50-Mb/s Diffuse Infrared Free-Space Link Using On-Off Keying with Decision-Feedback Equalization

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Abstract

We report an experimental 50-Mb/s free-space infrared link for indoor wireless communication, which achieves low bit-error rates (BERs) in the presence of multipath distortion, shadowing, and ambient natural and artificial lighting. The eye-safe 805-nm transmitter, directed at the ceiling, emits an on-off-keyed signal having 475-mW average power. The receiver employs a 1-cm^2 silicon p-i-n photodiode coupled to a high-index hemispherical concentrator, which is covered by an optical bandpass filter of 30-nm bandwidth. A decision-feedback equalizer mitigates the effect of multipath ISI. In the presence of bright skylight, the link achieves a range of 2.9 m at 10^{-7} BER.

I. Introduction

As a medium for short-range, wireless indoor communication, infrared offers significant advantages over radio [1]-[3]. The infrared represents a vast, unregulated spectrum. As infrared does not pass through walls, it is possible to operate at least one link in each room of a building without interference. When intensity modulation and direct detection (IM/DD) are employed, the short carrier wavelength and large, square-law detector lead to efficient spatial diversity that prevents multipath fading [4].

For wireless networking of portable terminals, it is desirable to employ non-directional transmitters and receivers, but this results in significant impairments to high-bit-rate communication. Multipath propagation leads to intersymbol interference (ISI) that is significant at symbol rates above 10 Mbaud [3]- [5]. Non-directed links inherently have high path loss, but an IM/DD system can tolerate only limited path loss, as its signal-to-noise ratio (SNR) is proportional to the square of received power. Slowly varying ambient light sources, such as sun, sky and incandescent lamps, induce a shot noise that is white and nearly Gaussian. Infrared emission from fluorescent lamps induces noise at harmonics of the lamp drive frequency, extending from near d.c. up to about 1 MHz [3], [6]. These effects have limited non-directed infrared links to bit rates no higher than 4 Mb/s [7]. Here, we describe a 50-Mb/s non-directed infrared link using baseband on-off keying (OOK), which achieves low bit-error rates (BERs) in the presence of ISI, ambient lighting, and shadowing.

II. System description

The configuration of our experimental link is shown in Fig. 1. The transmitter utilizes an array of eight laser diodes whose output is passed through a 3-mm-thick, translucent Plexiglas diffuser to produce an essentially Lambertian radiation pattern. When directly modulated with a 50-Mb/s, non-return-to-zero (NRZ) OOK waveform, the source emits a total time-averaged power of 475 mW, with an on-axis, time-averaged irradiance of 97.2 W/m^2-sr, which is eye-safe, even under newly proposed standards [8]. The source emission spectrum is peaked at a wavelength of 806.3 nm, and has a full-width of 5.6 nm (at -10 dB), caused by emission in multiple longitudinal modes and variations among device emission wavelengths.

The receiver employs a 1-cm^2 silicon *p-i-n* photodiode. To provide omnidirectional optical gain [1], a glass hemisphere, having 2-cm radius and refractive index $n = 1.76$, is bonded to the A/R-coated photodiode, using a thermoplastic of refractive index 1.68. This combination achieves a field of view (FOV) of 78° (half-angle) and a gain of 4.5 dB, close to the theoretical maximum of $10 \log_{10} n^2 = 4.9$ dB. To reject background light, a multilayer interference filter, having 815-nm center wavelength, 30-nm bandwidth and 68% peak transmission, is bonded to the outer surface of the hemisphere. The filter-lens combination achieves a peak gain of 1.5 dB and a FOV of 65°. Use of a hemispherical filter enables our receiver to

