Imaging Diversity Receivers for High-Speed Infrared Wireless Communication

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ABSTRACT We discuss two modifications to the design of wireless infrared links that can yield significant performance improvements, albeit at the price of increased complexity. In line-of-sight and non-line-of-sight links, replacement of a single-element receiver by one employing an imaging light concentrator and a segmented photodetector can reduce received ambient light noise and multipath distortion. For a fixed receiver entrance area, such an imaging receiver can reduce transmit power requirements by as much as about 14 dB, depending on the link design and the number of photodetector segments. Imaging receivers also reduce co-channel interference, and may therefore enable infrared wireless networks to employ space- division multiplexing, wherein several transmitters located in close proximity can transmit simultaneously at the same wavelength. In nondirected non-line-of-sight links, replacement of the diffuse transmitter by one that projects multiple narrow beams can reduce the path loss, further reducing the transmit power requirement by several decibels. We describe the design of an experimental 100 Mb/s infrared wireless link employing a multibeam transmitter and a 37-pixel imaging receiver.

The emergence of portable computing and multimedia terminals in work and living environments is currently driving the introduction of wireless digital links and local area networks (LANs). Infrared (IR) is establishing itself as a promising medium for short-range wireless communication systems [1, 2]. In such systems, infrared radiation offers several potential advantages over radio. Infrared emitters and detectors capable of high-speed operation are available at low cost. The infrared spectral region offers a virtually unlimited bandwidth that is unregulated worldwide. Infrared light is blocked by walls or other opaque barriers, so infrared transmissions are confined to the room in which they originate. This signal confinement makes it easy to secure transmissions against casual eavesdropping, and prevents interference between links operating in different rooms. Thus, infrared wireless LANs can potentially achieve a very high aggregate capacity, and their design may be simplified since transmissions in different rooms need not be coordinated. When an infrared link employs intensity modulation with direct detection (IM/DD), the short carrier wavelength and large-area square-law detector lead to efficient spatial diversity that prevents multipath fading. By contrast, radio links are typically subject to large fluctuations in received signal magnitude and phase. Freedom from multipath fading greatly simplifies the design of infrared links.

The infrared medium has several potential drawbacks, however. Because infrared cannot penetrate walls, communication from one room to another requires the installation of infrared access points that are interconnected via a wired backbone. In many indoor environments there exists intense ambient infrared noise arising from sunlight, incandescent lighting, and fluorescent lighting, which induces noise in an infrared receiver. In virtually all short-range indoor applications, IM/DD is the only practical transmission technique. The signal-to-noise ratio (SNR) of a direct-detection receiver is proportional to the square of the received optical power, implying that IM/DD links can tolerate only comparatively limited path loss. Often, infrared links must employ relatively high transmit power levels and operate over a relatively limited range. While the transmitter power level can usually be increased without fear of interfering with other users, transmitter power may be limited by concerns of power consumption and eye safety, particularly in portable transmitters.

Simple infrared links can be classified based on the directionality of the receiver and transmitter, and on whether an uninterrupted line of sight (LOS) is necessary between the receiver and transmitter [2]. Currently, directed LOS links, such as those standardized by the Infrared Data Association (IrDA) [3], are the most widely used IR links. Directed LOS links offer low path loss, but require aiming of the transmitter and are subject to interruption by blockage of the beam. Nondirected non-LOS links, also known as *diffuse* links [1], are also becoming increasingly popular. Diffuse links, which rely on reflection of the transmitted beam from an extended reflecting surface, avoid the need for aiming and can tolerate partial obstruction of the transmission path, but suffer from increased path loss and multipath distortion. Almost all current IR communication systems, whether LOS or non-LOS, directed or nondirected, employ a single-element receiver. A *single-element receiver* consists of an optical concentrator (usually nonimaging) whose output is coupled to a single photodetector. In a single-element receiver, the desired signal, delayed multipath components, ambient light noise, and co-channel interference are combined into a single electrical signal.

