Fast-Polarization-Hopping Transmission Diversity to Mitigate Prolonged Deep Fades in Indoor Wireless Communications

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Abstract

Fast-polarization-hopping (FPH) transmission diversity is herein proposed to mitigate prolonged deep fades at the mobile receiver in, for example, the indoor propagation environment. Even if the individual multipaths are each sufficiently strong for detection, deep fades may occur due to the multipath signals' destructive summation at the receiver. The relative immobility of the transmitter, the propagation environment, and the receiver in the indoor environment means that a deep fade may last for a very long duration, dropping calls or severing links. By rapidly hopping the transmission polarization (say, alternating transmission between a vertically-polarized-dipole antenna and a horizontally-polarized-dipole antenna — or between two “X”-oriented dipoles), the effective propagation channel experiences consecutive polarization modes (each involving a different multipath summation), all within the duration allowed by the channel-coder’s interleaving depth. This scheme is usable for either frequency-shift keying (with incoherent demodulation), or for channel-coded phase-shift keying (with differential coding, or with pilot-symbol phase synchronization). This scheme requires no change in the mobile receiver (which does not need to be dual polarized). The base station also needs no spatially separated antenna array, nor any other additional hardware, no mechanical movement of the transmitting antenna(s), and no sophisticated signal processing (such as channel estimation or closed-loop feedback) nor any additional software. The proposed scheme’s cost — relative to using antenna arrays at the base station and/or the mobile — is a potentially doubling of the transmission bandwidth. The proposed scheme’s potential is illustrated by limited computer simulations using CINDOOR, a polarization-sensitive indoor wireless-propagation ray-tracing simulation software package based on Geometrical Optics and the Uniform Theory of Diffraction (GO/UTD).

Keywords: Dipole antennas; dispersive channels; diversity methods; fading channels; frequency hop communication; frequency shift keying; indoor radio communication; microwave communication; mobile communication; radio communication equipment

1. Problem: Prolonged Deep Fades at the Indoor Wireless Receiver

Wireless communication receivers are often plagued by prolonged deep fades, which degrade and possibly drop communication between the transmitter and the intended receiver. As the transmitted electromagnetic wave undergoes multiple reflections and diffraction through a highly cluttered electromagnetic propagation environment, the transmitted signal reaches the receiver through diverse propagation paths. Deep fades may occur for either of two reasons. (1) These signals from multiple propagation paths (i.e., multipath signals; “multipath signals” are often called “multipaths” in communications slang) may all arrive with powers too weak for the receiver to detect. Each such multipath signal’s power depends on the polarization interaction among the transmitter, the scatterers in the propagation environment, and the receiving antenna. (2) The multipath signals cancel each other at the receiver, even if one or more of these multipath signals are individually strong enough for detection by the receiver. For indoor radio systems, the typical delay spread is of the order of several nanoseconds: very small compared to the typical information symbol’s duration, which is on the order of microseconds. Thus, the indoor radio channel is largely non-frequency-selective (i.e., frequency-flat), and the arriving multipath signals’ arrival delays are largely synchronized among themselves at the receiver. Whether these multipath signals sum constructively or destructively depends mostly on their relative phases and their respective polarizations. If the receiver happens to be immobile for many symbol periods, such deep fades may lead to a disconnection of the link between the transmitter and the receiver.
2. Earlier Transmitting/Receiving Diversity Solutions

One common remedial technique, often efficacious for an outdoor cellular base station, deploys multiple spatially separated [1] and/or diversely polarized antennas [2] at the receiver. Such “receiving-diversity” schemes’ motivation is that if destructive summation occurs at one reception spatial location or polarization, constructive summation may occur at another reception location and/or polarization. However, the bulky physical profile of such a multiple-antenna system would prove too awkward for use on mobile handsets. The complex signal-processing capability required by such a multiple-antenna system implies expensive circuitry, rendering the unit cost unrealistic for a handset, or for a peer-to-peer mobile transceiver. “Transmitting diversity,” implemented at the base station but not at the mobile transceiver, is often more economically efficient than the aforementioned “receiving diversity.”

“Transmitting time diversity” can mitigate non-frequency-selective Rayleigh deep fades by interleaving and error-correction encoding the to-be-transmitted information-symbol sequence. It has been shown [3, 4] that time diversity by itself may not suffice to significantly improve the error rate for a very slowly varying channel when the fade duration exceeds the interleaving depth, allowing the bit-error rate to possibly approach 0.5. When fade durations are shorter than the interleaving depth, the signal level will not fade over the entire interleaving depth; however, indoor deep fades often last much longer than the interleaving-depth delay considered tolerable in many telecommunication applications. For example, the handset user (which may well be an unattended sensor or a robot) can be motionless for many seconds, rendering interleaving-time diversity ineffective by itself for such an extremely slowly varying channel.

