical, and thus signals arriving from the transmitter to the receiver are *synchronous*. This makes identification and decoding of the received signals rather easy. In the case of satellite diversity, the satellites serving as diversity terminals are very far from each other. Thus difference of path lengths and so delays between the satellites and the ground terminal can be very high and highly variable. (This variability is self-evidently existing in the case of LEO satellites but very likely also in the GEO case.) As a consequence, the arrival time of signals from two satellites (forming part of a single code word) can be shifted by tens or hundreds of symbol times relative to each other. Synchronization of the received signals is in this case rather complicated—both acquisition and tracking. Reference [2] or [3] or other satellite/MIMO papers known by the authors do not deal with this problem. General aspects of it are dealt with, for example, in [6–8], taking explicitly, however, short-range, that is, terrestrial situations only into account.

An alternative possible solution could be *cooperative satellite diversity* (CSD). In general, cooperative relaying systems have a source node (e.g., a terrestrial mobile terminal (TMT)) multicasting a message to a number of cooperative relays (satellites (SAT)), which in turn resend a processed version to the intended destination node (another TMT). The destination node combines the signal received from the relays, possibly also taking into account the source's original signal. Recently, it has been shown that cooperative diversity systems provide an effective way of improving spectral and power efficiencies of the wireless networks without the additional complexity of multiple antennas [7–11]. However, a study on CSD systems, where the relays are satellites, to the best of the authors' knowledge does not exist in the literature.

A third possible method is to apply *compact* antennas, in which case the synchronization problem is nonexistent. Compact antennas with low radiator spacing and dimensions as small as $\lambda/20$ or so are described, for example, in [12–14]. These antennas were mainly developed for application in handheld terminals, in which the available space is very limited. In the case of onboard antennas, the whole antenna need not be small, however, the radiator elements need to be colocated, that is, their ports need to be very close to each other. Note that polarization, and in many cases the 3D character of it, has a significant role in each of the known compact antennas.

In this paper, the concept of cooperative satellite diversity is briefly introduced, without, however, a detailed discussion; this is done in Section 2. Polarization diversity and the application of space-time coding concepts in polarization diversity are dealt with in Section 3. (In analogy to the name STC, we call that polarization time coding (PTC). Note that according to the authors' understanding, the term STC is used to distinguish a transmit-and-receive-space-diversity situation from a simple receive diversity. The same understanding is applied in this paper; so we will call our topic PTC even if particular coding problems are not at all dealt with but coded signals are assumed.) Section 3.1 deals with dual-polarized MIMO channels, stating a physical-statistical model, presenting measuring results and validating the model; in this discussion conventional dual-polarized antennas are applied. In Section 3.2, PTC antennas of 3-dimensional polarization are dealt with, introducing the concept of 3D polarization, presenting a few compact MIMO antennas and showing the essential difference between terrestrial and satellite links from the point of view of 3D PTC. In Section 4, electromagnetic simulation results are given; in these it is verified that application of the FDTD method is suitable to investigate MIMO channel characteristics of very complex environments; capacity as well as diversity behavior are presented; these verify (at least for the present example) the statements of Section 3.2 and of the authors' references [15, 16]. Conclusions are drawn in Section 5.

2. A FEW WORDS ON COOPERATIVE SATELLITE DIVERSITY

In general, cooperative relaying systems have a source node (e.g., TMT) multicasting a message to a number of cooperative relays (SAT), which in turn resend a processed version to the intended destination node (another TMT). The destination node combines the signal received from the relays, possibly also taking into account the source's original signal. An example of a CSD system with two satellite relays is shown in Figure 1.

The idea of merging cooperation with space-time coding resulted in the so-called *distributed or cooperative space-time coding* (CSTC). Compared to the conventional space-time coding with collocated antennas, CSTC can be implemented when transmitter and relays share their antennas to create a virtual transmit array.

A possible cooperation scenario is applied for the configuration of Figure 1, proposed in [9] as TMT1 communicates with SAT1 and SAT2 in a broadcasting mode during

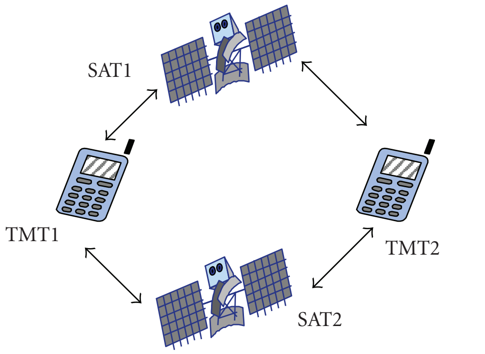

FIGURE 1: A virtual array: 2 satellites and 2 terminals.

the first signaling interval and there is no transmission from SAT1 or SAT2 to TMT2 within this time interval. In the second signaling interval, both SAT1 and SAT2 communicate with TMT2. This scenario assumes perfect knowledge of the channel fading coefficients at the receiver side of TMT2 and synchronization as an a priori condition. However, the delays due to distance between SAT1 and SAT2 (and the different local oscillators at SAT1 and SAT2) make cooperative diversity asynchronous in nature.