Significant performance improvements can be achieved by using an *angle-diversity receiver*, which utilizes multiple receiving elements that are pointed in different directions [4–6]. The photo-currents received in the various elements are amplified separately, and the resulting electrical signals can be processed in one of several ways, as described below. Angle-diversity receivers offer several advantages. They can achieve

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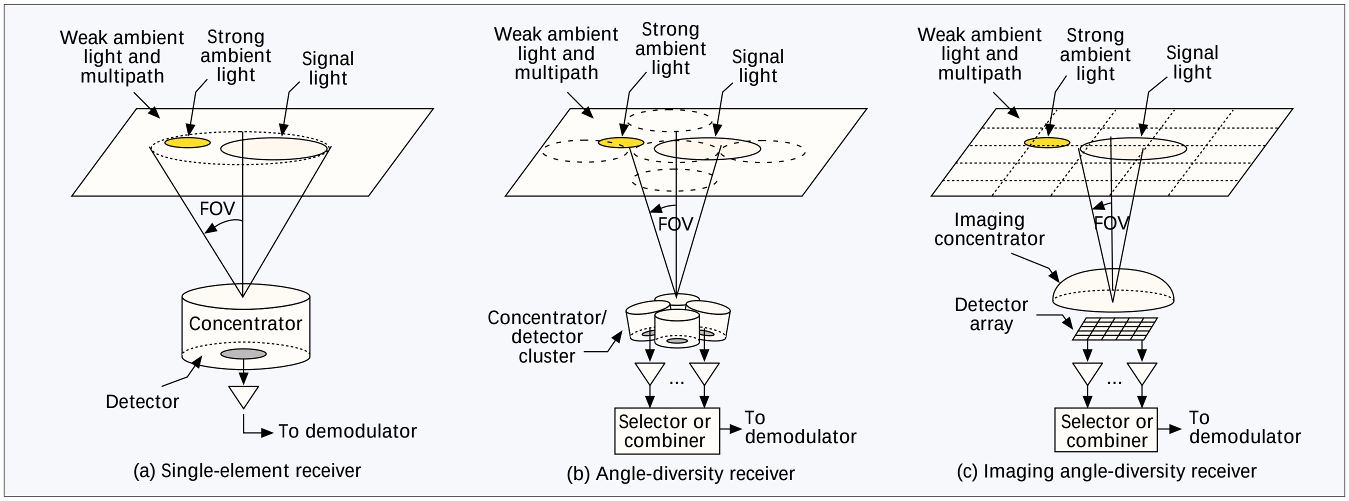


Figure 1. *Types of free-space optical receivers. a) Single-element receiver, which may utilize non-imaging or imaging optics; b) angle-diversity reciever, which utilizes a collection of narrow-FOV elements, each equipped with a separate light concentrator, which are oriented in different directions; c) imaging angle-diversity receiver, which utilizes a single imaging lens and a photodetector segmented into multiple pixels.*

high optical gain over a wide field of view (FOV). They can significantly reduce the effects of ambient light noise, co-channel interference, and multipath distortion, due to the fact that these unwanted signals are in many cases received from a different direction than the desired signal. An angle-diversity receiver can be implemented using multiple nonimaging elements that are oriented in different directions, as in [6]. Performance gains achieved by nonimaging angle-diversity receivers have been studied theoretically [5, 6]. Carruthers and Kahn have reported an experimental 70 Mb/s link using a nine-element angle-diversity receiver [6].

Implementation of angle diversity using nonimaging elements requires a separate optical concentrator for each receiving element, which may be excessively bulky and costly. Yun and Kavehrad proposed the *fly-eye receiver* [4], which consists of a single imaging optical concentrator (e.g., a lens) that forms an image of the received light on a collection of photo-detectors, thereby separating signals that arrive from different directions. In this article, we refer to this design as an *imaging angle-diversity receiver*, or simply an *imaging receiver*. Implementation of an angle-diversity receiver using imaging optics offers two advantages over a nonimaging implementation. First, all photo-detectors share a common concentrator, reducing size and cost. Second, all the photo-detectors can be laid out in a single planar array, facilitating the use of a large number of receiving elements or pixels.

Yun and Kavehrad also proposed the *spot-diffusing transmitter* [4], which utilizes multiple narrow beams pointed in different directions, as a replacement for the conventional diffuse transmitter, which utilizes a single broad beam aimed at an extended reflecting surface. In this article, we refer to the spot-diffusing transmitter as a *multibeam* or *quasi-diffuse transmitter*. While the diffuse transmitter provides considerable immunity against beam blockage near the receiver, it yields a high path loss. The quasi-diffuse transmitter is expected to reduce path loss compared to the diffuse transmitter, because the narrow beams experience little path loss traveling from the transmitter to the illuminated reflective surface.

