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Orthogonal Frequency-Division Multiplexing in Wireless Communication Systems With Multimode Fiber Feeds

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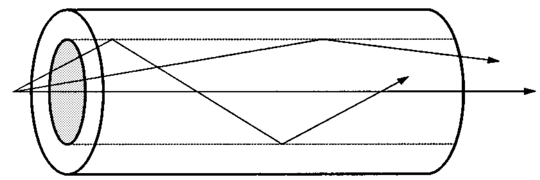
***Abstract*—The feasibility of using multimode fiber as an inexpensive cell feed in broad-band indoor picocellular systems is investigated in this paper. The performance of coded orthogonal frequency-division multiplexing (OFDM) for a variety of multimode fiber profiles, including stepped index and α-profile graded index fibers, is assessed. In addition to its ability to perform well in a frequency-selective multipath environment, OFDM is shown to offer good protection against the frequency selectivity of a dispersive multimode fiber. Data rates in excess of 100 Mb/s (without equalization) over a multimode fiber channel are possible, whereas they may be limited to some 20–30 Mb/s using conventional ASK modulation.**

***Index Terms*—Broad-band indoor picocellular systems, fiber-radio systems, OFDM modulation, optical fiber dispersion.**

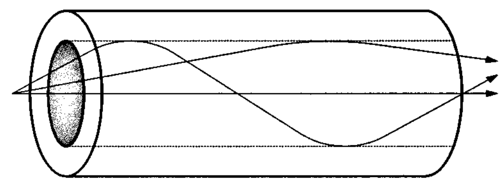
I. Introduction

MILLIMETER-WAVE wireless systems employing fiber feeds are seen as having the potential to provide bit rates in excess of 100 Mb/s to both mobile and fixed users [1]. A common theme in fiber-radio technology, especially at 60 GHz, is the small cell sizes and the corresponding need for mass production of low-cost base stations and confinement of millimeter-wave sources at the central office [2]. This has motivated the investigation of a large number of alternative architectures for fiber-radio picocells and fiber-radio networks. The ultimate success of millimeter-wave fiber-radio technology, however, will not only depend on the network and picocell implementation, but also on the modulation formats and communication protocols adopted. In addition to overcoming the significant problems of multipath fading for high bit-rate signals in a millimeter-wave wireless environment, they will have to be compatible with the fiber backbone. Moreover, the technique should provide for a seamless transition between the millimeter-wave wireless and fiber parts of the system.

Coded orthogonal frequency-division multiplexing (COFDM) has become the popular choice for broad-band transmission in a frequency selective indoor multipath environment and is now the focus of emerging standards [3]. In COFDM, the fast serial data stream is reduced to many parallel low-speed channels, which are frequency multiplexed on overlapping subcarriers using an inverse fast Fourier transform (IFFT) [4]. The bandwidth of each of these lower data-rate carriers is less than the coherence bandwidth of the room and is, therefore, less sensitive to channel dispersion since fading on a given subcarrier can be considered flat [5]. Data loss on carriers situated about nulls in the channel's frequency response can be recovered using forward error correction (FEC) because the data on the other carriers remains intact. Since the subcarriers

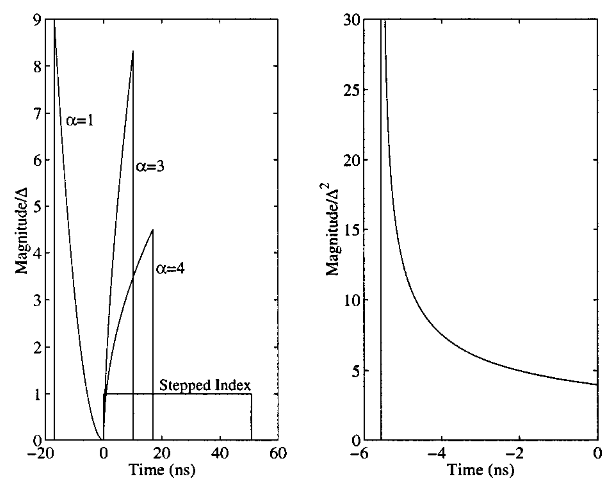


(a)



(b)

Fig. 1. Intermodal dispersion in multimode fiber (shading represents refractive index profile of the core). (a) Stepped index fiber. (b) Graded index fiber.