Yet another remedial “transmitting-diversity” technique uses multiple transmitting antennas to simultaneously send the same information signal from different locations [5, 6] and/or possibly with different polarizations [7]. A notable shortcoming of this “transmitting spatial diversity” technique is that the transmitting antennas need to be sufficiently separated from each other such that the corresponding signals at the receiver will be independent of each other. This transmitting spatial- and/or polarization-diversity technique thus suffers shortcomings similar to those of its receiving counterpart. Moreover, the effective propagation channel remains confined to one physical propagation channel, and the aforementioned destructive-summation problem remains. Analogously, cell-site diversity [8] connects each user simultaneously to two or more base stations, thereby adding robustness at the cost of reduced spectral efficiency plus additional hardware and software.

Still other recently proposed “transmitting-diversity” techniques [3, 9-14] attempt to produce fast-varying channel-fading effects in a physically slowly varying fading channel. This is done via deliberately induced phase and/or frequency variations at the transmitter: small but independent time-varying phase offsets or frequency offsets at several transmitting antennas (all transmitting the same information signal) cause the phase of each antenna’s transmitted signal to undergo a phase rotation independent of the other antenna’s transmitted signal. The phase pattern of the received signal will thus vary even if the physical channel itself remains time invariant and has zero Doppler spread. Such a deliberately induced time-varying multipath pattern at the receiver will result in a quick succession of constructive and possibly destructive summation of the multipath signals, thereby forestalling prolongation of any deep fade at the receiver. Such “space-frequency/space-phase transmitting diversity” techniques in fact constitute a variation of the frequency-hopping motif.

The system complexity of the various above-mentioned “receiving-diversity” and “transmitting-diversity” methods may be avoided by the proposed “fast-polarization-hopping transmitting-diversity” scheme, at the cost of increased transmission bandwidth. However, any of these other aforementioned methods may also be used in conjunction with the presently proposed scheme. Specifically, this fast-frequency-hopping strategy can be applied to the IEEE 802.15.1 standard for Bluetooth. This proposed strategy can also decorrelate the channels of a multiple-input multiple-output (MIMO) system, which is sensitive to cross correlation among its multiple channels [15].

3. Fast-Polarization-Hopping Transmitting Diversity

Complementary to the above mentioned “transmitting frequency/phase diversity” techniques, this work explores rapidly time-varying polarization diversity at the transmitter to produce at the receiver a multipath pattern that varies rapidly with time, relative to an information symbol’s duration (for FSK modulation, or for PSK modulated without symbol interleaving) or relative to the information-symbol stream’s interleaving depth. The transmitter consists of a suitably selected single antenna (for example, a circularly polarized antenna to transmit a right-circularly or left-circularly polarized electromagnetic wave) or a composite antenna (for example, a pair of diversely oriented, and perhaps collocated, electric dipoles and/or magnetic loops). This rapid and regular time variation of the transmitter’s polarization aims to manipulate the multipath profile (and thus the vector sum of the multipath signals’ amplitudes) at the receiver, so as to preclude any prolonged destructive summation at the receiver. Compared to other transmitting-diversity techniques, this proposed approach can result in physically more compact transmission antennas, can simplify electronic circuitry, and can lower hardware cost per unit. This polarization-hopping transmission scheme may be readily used with frequency hopping, say, by changing the circularly polarized transmitting antenna’s polarization or the current division between two transmitting dipoles, from frequency hop to frequency hop.

The pivotal idea here is the deliberate, rapid time variation of the multipath signals’ pattern at the receiver, not that diversely polarized multipath signals exist at the receiver. Cross-polarization and depolarization of the transmitted electromagnetic signal(s) would occur, regardless of the number and/or polarization of the antenna(s) used at transmitter and regardless of the radio wave’s particular frequency; this is because of the unavoidable multiple reflections, diffraction, and diffractions that the transmitted electromagnetic wave would undergo in the indoor telecommunication channel. This work’s pivotal recognition is that the multipath-signal pattern at the receiver can be made to change rapidly (relative to the information-symbol’s duration or relative to the information-symbol-stream’s temporal interleaving depth) to shorten the duration of any destructive summation of the multipath signals by rapid variation of the transmission polarization.