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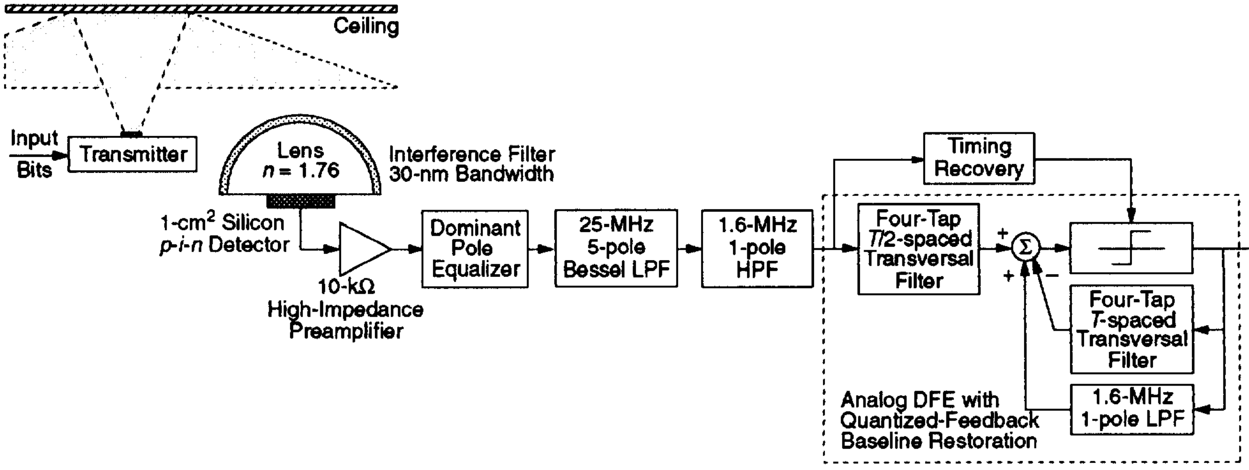

Fig. 1. Block diagram of experimental 50-Mb/s diffuse infrared link.

achieve simultaneously a narrow bandwidth and a wide FOV [1], [3].

The detector output is amplified using a hybrid high-impedance preamplifier. The dominant pole arising from the 35-pF detector capacitance and 10-kΩ load resistance is compensated by a passive *R-C* circuit. However, even at a detector bias of -180 V, the receiver -3-dB cutoff frequency is limited to 23.4 MHz, by the transit time of holes across the 320-µm-thick, *n*-illuminated photodiode [9]. Averaged over the bandwidth of the 25-MHz, five-pole Bessel low-pass filter, the receiver has a one-sided, input-referred noise current density of 7.8 pA/$\sqrt{\text{Hz}}$, equivalent to the shot noise from a d.c. photocurrent of 192 µA. Noise arising from fluorescent lamps is removed using a single-pole, 1.6-MHz high-pass filter. The resulting baseline wander is corrected using quantized feedback (QF) [10], i.e., the output of a decision circuit is passed through a single-pole, 1.6-MHz low-pass filter and added to the high-pass-filtered signal at the decision-circuit input. ISI, arising from multipath propagation and from the limited receiver bandwidth, is compensated using a decision-feedback equalizer (DFE) [11]. The DFE contains a four-tap, half-baud-spaced forward filter and a four-tap, baud-spaced reverse filter, implemented using coaxial-cable delays and manually adjusted, variable-gain analog amplifiers. Timing recovery is performed using a second-order phase-locked loop having a natural frequency of 30 krad/s and a damping constant of 0.71.

III. System performance

System operation was characterized in a 8.4 m × 6.3 m room having a ceiling height of 3.9 m, and large windows facing south and west. The painted plaster walls and acoustical ceiling tiles are off-white in color, and have diffuse reflectivities of approximately 0.7. The transmitted data consisted of a 50-Mb/s, $2^7 - 1$ PN sequence in NRZ format. As the link is intended to operate without any aiming of the transmitter or receiver, both of them were pointed directly upward during all measurements. The resulting illumination of an extended ceiling area created a diffuse link configuration, providing some immunity to shadowing of the receiver [4]. Received signal irradiance was measured using an optical power meter having the same FOV as the receiver.

Fig. 2 presents the BER-vs.-power performance measured in the absence of background light for transmission over a horizontal range of 3 m. Even in the absence of shadowing, available transmitter power was insufficient to achieve a BER lower than 10^{-4} without equalization, because of ISI caused by multipath propagation and limited receiver bandwidth. Use of the DFE reduced the ISI penalty by 2.75 dB, allowing achievement of 10^{-9} BER at an average received irradiance of -32 dBm/cm^2. We note that in this IM/DD link, this corresponds to a 5.5-dB improvement in electrical SNR.