(a) (b)

Fig. 2. Impulse responses for: (a) suboptimum case $\alpha = 1, 3, 4$ and ∞ (1 km, $\Delta = 0.01$) and (b) optimum case $\alpha = 2 - 2\Delta$ (10 km).

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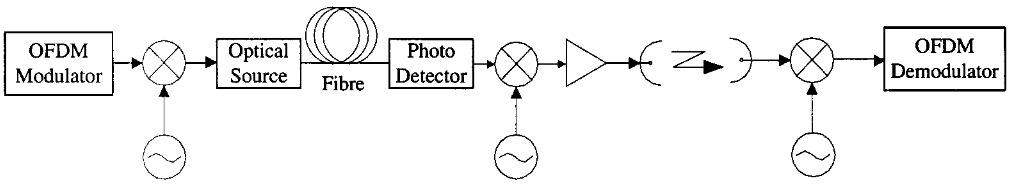

Fig. 3. Simulated fiber-radio system.

are densely packed in the frequency domain, a further advantage of orthogonal frequency-division multiplexing (OFDM) is that it achieves its resilience to multipath fading without sacrificing bandwidth [6].

Remote upconversion, in which the fiber backbone is used for data transmission alone, and the millimeter-wave signals are generated at the picocells is being advocated as a low-cost route to fiber radio [7]. This approach allows the modulation to be performed at a central office, thus reducing the size, complexity, and power requirements of the remote hubs [8]. Such an approach may also allow the use of multimode fiber.

Although in many respects the performance of multimode fiber is far inferior to that of single mode, it is cheaper and also allows less stringent connection tolerances. For low data-rate communications, it therefore proves to be the more appropriate choice. However, for broad-band communications (>30 Mb/s), multimode dispersion can become a serious problem. This dispersion is a result of the different group velocities of the large number of modes that the fiber allows to propagate [see Fig. 1(a)]. Although not totally alleviated, the effect is considerably reduced by the use of graded index fiber, which can, to a great extent, equalize these group velocities by varying the refractive index of the fiber as a function of the radial distance from the core center [see Fig. 1(b)].

The resilience of OFDM to multipath fading in the RF channel suggests that it may also be tolerant of the effects of dispersion in multimode fiber, thus permitting the use of easily installed inexpensive fiber-radio picocells. This paper proposes the use of OFDM to combat the effects of multimode fiber dispersion and reports on the feasibility of its use for a variety of refractive index profiles.

II. Evaluation of COFDM for Fiber Radio

The multimode fiber was simulated using impulse response models [9]. Fig. 2 shows the impulse responses for a selection of 1 km α profile fibers, and also that of the optimum profile, which exists at $\alpha = 2 - 2\Delta$ (shown for 10 km).

The performance of COFDM over multimode fiber has been evaluated by means of a sophisticated link-budget simulation for a 150-Mb/s 60-GHz remotely upconverted fiber feed picocell. A system level diagram of the fiber-radio simulation is given in Fig. 3, and the OFDM modulation format employed is summarized in Table I. The 60-GHz indoor channel was simulated using a realistic finite-impulse-response model [10].