Tang *et al.* presented an analysis comparing the performance of LOS links using imaging receivers to their counterparts employing single-element receivers [7]. They also compared non-LOS links using quasi-diffuse transmitters and imaging receivers to conventional diffuse/nonimaging links. Djahani and Kahn [8] have recently performed a more refined analysis of imaging receivers and quasi-diffuse transmitters. They have also studied the possibility of IR LANs using imaging receivers to enable space-division multiplexing (SDM) [2]. In SDM, multiple transmitters located in close proximity to each other emit signals simultaneously at the same wavelength, and the imaging receiver attempts to detect one or both of these signals with acceptably small co-channel interference.

Experimental work on imaging receivers is currently being conducted by our group at the University of California, Berkeley, and by groups at BT Laboratories [9] and Oxford University [10].

The remainder of this article is organized as follows. In the following section, we discuss angle-diversity detection techniques, including optical implementation and relevant signal-processing techniques. We analyze the performance of LOS and non-LOS links, and then discuss SDM using imaging receivers. We then describe the design of our experimental 100 Mb/s link using an imaging receiver. Concluding remarks are presented in the last section.

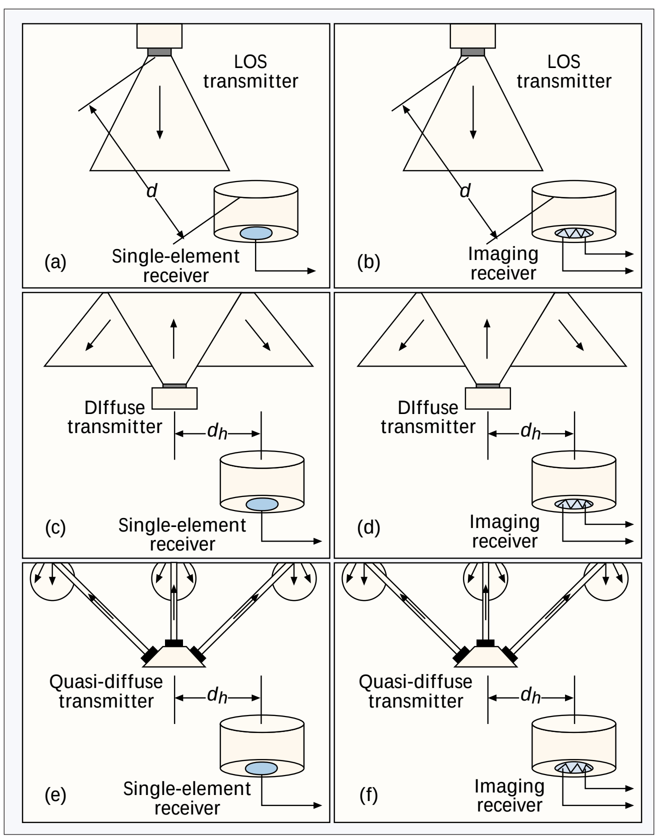
Angle-Diversity Reception

Angle diversity is a technique most applicable to nondirected links, that is, those that employ transmitters and receivers with wide angular coverage. The conventional approach to nondirected receiver design is depicted in Fig. 1a. A single element, consisting of a light concentrator, optical filter (not shown), and photodetector, receives from a wide FOV. This element collects not only the desired signal, but also unwanted ambient light noise. Steady light sources, such as the sun and incandescent lamps, lead to white, nearly Gaussian shot noise, while periodically modulated sources, such as fluorescent lamps, lead to a cyclostationary noise component [2]. A wide-FOV receiver collects not only the primary beam, but also signals that have undergone one or more reflections from room surfaces, and are thus delayed. These reflected components, while increasing the collected signal power, lead to multipath distortion [2].

Angle-diversity reception is shown in Fig. 1b. An array of narrow-FOV elements are oriented along different directions, to cover a wide FOV. Each receiving element is equipped with a separate preamplifier, and the resulting electrical signals can be processed in various ways, as discussed below. An angle-diversity receiver can reject ambient light not received by the same element(s) as the desired signal. Furthermore, multipath distortion is reduced, since only a small fraction of the delayed light signal is received by the same element(s) as the primary signal component. Indeed, multipath distortion was found to be nearly negligible in an experimental 70 Mb/s angle-diversity receiver [6] employing nine receiving elements, each having a FOV of 22° (semi-angle).