Several methods have been proposed to apply CSTC, in the presence of asynchronity between relays (see [17, 18] and references therein). However, a theoretical analysis on the effect of the (high) asynchronity in *cooperative satellite* diversity systems does not exist in the literature. Such an analysis is out of the scope of the present paper and is left for further study.

3. POLARIZATION-TIME CODING IN SATELLITE COMMUNICATIONS

3.1. *Physical-statistical model for the dual polarized LMS MIMO channel*

In [19], a basic investigation of PTC was presented, using a simple theoretical MIMO channel model. It was assumed that in a multipath environment—of whatever polarization the transmit antenna(s) is (are)—the received signal is of completely random polarization, that is, any state of polarization is equally likely. With a simulation study, we did show that applying normal dual-polarized antennas at both terminals and transmitting Alamouti-type coded signals [20], there is a 2×1 or 2×2 diversity effect if polarization of the received signals is fully correlated or completely uncorrelated, respectively. Incidentally, polarization characteristics are described there via Stokes parameters and related concepts. In order to assess the benefits of MIMO techniques applied to mobile satellite links, real channel data or accurate channel models are required. In this section, a physical-statistical 2×2 dual-polarized MIMO channel model is presented.

3.1.1. *Channel model construction*

The following dual-polarized physical-statistical LMS MIMO channel model is an extension to the multiple-satellite LMS MIMO model presented in [2]. In the present paper, a single satellite containing right-(RHCP) and left-hand circular polarization (LHCP) antennas communicates with a mobile vehicle, also containing RHCP and LHCP antennas. Note that taking into account the spherical symmetry of polarization states on the Poincaré sphere, actual choice of two orthogonal polarizations does not have too much significance [21].

Channel model construction is described in [2]. Additional insertion of polarization properties is achieved as follows. When the LOS path is unobstructed (clear), simple path loss is applied to the copolar channels and cross-polar channels are discarded. When the LOS path is blocked by a building (blocked), rooftop diffraction is applied to both the co- and cross-polar channels; the cross-polar component is scaled below the copolar component as observed from measured data. When the LOS path is shadowed by vegetation (tree), attenuation is applied to this path based on the distance traversed through the tree and using a typical attenuation factor of -1.3 dB per meter [22]. Similarly, the cross-polar component is scaled below the copolar component.

It is assumed in this model that the LOS paths are fully correlated between co- and cross-polar channels, and that the diffuse multipath components are fully uncorrelated between co- and cross-polar channels. This simplification is representative of many, but not all, real practical channels; a full presentation of measured satellite MIMO channel correlation is provided in [23].

The high-resolution time-series data $\alpha_{M,N}$ between each satellite antenna M and each mobile antenna N can be defined as follows:

$$\alpha_{M,N}=\begin{cases} P_{M,N}e^{jkd_{M,N}} \\ \quad +b\sum_{i=1}^{n}T_i\Gamma_iP_{M,N,i}e^{jkd_{M,N,i}} & \text{clear co-polar} \\ b\sum_{i=1}^{n}T_i\Gamma_iP_{M,N,i}e^{jkd_{M,N,i}} & \text{clear cross-polar} \\ D_{M,N}P_{M,N}e^{jkd_{M,N}} \\ \quad +b\sum_{i=1}^{n}T_i\Gamma_iP_{M,N,i}e^{jkd_{M,N,i}} & \text{block co-polar} \\ S_bD_{M,N}P_{M,N}e^{jkd_{M,N}} \\ \quad +b\sum_{i=1}^{n}T_i\Gamma_iP_{M,N,i}e^{jkd_{M,N,i}} & \text{block cross-polar} \\ T_{M,N}P_{M,N}e^{jkd_{M,N}} \\ \quad +b\sum_{i=1}^{n}T_i\Gamma_iP_{M,N,i}e^{jkd_{M,N,i}} & \text{tree co-polar} \\ S_tT_{M,N}P_{M,N}e^{jkd_{M,N}} \\ \quad +b\sum_{i=1}^{n}T_i\Gamma_iP_{M,N,i}e^{jkd_{M,N,i}} & \text{tree cross-polar} \end{cases} \quad (1)$$

where $P_{M,N}$ is the LOS path loss between satellite antenna M and moving mobile antenna N, k is the wavenumber, n is the total number of valid scatterers, T_i is the tree attenuation applied to a reflected contribution from scatterer i, Γ_i is the complex reflection coefficient at scatterer i, $P_{M,N,i}$ is the path loss from satellite antenna M to moving mobile antenna N via scatterer i, $d_{M,N,i}$ is the distance between satellite antenna M and moving mobile antenna N via scatterer i, $D_{M,N}$ is the LOS diffraction loss, and $T_{M,N}$ is the LOS tree loss. The terms S_b and S_t account for the attenuation of the cross-polar terms for blocked and tree-shadowed conditions, respectively and are derived from measured data. The term b is a clutter factor parameter also derived from measurements in each environment.

3.1.2. Measurement campaign

Extensive measurements were carried out in Guildford, UK, where an artificial platform situated on a hilltop (acting as the satellite), containing directional RHCP and LHCP patch antennas, communicated with a mobile van fitted with omnidirectional RHCP and LHCP antennas. Further details of the experiment are given in [23, 24].