In many cases, the frequency response of the dispersive fiber exhibited significant phase variations within a narrow bandwidth. The influence of this phase distortion can be seen clearly in Fig. 4. This shows the constellation plots of demodulated OFDM–QPSK symbols after transmission over fibers with

TABLE I
MODULATION FORMAT

FFT Size	256
Carriers	200
Modulation	DQPSK
Guard Time	120 ns
Net Data-rate	150 Mb/s
FEC (convolutional Encoder with Soft Decision Viterbi Decoding)	×2 overhead
Gross Data-rate	300 Mb/s
Subcarrier Bandwidth	830 kHz
Total RF Bandwidth	166 MHz

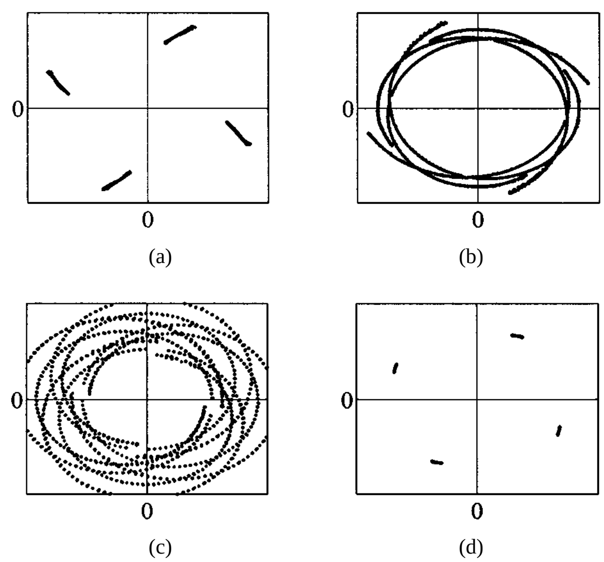

Fig. 4. Constellation plots for 1 km of fiber without differential modulation. (a) $\alpha = 1$ km, (b) $\alpha = 3$ km, (c) $\alpha = 6$ km, (d) $\alpha = 2 - 2\Delta$ km.

profiles $\alpha = 1$, 3, 6 and $2 - 2\Delta$. In all cases, both amplitude and phase distortion is present. However, for systems with $\alpha > 2$, the phase distortion is quite severe and, without some method of phase compensation, these profiles are unsuitable for broad-band OFDM signals. In addition, as α increases (i.e., the profile tends toward that of a stepped index), the amplitude and phase distortion increase significantly. This is reflected in the link-budget performance comparisons given below.

By differentially encoding data between adjacent carriers, the problem is overcome without the need for equalization, albeit at the expense of 3-dB degradation in performance. This method alleviates the need for pilot tones and reduces the receiver complexity [11]. It is, therefore, often favored over using equalization for high data-rate OFDM.

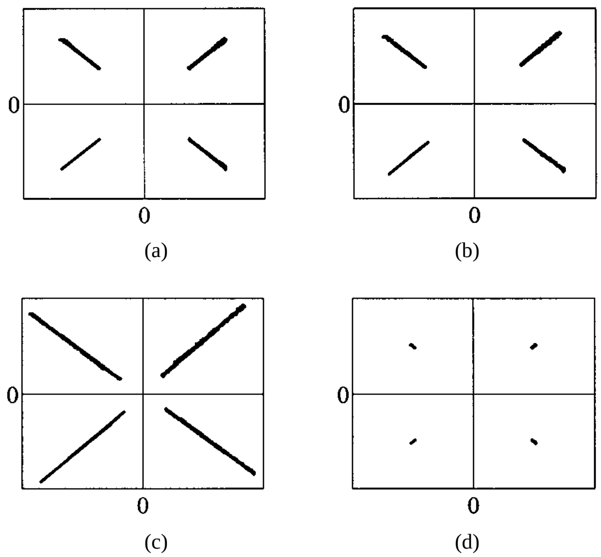

Fig. 5. Constellation plots for 1 km of fiber showing improvement offered by DQPSK. (a) $\alpha = 1$, (b) $\alpha = 3$, (c) $\alpha = 6$, (d) $\alpha = 2 - 2\Delta$.