The exact pattern of the transmitted polarization’s temporal variation (beyond having a sufficiently high variation rate) is unimportant and does not need to be known to the receiver, thereby avoiding the need for extensive electronics to coordinate the precise frequency-phase patterns among various transmitting antennas.
and/or with the receiver, as required in many of the earlier-mentioned schemes in [3, 9-14]. No additional signal processing is required at the receiver, as the proposed receiver does not need to be synchronized to the polarization's time variation.

Because as few as one compact antenna (in the case of a circularly polarized antenna [16, 17]) or one composite antenna (in the case of collocated but diversely oriented dipoles and/or loops) is needed at either the transmitter or the receiver, easier and less obstructive antenna system deployment in the space-limited indoor or mobile outdoor environment can be achieved, compared to what would be possible with the earlier-mentioned methods.

The transmitted signal's carrier phase may be temporally discontinuous between hops, due to electromagnetic difficulties in phase synchronizing the antenna's transmission across different polarizations. This implies a need for either (1) a phase-independent modulation-detection scheme, such as frequency-shift keying, or (2) pilot symbols and/or phase-incoherent demodulation to phase synchronize each hop polarization's information-symbol stream. The former would require a higher polarization hop rate than would the latter, for the same information-symbol period.

4. CINDOOR: Software for Polarization-Sensitive Simulation of Indoor Channels

CINDOOR [18, 19] is a polarization-sensitive ray-tracing simulation software package for the indoor radio wave propagation environment (for more information about the CINDOOR software, please see http://www.grs.unican.es/cindoor/). CINDOOR implements three-dimensional Geometrical Optics and the Uniform Theory of Diffraction (GOUTD), combining "image theory" with the "binary space partitioning" algorithm. CINDOOR has been verified in [18-20] to closely approximate empirical fading measurements, including those where cross polarization exists [20].

CINDOOR allows its user to design the floor plan, to add furniture, and to specify the electromagnetic properties (e.g., the relative dielectric constant, the conductivity, and the transmission loss). The user may also define the transmitting and the receiving antennas spatial locations, orientations, polarizations, and electromagnetic gain patterns. CINDOOR produces each received multipath signal's amplitude, propagation delay, polarization, and other propagation history (e.g., the number of reflections and diffractions). CINDOOR also allows the entire floor area to be subdivided into small spatial pixels. In the center of each pixel and at a user-specified height, the multipath signals' vector-sum power (i.e., summed accounting for the multipath signals' complex phases) or the root-sum-square power may be computed.

5. The Proposed Fast-Polarization-Hopping Enhancement of the Vector-Summed Power

The proposed "fast-polarization-hopping transmitting-diversity" scheme's potentials are illustrated below via limited simulations using the CINDOOR ray-tracing software. The authors are preparing an experimental setup to demonstrate this proposed scheme.

Figure 1 shows the particular floor plan under investigation. The entire floor area was 7.07 m wide and 8.52 m long, encompassing ten small personal offices along two corridors. A wooden desk, 0.75 m high, was inside each personal office. The ceiling and the walls were all 3 m high. Four metal cabinets, all 1.5 m high, were located near but below the transmitter. CINDOOR's default values for the electrical properties for walls, wood, and metal were used and are listed in Table 1.

The symbol "T" (two pixels from the upper-left corner of the caption box) on the floor plan was the location of the transmitter, affixed to the ceiling at 3 m above the floor. This transmitter consisted of two collocated half-wavelength-dipole antennas in an "X" vertical orientation: i.e., one antenna at 45° and the other at −45° from the vertical. This "X" orientation was used (as in most polarization-diversity schemes) instead of the "+" orientation to

![Image](https://example.com/image.png)

Figure 1. The indoor floor plan, and associated improvements in coherently summed received power of the +45° transmission polarization over the −45° transmission polarization, and vice versa.