Two of the measured environments were modeled: (a) tree-lined road/highway, characterized by a high likelihood of dense tree matter at either side of the road with occasional clearings and occasional two-storey houses beyond the vegetation, and (b) urban, characterized by densely placed two-to-four-storey buildings and sporadic tree matter.

3.1.3. Model output and validation

The model was optimized by fitting its parameters to the measured data. The model is capable of producing statistically accurate wideband channel time-series data and first- and second-order statistics. In this paper, the first-order statistics of the model are presented showing their validation against measured data. Validation of second-order statistics, not relevant to the diversity gain analysis presented below, is a work to be published.

An example of the copolar model output high-resolution path loss time-series data is shown in Figure 2. Similar data were obtained between each mobile antenna and satellite, for both polarizations.

Data were collected using three samples per wavelength in the model and measurement campaign, ensuring a sampling frequency well over twice the maximum Doppler frequency.

The narrowband first-order modeled and measurement data are compared. Cumulative distribution functions of co- and cross-polar channels for highway and urban environments are shown in Figure 3. The 2×2 dual-polarized MIMO channel matrix data were also used to estimate the diversity gain from a 1 × 2 maximum ratio receive combining system, a 2 × 1 polarization time block code approach [20], and a 2 × 2 polarization time block code system. An example from the highway environment data is shown in Figure 4.

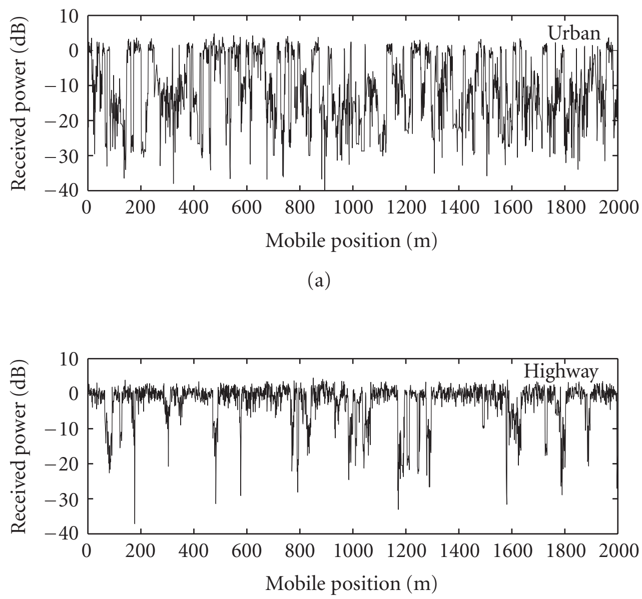

Figure 2: Example copolar time-series data of model.

3.1.4. A short concluding remark on this model

This model can be used to generate more statistically accurate channel data, which can be used to evaluate the performance of polarization time channel codes and algorithms, and therefore evaluate the capacity and diversity benefits of MIMO techniques applied to LMS systems. However, it models usual double-polarized channels/systems only, resulting in at most 4-fold diversity gain and 2-fold increase in capacity. Taking the generalized 3-dimensional (3D) character of wave polarization state into account (and applying relevant antennas), diversity gain can be increased. In terrestrial applications, capacity can also be increased, however, as we did show in [15] and briefly discuss here as well, this is not the case in satellite links. 3D polarization and its application in PTC will be dealt with in what follows. Note that important practical issues, like possible loss of capacity due to polarization mismatch, and practical antenna configurations are beyond the scope of the present paper.

3.2. PTC with 3D polarization satellite antennas

3.2.1. The concept of 3D polarization

Polarization state is characteristic to an electromagnetic wave. Plane waves are TEM, that is, electric and magnetic field vectors are in the plane perpendicular to the direction of propagation. Thus, polarization is a 2-dimensional phenomenon and 2 orthogonal polarization states exist. 2D polarization state of a wave, polarization properties of an antenna, as well as functioning of conventional polarization diversity and conventional PTC can well be described by the classical Stokes parameters. (For details see, e.g., [19, 25] for