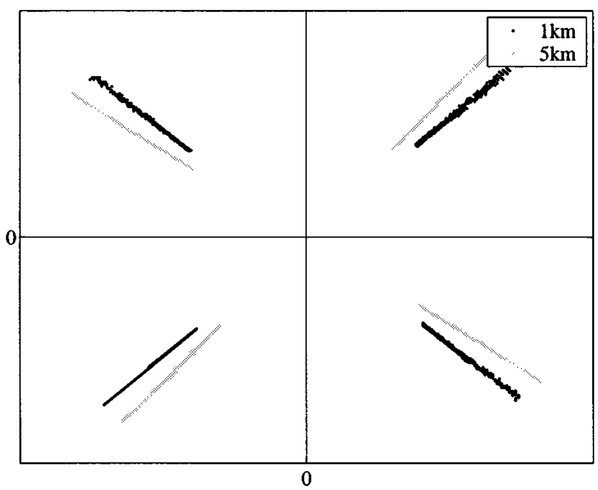

Fig. 6. Comparison of DQPSK constellation plots for 1 and 5 km for fiber where $\alpha = 3$.

Although amplitude distortion is still present, the ability of differential quaternary phase-shift keying (DQPSK) to combat the phase distortion is clearly evident when comparing Figs. 4 and 5. Upon closer inspection of Fig. 5(a) and (b), a residual phase error is found to exist in the corrected constellation. This phase offset results from applying differential encoding between adjacent OFDM carriers where the phase distortion introduced by the fiber cannot be considered constant over such a bandwidth. This phase error is approximately 1.4° worse for $\alpha = 3$. It is also noteworthy that this residual phase offset worsens with increasing distance for $\alpha = 3$ (Fig. 6). The problem could be alleviated by applying DQPSK between symbols on a given carrier in the time domain. However, this method assumes that the channel is stationary between OFDM symbols. Although such an assumption holds for fiber, it is not normally valid for the RF channel. This method of differential encoding is also less resilient to the effects of oscillator phase noise, which is a very important consideration in millimeter-wave systems.

TABLE II
EXAMPLE OPTICAL LINK BUDGET

Transmit Power	1.0 dBm
Fibre Subcarrier Frequency	250.0 MHz
Total Fibre Losses	20.0 dB
Incident Power	−19.0 dBm
Responsivity	0.56 A/W
Photo detector Pre-amp Noise Figure	3.0 dB
Post Detection Bandwidth	166.0 MHz
Load Resistance	10.0 kΩ
Laser RIN	−140.0 dB/Hz
Thermal Noise	−155.7 dB
Total Shot Noise	−154.4 dB
Resulting SNR	45.2 dB

TABLE III
EXAMPLE RF LINK BUDGET FOR 60-GHz INDOOR 30-m RADIUS CELL

Receiver Noise Figure	8.00 dB
Noise power density Per Hz	−165.97 dBm
Signal Bandwidth	166.00 MHz
Minimum Rx SNR (BER $\approx 10^{-9}$)	12.00 dB
Minimum Rx signal Power	−71.77 dBm
Combined Antenna Gain	25.00 dB
Path Loss in a 30m 60GHz cell *(propagation exponent n=3)*	112.32 dB
Minimum Tx Power	15.6 dBm

Although frequency selectivity is overcome by transmitting the data on many narrow-band carriers, consecutive OFDM modulation blocks can still overlap. This is prevented by inserting a time-domain guard region between blocks, the duration of which equals the maximum delay spread of the channel. It is important to note that the dispersion of the fiber increases the effective channel delay spread of a fiber-radio link. Simulations show that significant penalties are incurred if the guard region is not increased accordingly. The added overhead is, however, relatively small in terms of increased signal bandwidth (140 kHz/ns for 150-Mb/s 256-carrier QPSK–COFDM).

Table II shows a typical optical link budget used to evaluate the SNR after optical detection, while Table III shows an example of the link budget used to evaluate the RF performance. In the case of the optical link budget, a simple low-impedance photo detector front end is assumed; however, increased link length and dynamic range could be achieved by the use of a transimpedance design.