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative Dielectric Constant</th>
<th>Electrical Conductivity (mhos/m)</th>
<th>Transmission Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall</td>
<td>15.0</td>
<td>7.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Wood</td>
<td>3.5</td>
<td>8.5×10⁻³</td>
<td>1.5</td>
</tr>
<tr>
<td>Metal</td>
<td>1</td>
<td>10⁰</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Table 1. Electromagnetic constants used in the CINDOOR simulations.

better conform the dipoles' radiation pattern to the ideal isotropic pattern on the horizontal plane. The "+z" orientation involved one horizontally oriented dipole and one vertically oriented dipole, collocated in space. The "X" orientation was used here also because horizontally polarized electromagnetic waves often experience greater amplitude attenuation than vertically polarized electromagnetic waves; the "+z" orientation would thus have offered less polarization diversity. The "X" dipole-pair ("X" with respect to the elevation angle) had a -45° azimuth angle from the x-axis (i.e., the horizontal axis in Figure 1, pointing to the right). The time-invariant diversity gain obtained from this "X"-oriented dipole pair or from alternative diversely polarized antennas were investigated in detail in [21]. Mutual coupling was assumed to be absent between these two orthogonal dipoles and with their immediate surroundings (e.g., the antenna's physical support). Each antenna alternately transmitted half the time, e.g., half of each information symbol's duration if there was no temporal interleaving, or half the inter-leaving depth. The radio wave's carrier frequency was set at 2100 MHz.

The mobile receiver's antenna, the location of which is represented by an "R" on the floor plan, was also a half-wavelength-dipole antenna, but with an azimuth angle of 90° from the x-axis. It was at a vertical distance of 1.5 m from the floor. To mimic a common body posture of the handset user, this receiving antenna made a 60° elevation angle from the positive vertical coordinate. All subsequent numerical data and simulations had the receiver at this height, elevation angle, and azimuth angle. This half-wavelength-dipole antenna's gain was

\[
G(\theta) = 1.64\pi \left[ \frac{\cos \left( \frac{\pi}{4} \cos \theta \right)}{\sin \theta} \right]^2,
\]

(1)

where \( \theta \) denotes the angle measured from the axis along the dipole's length, \( \eta = \frac{R_c}{R_c + R_p} \) refers to the efficiency, \( R_c = 73 \text{ ohms} \) is the radiation resistance, and \( R_p = 0 \text{ ohm} \) denotes the loss resistance.

Improvements in the received signal's coherently summed power for all transmission polarization over the other is shown in Figure 1 for the entire floor plan. The coherently summed power ignores the multipath signals' arrival delays, and was applied when the symbol period greatly exceeded the effective channel's relative delay spread at either transmission polarization. In Figure 1, a pixel with an upward-sloping line pattern represents an improvement in the received signal power when the transmission polarization was switched from +45° to -45°. A pixel with downward-sloping line pattern represents an improvement in the received signal power when the transmission polarization was switched from -45° to +45°.

Table 2 quantifies the above improvement in the received power as a function of the receiver's required signal power threshold. The transmission power was 1 mW. Each row of Table 2 represents the fraction of the indoor area that would be (a) above the specified received power thresholds if one transmission polarization was used, but (b) below the same received power threshold if the other transmission polarization was used. Specifically, Table 2 shows that if the transmission polarization rapidly alternated between the +45° polarization and the -45° polarization, such that both polarizations were used for half of the time, about 13%-15% less of the total indoor area experienced a "below -49.6 dBm" fade relative to the case where a single polarization was used.

Table 2. The percentages of the indoor region with received power that exceeded particular power thresholds at one but not the other transmission polarization. The mobile handset's receiving antenna had a 60° elevation angle.

<table>
<thead>
<tr>
<th>Received Power Threshold (dBm)</th>
<th>% Under Threshold @ El. Pol. = +45° But Above Threshold @ El. Pol. = -45°</th>
<th>% Under Threshold @ El. Pol. = -45° But Above Threshold @ El. Pol. = +45°</th>
</tr>
</thead>
<tbody>
<tr>
<td>-44.6</td>
<td>6.32%</td>
<td>9.62%</td>
</tr>
<tr>
<td>-49.6</td>
<td>12.91%</td>
<td>15.66%</td>
</tr>
<tr>
<td>-54.6</td>
<td>10.99%</td>
<td>14.56%</td>
</tr>
<tr>
<td>-59.6</td>
<td>7.97%</td>
<td>10.16%</td>
</tr>
<tr>
<td>64.9</td>
<td>8.24%</td>
<td>7.69%</td>
</tr>
<tr>
<td>69.9</td>
<td>8.79%</td>
<td>5.77%</td>
</tr>
</tbody>
</table>

Figure 2 shows the fraction of all floor plan pixels with their received power enhanced with the transmission polarization switched from +45° to -45°, or vice versa. About 39% (corresponding to the four right-most bars summed) of the total floor-plan increased by over 5 dB, whereas another 18% (corresponding to the sum of the fifth to seventh bars from the right) increased from 0 to 5 dB. If the transmission polarization was switched the other way, from -45° to +45°, the corresponding numbers were 28% and 15%. This means that two-thirds of the floor area benefited by over 5 dB from the proposed fast-polarization-hopping scheme.