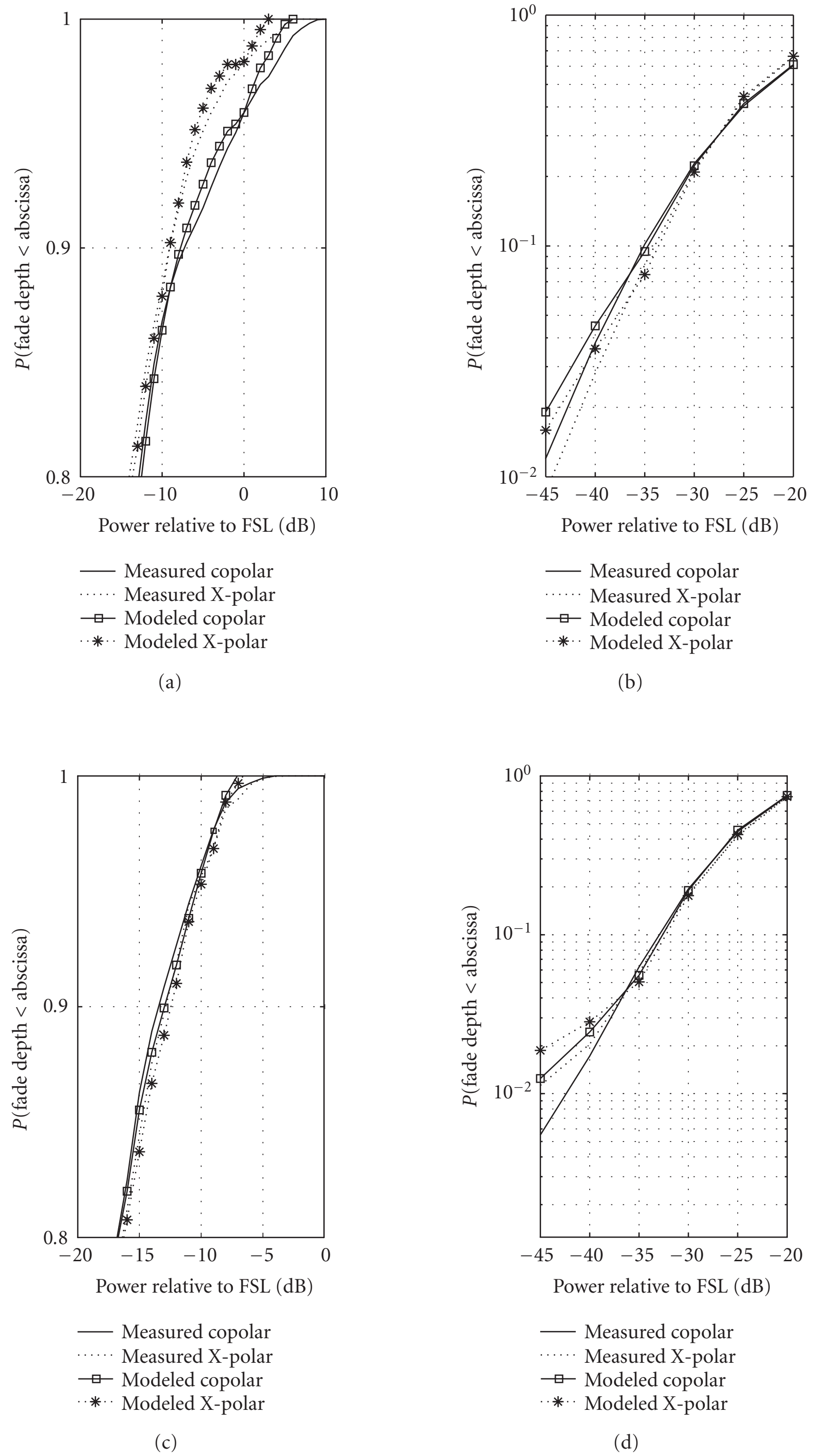

FIGURE 3: Comparison of modeled and measured cumulative distributions; upper figures: highway channel; lower figures: urban channel.

application. It is also mentioned that Stokes parameters form a 4-vector in a Minkowskian space; their transformation, e.g., by scatterers or polarization filters, is a Lorentz transformation [26]; these properties, however, are not used in this discussion.)

In the case of multipath propagation (or if the direction of propagation is unknown), wave polarization is a 3D phenomenon. In that case, the number of orthogonal polarization states is 3. This can increase the number of orthogonal channels to 3 if these are discriminated by polarization

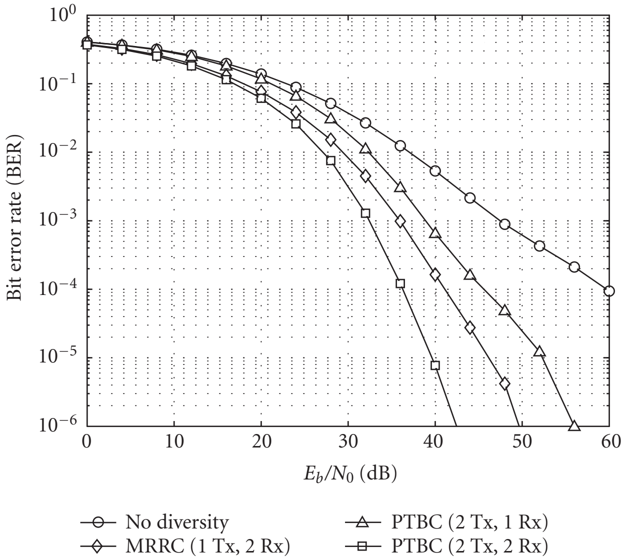

FIGURE 4: Bit error rate curves for highway environment.

only; as far as known by the authors, reference [27] was the first drawing the attention of the MIMO community to this fact. Combining antenna polarization and radiation pattern in discriminating channels, this number can be significantly higher, as this will be briefly discussed in the following subsection.

(Note that Stokes parameters together with their symmetry and invariance properties can be generalized to the 3D case as well [28]. It is not known by the authors, however, if these were ever applied in MIMO or communication antenna problems.)