The dependence of bit error rate (BER) performance on fiber length is assessed in Figs. 7–10. No FEC has been employed in this set of simulations, although the gross data rate has been maintained to keep the remaining system parameters consistent with all other simulations presented here. For practical applications, the suboptimum profiles are limited to lengths of less than 3 km. In fact, for $\alpha \geq 6$, fiber lengths of 1.5 km or less would be recommended. This is emphasized by the link budget evaluation for the stepped index profile shown in Fig. 11.

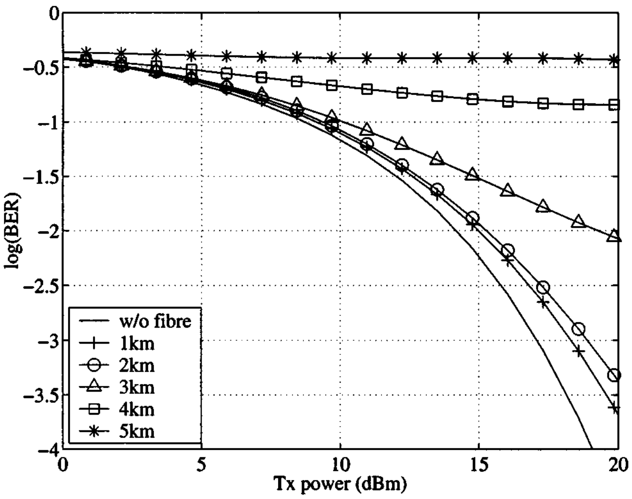

Fig. 7. BER dependence on fiber length for $\alpha = 1$.

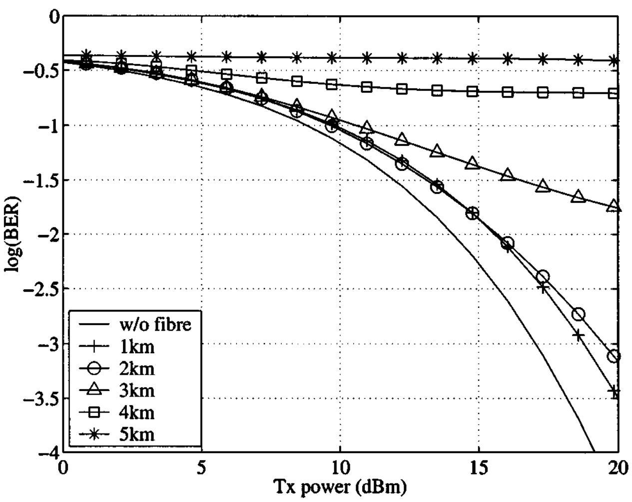

Fig. 8. BER dependence on fiber length for $\alpha = 3$.

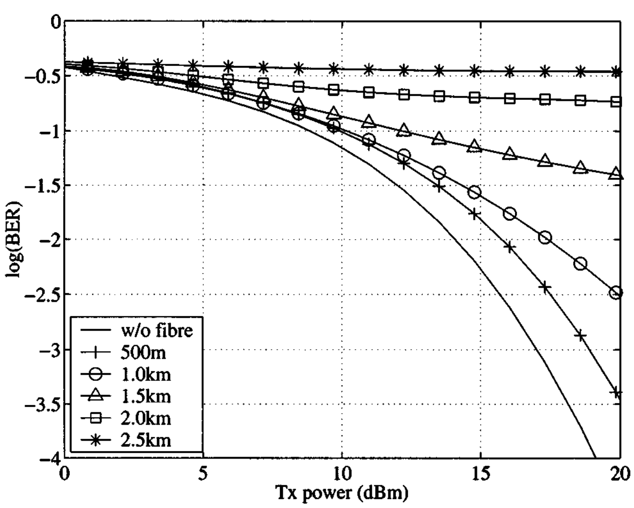

Fig. 9. BER dependence on fiber length for $\alpha = 6$.