Because the individual receiving elements can utilize narrow-FOV concentrators having very high optical gain [2], each photodetector in the angle-diversity receiver is much smaller than the single detector in the conventional receiver. This reduces detector capacitance, potentially increasing receiver bandwidth and significantly reducing preamplifier thermal noise.[1] The main drawbacks of the approach shown in Fig. 1b are the potentially large size and high cost of the multiple receiving elements.

Angle-diversity reception can also be implemented using a lens that forms an image on a photodetector that is segmented into multiple pixels, as shown in Fig. 1c. In contrast to the implementation of Fig. 1b, which requires a separate light concentrator for each receiving element, the imaging angle-diversity receiver needs only a single imaging component. This, and the fact that in the imaging receiver the photodetector and associated preamplifiers can be fabricated as (probably separate) monolithic arrays, facilitates the use of a large number of pixels, leading to enhanced performance. The potentially high power consumed by the multiple preamplifiers can be minimized if preamplifiers not receiving the desired signal are turned off. Since Figs. 1a, 1b, and 1c represent both non-LOS and LOS links, the planes above the receivers may depict a reflecting surface (non-LOS case) or simply the range of angles from which rays are incident (LOS case). The dashed lines in Fig. 1 depict the boundaries of the regions veiwed by the respective recieving elements.



■ **Figure 2.** *Types of free-space optical links, designated by transmitter/reciever types: a) LOS/single-element; b) LOS/imaging; c) diffuse/single-element; d) diffuse/imaging; e) quasi-diffuse/single-element; f) quasi-diffuse/imaging.*

When the signal from a single transmitter is received by the angle-diversity receivers of Fig. 1b and c, the overall communication system can be described as a single-input, multiple-output system:

$$Y_j(t) = RX(t) \otimes h_j(t) + N_j(t),\ j = 1, \ldots, J, \tag{1}$$

where J is the total number of receiving elements and the symbol $\otimes$ denotes convolution. Here, R is the detector responsivity, $X(t)$ is the transmitted optical signal, $h_j(t)$ is the impulse response between the transmitter and the jth receiving element, $N_j(t)$ is the noise in the jth element, and $Y_j(t)$ is the photo-current in the jth element. Various optimal and suboptimal techniques for performing signal detection have been described and evaluated in [6]. Assuming that the $N_j(t)$ are independent, white, and Gaussian, the optimal detection technique is called matched-filter combining (MFC), in which the jth signal is passed through a matched filter $h^*(-t)$, the result is sampled at the symbol rate, and these samples are combined with weights inversely proportional to the power spectral densities (PSDs) of $N_j(t)$. This weighted sum of symbol-rate samples is a sufficient statistic, and may be used to perform maximum-likelihood sequence detection (MLSD).

For simplicity, we confine further discussion to the case that the J channels are memoryless (i.e., multipath distortion is negligible).[2] In this case, the optimal combining technique is the well-known maximal-ratio combining (MRC), wherein the $Y_j(t)$ are summed with weights proportional to the signal-amplitude-to-noise PSD ratios. Another well-known suboptimal technique is select best (SB), wherein only the single photodetector output having the highest SNR is used for detection purposes. It is easy to show that the SNR achieved using MRC is always higher than with SB (e.g., see [8]). The performance achieved using MRC and SB will be compared in the next section.

When an imaging receiver employs either SB or MRC, for a fixed pixel size and noise variance per pixel, in order to maximize the worst SNR achieved as the signal spot moves to various positions in the pixel array it is necessary to minimize the maximum number of pixels the spot can illuminate. Use of hexagonal pixels ensures that the spot illuminates no more than three pixels, provided that the spot is sufficiently small relative to the pixel size.

In practical implementation of an angle-diversity receiver, some real-time channel and noise estimation technique must be employed to determine the proper combiner weights for MRC or, in the case of SB, to identify the channel having the highest SNR. Various techniques based on one-shot parameter estimation or iterative adaptive estimation have been analyzed and evaluated in [6]. Due to the relatively high SNRs and slow rate of channel variations encountered in typical infrared links, these techniques are easily implemented in practice [6].

POINT-TO-POINT LINKS

In this section, we discuss the design of LOS and non-LOS links using imaging diversity receivers, comparing their performance to links using single-element receivers. The links under consideration are depicted in Fig. 2.