3.2.2. *Compact MIMO antennas*

If the degree of asynchronism arising in multisatellite-to-ground links is too high so that synchronization or cooperative diversity is not possible or is too complicated, MIMO antennas have to be colocated onboard a single satellite. This situation is similar although not identical to handheld terminals. Like in that case, *space* is not an available dimension for diversifying multiple signals: polarization and antenna pattern are only available. It is different on the other hand as available space is not as much limited as in the case of handheld terminals; so the antennas can be large, and aperture or array antennas of sufficiently high gain can be applied. In recent times, there is a significant progress in the field of compact multielement antennas. We mention three new structures investigated in the literature.

Reference [12] deals with what is sometimes called a *vector element antenna*. This contains 6 rectangular placed Hertzian dipoles, 3 electric and 3 magnetic. Rectangular electric and rectangular magnetic dipoles as well as electrical dipoles parallel to magnetic are fully uncorrelated, while rectangular placed electric to magnetic dipoles are of zero or of very low correlation; the latter is due to different angular patterns. Thus in the case of very rich scattering environment, 6-fold receive diversity gain can be achieved or in principle even 6×6 diversity gain if both the transmitter and the receiver operate with vector element antennas. Increase in capacity, however, cannot be more than 4-fold, as shown by [29].

In [13], the so-called *MIMO cube* is dealt with. This contains 12 electric dipoles arranged at the edges of a cube. Cube-to-cube capacity and other parameters are computed, showing surprisingly good performance; note, however, that even very small cubes are investigated, (cube edges as short as 0.05λ) the problem of superdirectivity is not stressed in that paper.

In [14], behaviors of three colocated monopole and dipole antennas are investigated, versus their mutual angles, via simulation. It is shown that their performance is very close to ideally orthogonal ones and also that the main cause of achieving that is their different polarizations rather than different angular patterns.

3.2.3. *Compact antennas and 3D polarization in satellites*

There is a significant difference between the environment of a terrestrial multipath link and a satellite multipath link. In Figure 5, terrestrial multipath links for indoor or mobile communication are schematically shown. The system depicted in Figure 5(a) is of double-bounce scattering, whereas that of Figure 5(b) is of single bounce. "Compact antennas" are used in both terminals—as an example realized in the form of triple dipoles. It is self-evident from Figure 5(a) that waves are arriving to the receive antenna from multiple directions—resulting in three orthogonal polarization components. But the case is similar in situations like Figure 5(b); this is due to the relatively short distance—characteristic in terrestrial, in particular in indoor links.

A satellite-to-indoor/mobile link, shown in Figure 6, is much different, as in this case terminals are (i) very far from each other and (ii) scatterers are very far from one of these. Due to (i), antenna must be of high gain, shown in the figure as an aperture. And, due to (ii), TEM waves travel between the satellite and the neighborhood of the ground terminal. Propagation is multipath only in that—relatively short—distance. The aperture itself can be realized either as a dish or as an array. It could be illuminated by any 3D polarized wave, however, only the 2D component of that would travel towards the ground terminal.

Based on this fact, we have shown in [15] that in a satellite link relative to the single-channel case, only a 2-fold increase of capacity can be achieved by PTC. This is in contrast to the terrestrial case in which this increase is 4-fold. In more details, while any small multielement antenna *can* be applied in the ground terminal, onboard *one* satellite at most conventional double-polarized antennas are applicable, or more precisely, are reasonable. On the other hand, diversity can take the full advantage of the capabilities of multiple antennas if these are applied in the ground terminal. As a consequence of these, this type of channel is asymmetric: the downlink is a double-input multiple-output channel, the uplink is its inverse, that is, multiple-input double-output.

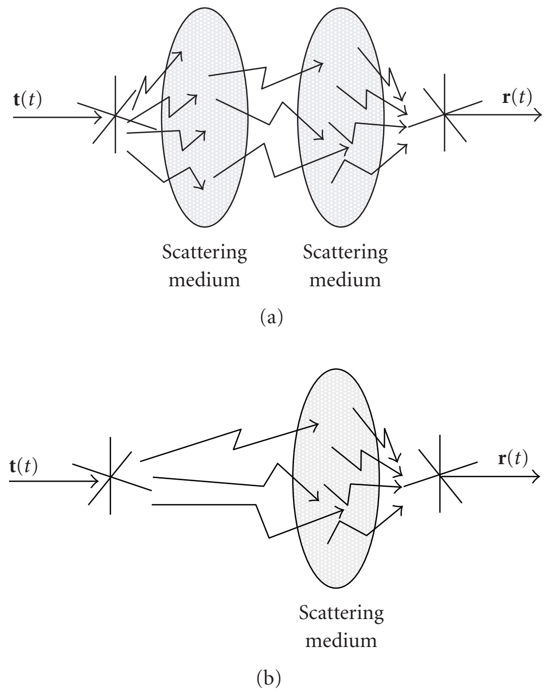

Figure 5: Terrestrial multipath links with compact MIMO antennas in scattering media; (a) double-bounce scattering; (b) single bounce.