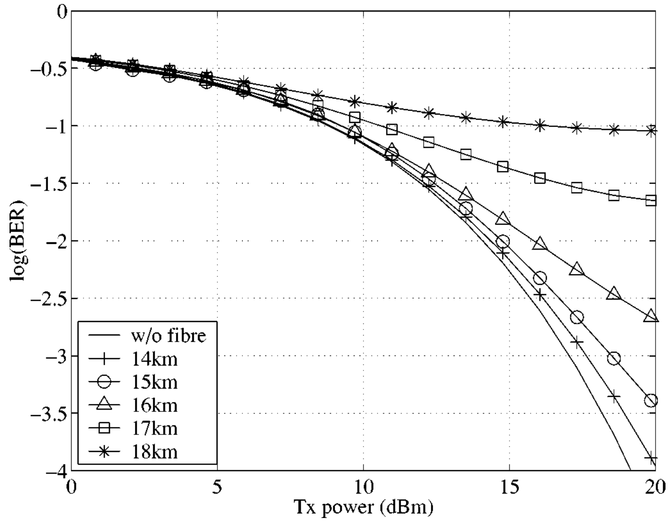

Fig. 10. BER dependence on fiber length for $\alpha = 2 - 2\Delta$.

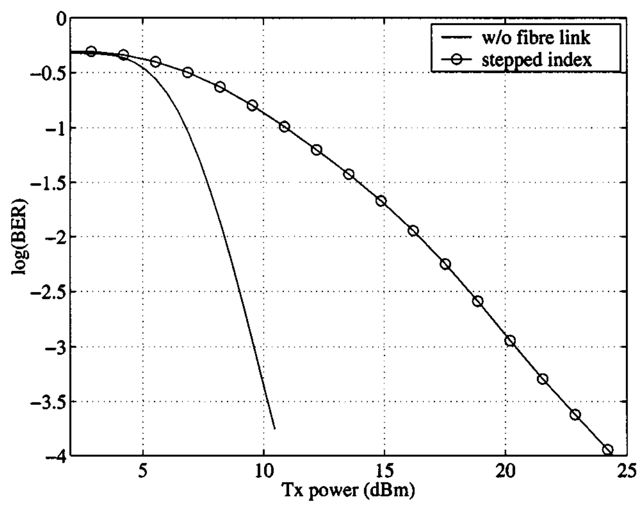

Fig. 11. Link budget evaluation for 700 m of stepped index fiber with 100-Mb/s COFDM.

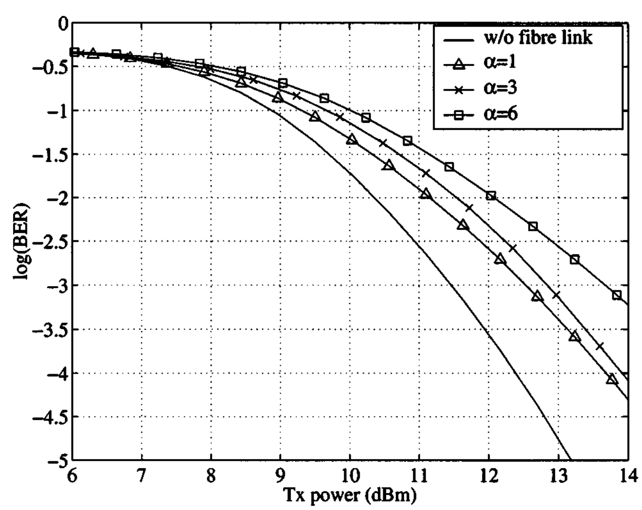

Fig. 12. Link budget evaluation for $\alpha = 1, 3$, and 6 using 1 km of fiber.