Figure 2 shows the fraction of pixels with their received power increased by the transmission polarization switched from +45° to -45° or vice versa.

6. The Effective Channel Impulse Response of the Proposed Fast Polarization Hopping

As each information-symbol or each interleaving-depth worth of information symbols is transmitted via two different polarizations in succession, the overall fast-polarization-hopping channel's effective impulse response (as experienced by the symbols in one polarization-hop period) is a temporal conjoining of the propagation channel's impulse responses corresponding to the two transmitted polarizations. Figure 3 illustrates how the individual transmitted power distributions for each polarization are combined.
polarizations' impulse responses form the fast-polarization-hopping effective channel's overall impulse response. Figure 3c illustrates the case when each transmission polarization was used for $T/2$, half an information-symbol's period or half of the interleaving depth. The sequence of transmission polarization was $\{+45^\circ, -45^\circ\}$. Figure 3d illustrates the case for a transmission-polarization sequence of $\{-45^\circ, +45^\circ\}$.

One system-design parameter is the polarization hop rate, $1/T$, relative to the channel's RMS excess-delay spread, $\tau_{rms}$ (a multipath signal's "excess delay" equals that multipath signal's time of arrival at the receiver relative to the time of arrival of the multipath signal that arrives first). Although the indoor channel is not very frequency selective, the multiple reflections and diffraction undergone by different multipath signals translate into different propagation lags, however small these lags may be. Table 3 shows

![Figure 3a. The propagation channel's impulse response for a $+45^\circ$ transmission polarization with the receiver at receiver location R1.](image)

![Figure 3b. The propagation channel's impulse response for a $-45^\circ$ transmission polarization with the receiver at receiver location R1.](image)

![Figure 3c. The propagation channel's impulse response for a $+45^\circ$, $-45^\circ$ transmission-polarization-hop cycle with the receiver at receiver location R1.](image)

![Figure 3d. The propagation channel's impulse response for a $-45^\circ$, $+45^\circ$ transmission-polarization-hop cycle with the receiver at receiver location R1.](image)

samples at five mobile receiver locations (indicated by the letter "R" in Figure 1) to quantitatively illustrate the multipath signals' "typical" excess delays, with an RMS excess delay spread $\tau_{rms} < 5$ ns (other indoor scenarios may conceivably involve significantly longer relative delay spreads). If either transmission polarization has an excess delay of up to $\tau$, the effective propagation channel's impulse response for a two-polarization-hop cycle would last up to $T + \tau$. Each polarization-hop cycle's period, $T$, has an upper limit determined by the transmitted signal's interleaving time-diversity depth to avoid prolonged deep fades, but the period's lower limit is determined by the channel's RMS excess delay spread, $\tau_{rms}$, to avoid excessive inter-symbol interference.

If system-design considerations require the RMS delay spread to be capped to within a fraction $0 < \alpha < 1$ of a polarization hop's
duration, this proposed “fast-polarization-hopping transmitting-diversity” scheme can accommodate an information symbol rate of $\frac{\alpha}{2\tau_{rms}}$ as the number of information symbols per unit time, even in the worst-case scenario of no temporal interleaving of information symbols (which would then allow only one information symbol per polarization-hop cycle). With $\tau_{rms} = 5$ ns and $\alpha = 0.1$, this particular floor plan would nonetheless allow $1 \times 10^7$ information symbols per second. If the transmitter implemented symbol interleaving, then the information-symbol rate could be further increased. Moreover, a raw information-symbol stream with higher bit rates may be subdivided into several spectrally parallel information-symbol streams, each of which would occupy a separate frequency band and would satisfy the above transmission-rate constraints.

Because temporal phase continuity is exceedingly difficult to maintain across polarization hops in the transmitted analog physical signal, allowance must be made by the communication system’s modulator/demodulator for arbitrary phase discontinuities unknown to the receiver across polarization hops. The following are common mitigation strategies:

1. Frequency-shift keying (FSK) signal modulation at the transmitter would allow incoherent demodulation at the receiver.

2. Transmitting multiple information symbols at each polarization hop, with channel coding for error correction; the use of differential phase modulation and/or pilot symbols to phase synchronize each segment of information symbols in each polarization hop — with each polarization-hop cycle not to exceed the information-symbol-stream’s interleaving depth. However, the transmission bandwidth needs to be increased relative to the alternative strategies of using antenna arrays at the base station and/or the mobile.