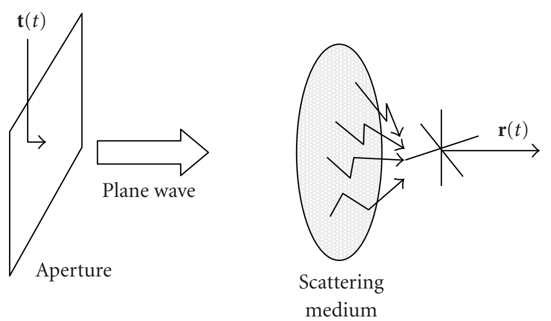

Figure 6: A satellite-to-mobile/indoor link.

This has the consequence that from the coding point of view, the system is not uniform. If as an example, space-time block coding of the Alamouti type or orthogonal space-time block coding (OSTBC) is chosen, $R_C = 1$ can be applied downlink, however in the uplink $R_C = 1/2$ or at most $R_C = 3/4$ can only be achieved. (R_C designates the coding rate.) It is questionable if this can be accepted from the frequency economy point of view. If not, only two of the three or more antennas are used in the uplink transmitter. Note that other types of coding can give different results.

On the other hand, the number of diversity routes is increased—say up to 2×3. (This is valid if terminal antenna is a tripole; with a vector element antenna, this is 2×6, with a MIMO cube even 2×12.)

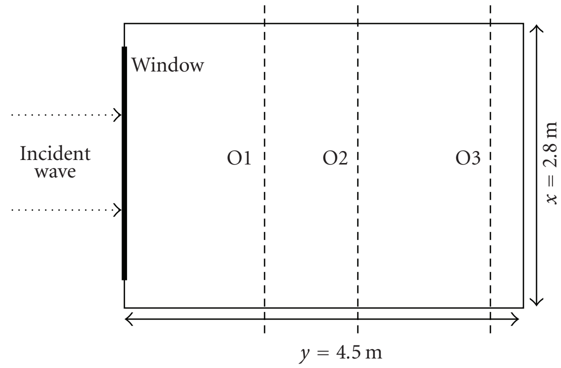

Figure 7: A satellite-to-mobile/indoor link.

In the next section, applying electromagnetic simulation we verify the capacity and the diversity characteristics as stated above.

4. FDTD SIMULATION OF A SATELLITE-TO-INDOOR LINK

In order to assess the performance of using three orthogonally polarized antennas in a satellite-to-indoor scenario, some simulations were performed using full-wave electromagnetic tools. The FDTD method [30] was used to calculate the time-dependent electromagnetic field inside a typical office room where the mobile terminal is assumed to be placed. The office dimensions were $2.8\,\text{m} \times 4.5\,\text{m} \times 3.0\,\text{m}$ (x, y, z), where the floor and the ceiling are lying in and parallel to the x-y plane, respectively, as seen in Figure 7. In the simulation, the furniture and the walls of the room are modeled by realistic material properties (brick walls, wooden and metallic furniture, and some plastic objects). These objects of various geometries are nearly uniformly distributed in the room. Linear orthogonally polarized plane waves enter the room through the window and through the external wall; one polarization during the first simulation run and the other one during a subsequent run. This method allows us to split the channel response according to the incoming polarizations. The waveform is a modulated Gaussian pulse centered at 1.2 GHz, entering through the x-z plane at $y = 0$ m.

The electric field components (E_x, E_y, and E_z) are recorded at various spots in the room. We use these field components directly to draw conclusions about the signals (voltages) which three antennas would produce if they would be placed at a given observation point. Although this approach does not consider the current distribution on electrically long antennas, mutual coupling, scattering by the antennas, and so forth, previous FDTD studies demonstrated that only a very low crosstalk exists between three thin-wire half-wave dipoles which are mounted parallel to the coordinate axes in an empty room [16]. Therefore, the results can be regarded as realistic, for short orthogonally mounted dipoles. The field components are recorded along various x-z cross-sections of the room, at three different observation planes (O1 at $y = 1.5$ m, O2 at $y = 2.4$ m, and O3 at $y = 4$ m), representing different propagation environments due to different shadowing and angle-of-incidence parameters. At each of the three planes, about 800 points were observed, spaced 7.5 cm apart in both x and z directions. In a first scenario (S1), the incident waves arrive horizontally (at 0 elevation and parallel to y-axis). In a second scenario (S2), the elevation was chosen to be 30 degrees and the azimuth angle 20 degrees off the y-axis. Thus, in the latter case, the line of sight is blocked at the points of O2 and O3. For each scenario, two simulation runs yielded 6 time functions of the fields (E_x, E_y, and E_z when using the one or the other polarization). From the observed fields, which were regarded as received voltages according to the reasoning presented above, signal portions weaker than a designated noise level, chosen to be −15 dB relative to the maximum power level, were discarded. Then the envelope of the received signals was calculated. Based on these data, three statistical parameters were derived for both Scenarios 1 and 2. First, the equal-power capacity [31, Equation (4)], was calculated and its CDF was determined. In Figures 8 and 11, the capacity CDF curves are shown for S1 and S2, respectively. As expected, at low outage, levels the capacity of the dual-polarized TX, dual-polarized RX antenna, (2, 2) and (2, 3) systems is about twice that of the (1, 1) SISO system, and the difference between the (2, 2) and the (2, 3) systems is rather small. In order to assess the diversity performance, the envelope correlation [32] was determined between the received signals (latter being the correlation coefficient between the envelopes of the received signals). Their CDFs are shown in Figures 9 and 12. As expected, in Scenario 2, lower (even negative) correlation is to be expected. Additionally, the relative received signal power for the (1, 1), (2, 2), and (2, 3) systems and their CDF was also determined, which results are shown in Figures 10 and 13 for the scenarios in consideration. Note that the confidence for very low-probability (less than 0.01 or so) portions of the curve might be low due to the relatively low number (about 2000) of observations, but still validates the claim based on the higher probability portion of the curves.