[1] *The noise in wideband optical receivers is often dominated by components whose power is proportional to the square of the preamplifier input capacitance [2].*

[2] *As an example, in an experimental angle-diversity receiver operating at 70 Mb/s, multipath distortion was found to be nearly negligible [6].*

Line-of-Sight Links

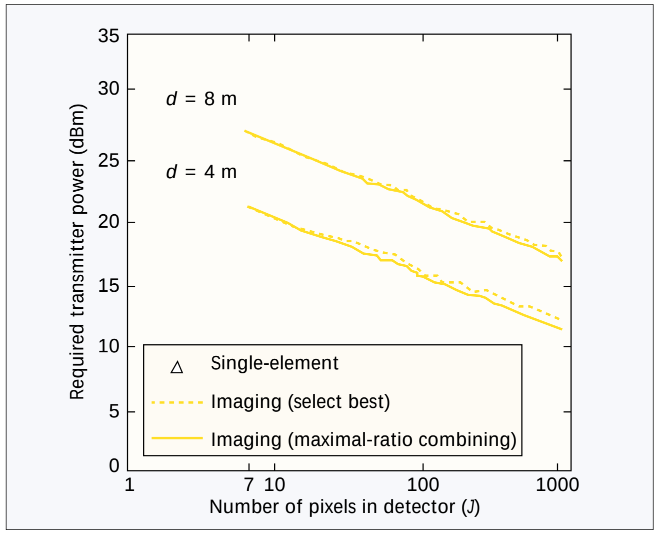
LOS links using single-element and imaging receivers are shown in Fig. 2a and b, respectively. The LOS separation between the transmitter and receiver is denoted by d. The performance of nondirected LOS links using these two receiver designs are compared in Fig. 3, which is taken from [8]. These links employ on-off keying (OOK) and operate at a bit rate of 30 Mb/s. The wide-beam transmitter emits a generalized Lambertian pattern [1] having a semi-angle of 45° (at half power). Both the imaging and non-imaging receivers have FOVs of 45° (semi-angle), and have equal entrance areas and identical bandpass optical filters to minimize noise due to the strong ambient skylight. All links use on-off keying and operate at 30 Mb/s. All receivers have entrance areas of $9\pi/4$ cm^2 and utilize 83-nm-wide bandpass filters. While the transmitter-receiver separation d is held fixed, the position and angular variation of the transmitter are taken to be random variables, corresponding to the user mobility that would be encountered in practice. As a result, even at fixed d, the SNR is a random variable. Figure 3 shows the transmitter power required to achieve a bit-error rate (BER) of 10^{-9} with 95 percent probability. The simplest imaging receiver (7 pixels) requires 3.7 dB less power than the non-imaging receiver, while increasing the pixel count to 1141 yields a reduction in power requirement of about 13 dB. These reductions in the power requirement result from reductions in both ambient light noise and receiver thermal noise. When the number of pixels is small, there is negligible difference between SB and MRC. For very high pixel counts, the latter technique yields a small, but discernible, reduction in power requirement.

Non-Line-of-Sight Links

In this subsection, we discuss the design and performance of nondirected non-LOS links.

The conventional diffuse link, as shown in Fig. 2c, uses a single-beam (diffuse) transmitter and single-element receiver. While it is possible to combine the single-beam transmitter with an imaging receiver, as shown in Fig. 2d, we will not consider this configuration here.[3] When d_h, the horizontal separation between the transmitter and receiver is large relative to the ceiling height, the single-beam transmitter yields a path loss[4] that is proportional to d_h^4, the fourth power of the horizontal separation. This high path loss results from the poor oblique-angle scattering of typical (Lambertian) reflecting surfaces, and from spreading of the wide beam as it propagates.

Path loss can be reduced if the diffuse transmitter is replaced by a multibeam transmitter, also known as a quasi-diffuse transmitter. The quasi-diffuse transmitter can be employed in conjunction with either a single-element or imaging receiver, as shown in Fig. 2e and f, respectively. Such a transmitter emits a collection of relatively narrow beams that illuminate a regular lattice of spots on the ceiling.[5, 6] If receiver shadowing is not to be guarded against, this lattice should be designed to cover the desired range with the minimum number of beams, while ensuring that at least one illuminated spot lies within the receiver FOV, which implies that the lattice should be triangular [8]. If at least two spots lie within the receiver FOV, the link can tolerate blockage of one beam; it is easily shown that this doubles the required number of beams [8]. With the quasi-diffuse transmitter, at large horizontal transmitter-receiver separation d_h, the equivalent path loss is proportional to d_h^2 (i.e., only the square of this separation). If the region that must be covered by the transmitter is large compared to the region of the ceiling viewed by the receiver (in any given location), the number of beams that must be transmitted to cover this region is proportional to the ratio of the areas of these two regions. If the region that must be covered has radius d_h, the required number of beams is proportional to d_h^2.