Fig. 3 illustrates the impact of various ambient light sources on the BER-vs.-power performance of the 50-Mb/s link. During all measurements shown in Fig. 3, the transmitter and receiver were kept in the same locations, separated by a horizontal range of 2.4 m, the receiver was unshadowed, and the DFE was used to counter ISI. Bright skylight, which induced a receiver photocurrent varying from 152 µA to 186 µA during the measurement, degraded performance by 1.5 dB at a BER of 10^{-9}. A penalty of only 0.1 dB was induced by the emission from fluorescent lamps driven by 22-kHz solid-state ballasts.

The variation of link BER with horizontal transmission distance, under various lighting conditions, is shown in Fig. 4. During all measurements, the DFE was employed. In the absence of shadowing, with no illumination or with

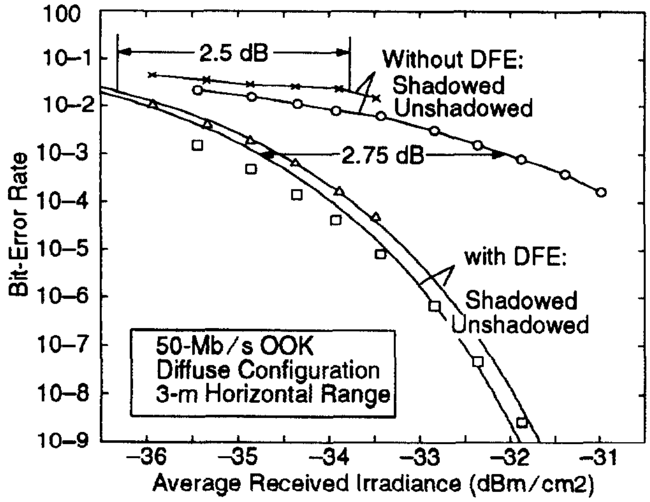

Fig. 2. Performance of the 50-Mb/s diffuse infrared link in the presence of multipath-induced intersymbol interference and shadowing. Data were taken in a 8.4 m x 6.3 m room having a ceiling height of 3.9 m, with a horizontal separation between transmitter and receiver of 3 m. Shadowing was provided by 1.74-m-high human silhouette placed 30.5 cm from the receiver, along the line joining the transmitter and receiver. No background illumination was present.

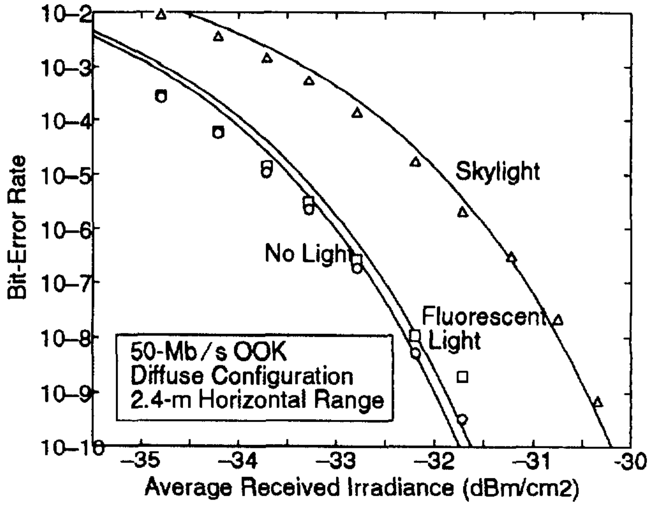

Fig. 3. Effect of background light on the performance of the 50-Mb/s diffuse infrared link. Data were taken in a 8.4 m x 6.3 m room having a ceiling height of 3.9 m, with windows facing south and west. Three different light conditions were used: no background light, fluorescent light, and skylight. Transmitter-receiver horizontal separation was fixed at 2.4 m. Decision-feedback equalization was employed in all cases.

fluorescent illumination, the link achieved a range of 3.9 m (defined as the maximum horizontal separation at which 10^{-7} BER could be achieved). Bright skylight, which induced a receiver photocurrent of about 135 μA, reduced the link range to 2.9 m.