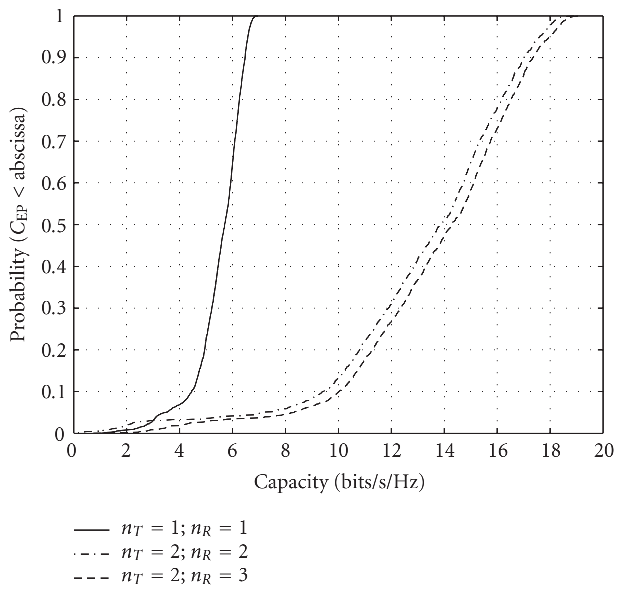

FIGURE 8: CDF of the equal-power capacity (Scenario 1).

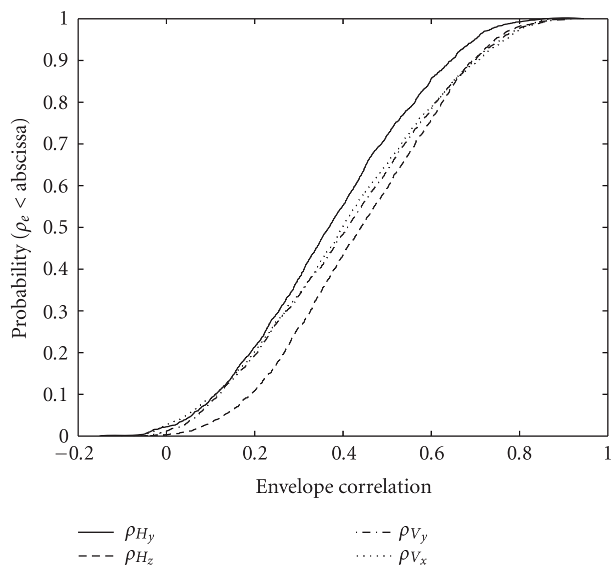

FIGURE 9: CDF of the envelope correlation (Scenario 1).

5. CONCLUSIONS

The main statement of this paper is that the generalized coded form of polarization diversity is a very good—maybe the best—way to apply the MIMO concept in multipath satellite links. Two main contributions are related to the modeling of the conventional (2D) polarization diversity channel and to the investigation via simulation of the 3D MIMO channel, respectively. (The relevant signal processing is called here PTC.)

Concerning the first of these (modeling), a physical statistical model is given for the urban and the highway satellite mobile channels. Besides giving a validated model, it verifies once again the authors' conviction that the best type of a multipath channel model is of the physical-statistical type.

Concerning the second of these (simulation), a very extensive simulation study is carried out about the 3D polarization characteristics of the satellite multipath channel. A synthetic satellite-to-indoor link is simulated and PTC characteristics are investigated. The main purpose of this study was to verify (for this example) the findings of two of these authors [15] about the capacity and diversity characteristics of this type of channels. Results of this simulation are as follows.

From the capacity point of view, (i) the difference between the 2 × 2 and the 2 × 3 cases is negligible (as stated in [15]); and (ii) with high probability capacity of the MIMO, the situation is nearly exactly 2-times as high as that of the SISO case, again in accordance with [15]. (Note that with low probability, this difference is higher.)