The required transmitter power to achieve a given BER for the full fiber-radio link has been simulated for a selection of fibers (Figs. 11–13). For 1 km of fiber, simulations indicate less than 3-dB performance degradation when $\alpha = 6$, and less than approximately 1.6-dB degradation for profiles with

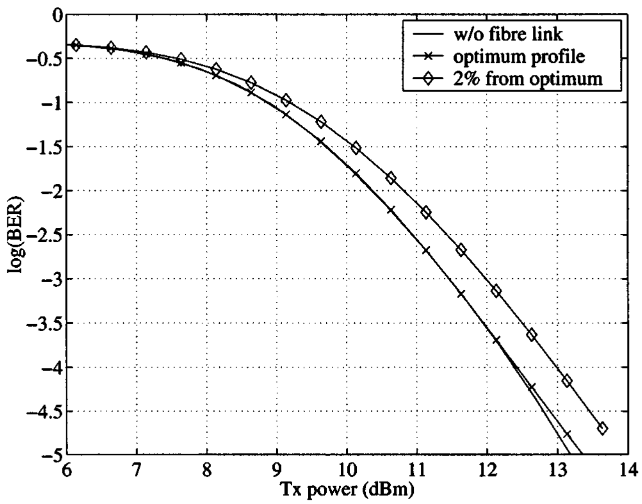

Fig. 13. Link budget evaluation for $\alpha = 2 - 2\Delta$ (optimum), also showing the effect of 2% deviation from optimum.

$\alpha \leq 3$ (Fig. 12). Although showing no indication of an actual BER floor, the required transmit power when using stepped index fiber is somewhat impractical by comparison (Fig. 11). To achieve a practical BER, for the system evaluated here, one is limited to lengths of less than 1 km and data rates of approximately 100 Mb/s. To achieve the results shown in Fig. 11, it was also necessary to use a 512-point IFFT with 400 carriers, as opposed to the 256-point IFFT system used in all other simulations. The comparatively poor performance of this fiber profile is thought to be mainly due to the number of spectral notches that it presents when approaching the limits of the system's FEC capabilities. Although interleaving in conjunction with soft-decision Viterbi decoding has been used, channel state information could possibly be used to further improve performance. This aside, the data rate achieved for this fiber is still higher than one could expect from many other modulation schemes, and the transmit power may not be impractical at lower frequencies.

For $\alpha = 2 - 2\Delta$, the delay spread of the fiber channel is obviously far less, therefore, its performance has been evaluated for 10 km of fiber. A point of interest is that only slight deviations from this optimum index result in significant increases in the delay spread [9]; however, the simulations here indicate that OFDM is very tolerant of such variations. Even a 2% deviation, which increases the delay spread by a factor of greater than eight ($\Delta = 0.01$, $N_0 = 1.5$), induces less than a 1-dB link-budget penalty (Fig. 13).

III. Conclusion

A comprehensive link-budget simulation has been used to assess the performance of a broad-band 60-GHz fiber-radio system. The resilience of OFDM to frequency-selective effects has been shown to permit the use of inexpensive multimode fiber in such systems. Performance has been evaluated for a variety of fiber profiles. The significance of amplitude and phase distortion introduced by the various fibers has been shown by means of constellation plots, emphasizing the need for phase compensation in particular. The performance of DQPSK has been investigated and proves to be an efficient method of tackling this issue, and one which is also appropriate given the RF system requirements. The BER limitations imposed by fiber length have been assessed and, for many situations, OFDM has been shown to be capable of offering a hardware-independent solution to dispersion in multimode fiber for lengths less than 2 km. For long distances (>10 km), a graded index fiber with the optimum profile of $\alpha = 2 - 2\Delta$ has been shown to perform well, with OFDM being extremely tolerant of variations in the profile that may be caused by fabrication defects. It is believed that these results augur well for the use of multimode fiber feeds for wireless COFDM networks and merit experimental investigation.

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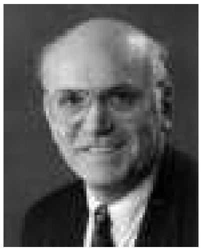

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