To simulate shadowing, a silhouette of a human being standing 1.74 m high was placed at a distance of 30.5 cm from the receiver, along the line joining the transmitter and receiver. Shadowing increased the link path loss by about 2.5 dB. As shown in Fig. 2, shadowing also increased the unequalized ISI penalty by 0.5 dB (at 10^{-2} BER). Use of the DFE reduced the incremental, shadowing-induced ISI penalty to only 0.25 dB. Fig. 4 illustrates the effect of shadowing on the range of the system. With shadowing, the link range was reduced to 2.3 m under conditions of fluorescent lighting or no lighting. In the presence of bright skylight, which induced a receiver photocurrent ranging from 133 to 157 μA, the range of a shadowed link was reduced to 1.5 m.

IV. Conclusion

We have demonstrated transmission of 50-Mb/s data at low BER using diffuse infrared radiation. OOK modulation with a DFE is effective in countering multipath-induced ISI. Through use of a hemispherical optical bandpass filter and high-index, hemispherical concentrator, the receiver achieves immunity to ambient infrared radiation, while maintaining a wide FOV. The impact of fluorescent lighting has been mitigated by means of high-pass filtering and QF baseline restoration. In a brightly skylit room, an unshadowed link achieves a range of 2.9 m. The effects of receiver shadowing could be overcome if we could increase the transmitter power by approximately 2.75 dB.

V. Acknowledgments

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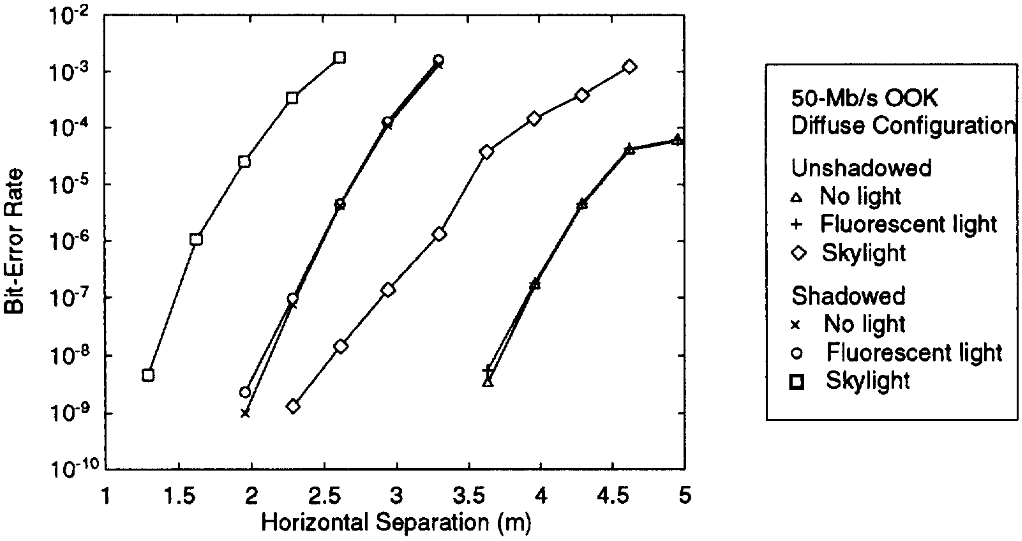

Fig. 4. Bit-error rate versus horizontal transmitter-receiver separation for the 50-Mb/s diffuse infrared link, illustrating the effect of shadowing and background illumination. Data were taken in a 8.4 m x 6.3 m room having a ceiling height of 3.9 m, with windows facing south and west. Shadowing was provided by 1.74-m-high human silhouette placed 30.5 cm from the receiver, along the line joining the transmitter and receiver. Three different light conditions were used: no background light, fluorescent light, and skylight. Decision-feedback equalization was employed in all cases. Note that the system has a range of 2.9 m in skylight without shadowing (at 10^{-7} BER).

VI. References

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