Beyond the above-mentioned, the proposed fast-polarization-hopping scheme imposes no change on the receiver’s architecture (parameter settings, such as information-symbol duration, within this architecture may need to be adjusted, as discussed above).

### Table 3. The received power and the RMS excess delay spread, $\tau_{rms}$, at the five receiver locations in Figure 1.

<table>
<thead>
<tr>
<th>Transmitter Polarization</th>
<th>Receiver Location</th>
<th>Total Power (dB)</th>
<th>RMS Excess Delay Spread $\tau_{rms}$ (ns)</th>
<th>Excess Delay Spread $\tau$ (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+45°</td>
<td>R1</td>
<td>-71.58</td>
<td>2.02</td>
<td>36.04</td>
</tr>
<tr>
<td>-45°</td>
<td>R1</td>
<td>-46.63</td>
<td>2.89</td>
<td>36.04</td>
</tr>
<tr>
<td>+45°</td>
<td>R2</td>
<td>-47.40</td>
<td>3.71</td>
<td>34.67</td>
</tr>
<tr>
<td>-45°</td>
<td>R2</td>
<td>-68.32</td>
<td>3.35</td>
<td>34.67</td>
</tr>
<tr>
<td>+45°</td>
<td>R3</td>
<td>-52.96</td>
<td>4.66</td>
<td>36.97</td>
</tr>
<tr>
<td>-45°</td>
<td>R3</td>
<td>-73.01</td>
<td>3.08</td>
<td>36.97</td>
</tr>
<tr>
<td>+45°</td>
<td>R4</td>
<td>-39.28</td>
<td>4.51</td>
<td>29.53</td>
</tr>
<tr>
<td>-45°</td>
<td>R4</td>
<td>-61.08</td>
<td>4.88</td>
<td>29.53</td>
</tr>
<tr>
<td>+45°</td>
<td>R5</td>
<td>-44.62</td>
<td>2.09</td>
<td>36.96</td>
</tr>
<tr>
<td>-45°</td>
<td>R5</td>
<td>-66.39</td>
<td>3.36</td>
<td>36.96</td>
</tr>
</tbody>
</table>

7. An Uncoded FSK Case Study for Fast-Polarization-Hopping System Design

To illustrate the proposed “fast-polarization-hopping transmitting diversity” scheme’s potential, the BER (bit-error rate) was obtained via Monte Carlo simulations, below, for the more disadvantaged of the two above alternatives: FSK without channel-correction coding. Figures 4 and 5 illustrate one possible binary FSK (BFSK) modulation and incoherent-demodulation scheme.

Limited Monte Carlo simulations of the proposed fast-polarization-hopping scheme illustrated its potential efficacy for an indoor BFSK incoherent-demodulation communication system for the floor plan in Figure 1 and the setup described earlier in Section 5, without temporal interleaving in the information-symbol stream and without any channel coding for error correction. The two BFSK instantaneous frequencies were 20 MHz apart, symmetrically on either side of the 2100 MHz carrier frequency.

For receiver locations R1 and R2, Figures 6 and 7 plot their respective bit-error rates (BERs) at various signal-to-noise ratios (SNR) and various values of $\frac{T}{2\tau_{rms}}$. The SNR is the ratio of the transmitted signal power over noise, i.e., noise added to CINDOOR’s ray-tracing simulation output in the MATLAB simulation of the receiver. As expected, a lower SNR and/or a lower $\alpha$ increased the BER. The latter relationship is because a higher $\alpha$ decreases the extent of inter-symbol interference (ISI) for a given RMS excess delay spread. Recall that the BER figures here are for an un-interleaved information-symbol signal, without any channel correction. Suitably designed channel encoding for error correction can decrease the BER by orders of magnitude from the values shown in Figures 6 and 7. Also, proper temporal interleaving of the information symbols can significantly decrease the polarization-hop rate, perhaps to one hop over many information-symbol durations, thereby very significantly increasing the fast-polarization-hopping effective channel’s information capacity. Temporal interleaving and channel coding are standard communication-engineering techniques.
9. Publication History and Acknowledgment

Part of the material in this paper was presented at the IEEE International Symposium on Circuits and Systems, Bangkok, Thailand, May 25-28, 2003. This work was supported by Canada's Natural Sciences & Engineering Research Council's Individual Research Grant #NSERC-RGPIN-249775-02.

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