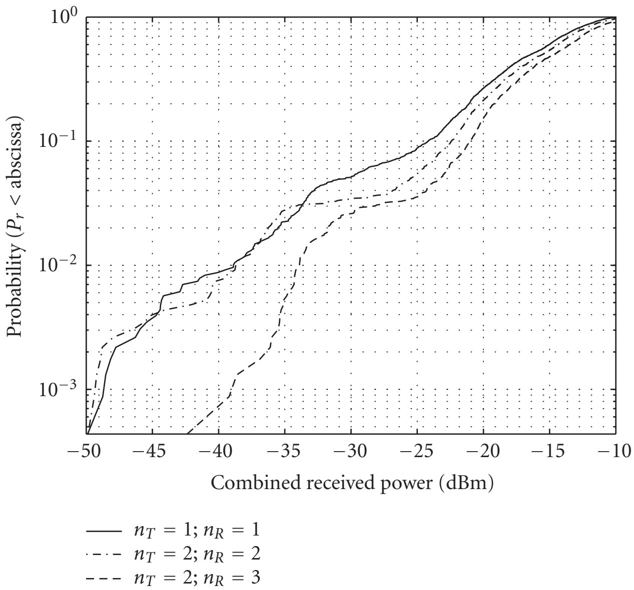

Figure 10: CDF of the received power (Scenario 1).

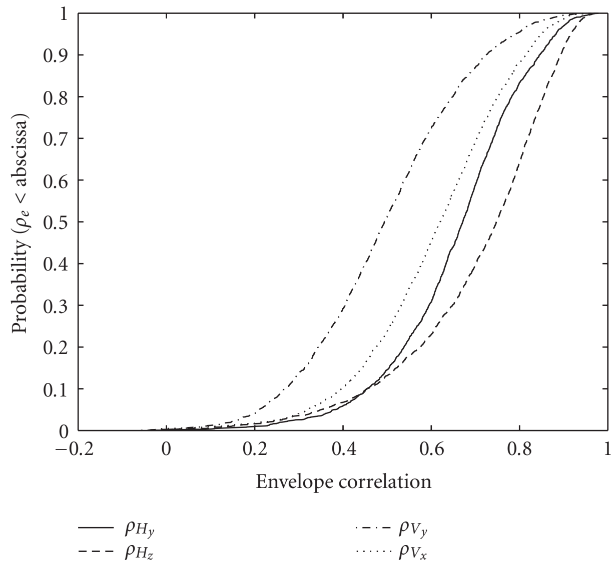

Figure 12: CDF of the envelope correlation (Scenario 2).

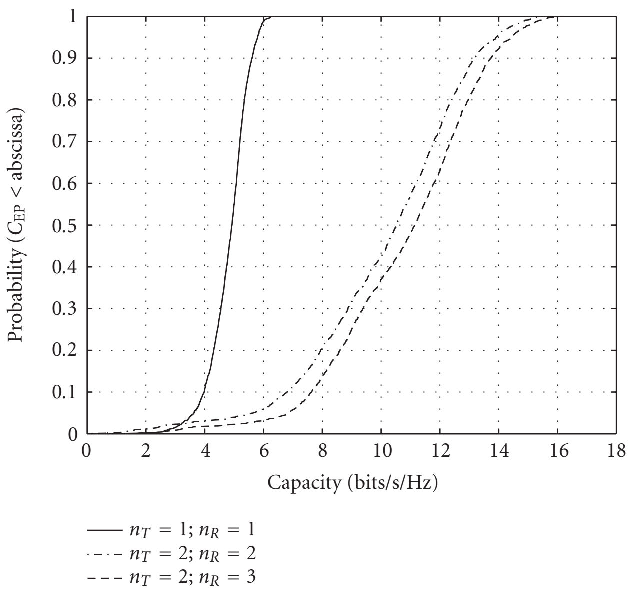

Figure 11: CDF of the equal-power capacity (Scenario 2).

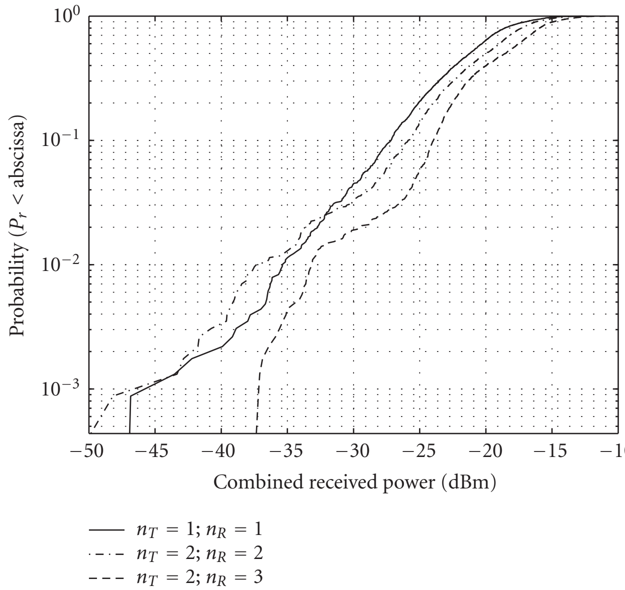

Figure 13: CDF of the received power (Scenario 2).

To characterize the diversity performance, CDF of the received power in the various situations is investigated; result shows that 3-fold (i.e., 3D) polarization diversity yields significantly higher received power than the 2-fold diversity (or the nondiversity case).

From the simulation point of view, this study shows that the FDTD method is very well applicable to investigate in an exact way such extremely complex structures as the one here. A statement of this paper (stated but not discussed in detail) talking about satellite-diversity-MIMO, the problems briefly dealt with in Section 3, that is, the effect of extremely large and variable difference between the path-lengths of MIMO branches must be taken into account.

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