■ **Figure 3.** *Transmitter power required to achieve a bit error probaiblity of 10^{-9} with 95 percent probability in nondirected LOS links as a function of* J*, the number of detector pixels.*

The imaging receiver, when used with MRC, can be considered a "spatial matched filter." When the quasi-diffuse transmitter is used with an imaging receiver, as shown in Fig. 2f, a synergistic performance enhancement occurs. The desired signal is concentrated in a small region, and the spatial matched filter is able to concentrate its observation on that region, rejecting as much ambient light noise as possible.

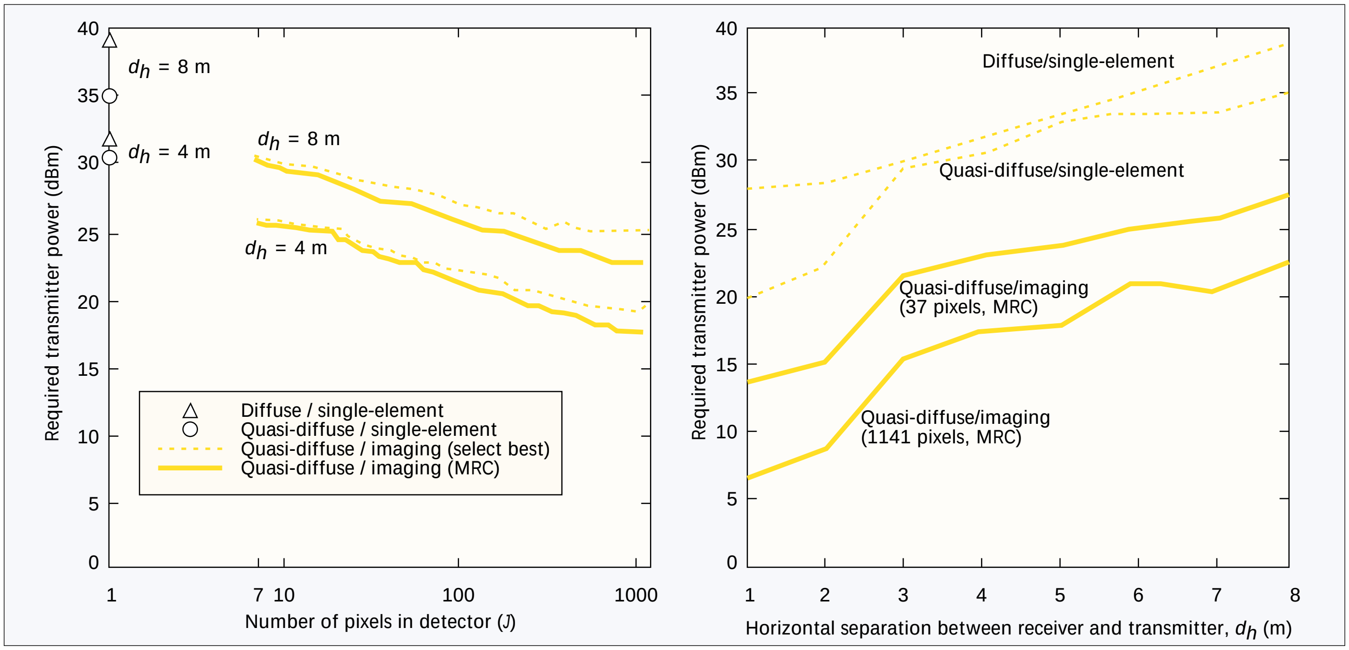
The performance of various nondirected non-LOS link designs is compared in Fig. 4a and b, which is taken from [8]. These systems employ OOK at a bit rate of 30 Mb/s, and operate in a room in the presence of window light and incandescent lighting. The transmitter-receiver separation is fixed, but the transmitter position and angular orientation are random variables, so the SNR is a random variable, even at fixed range. Figure 4a presents the transmit power required to achieve 10^{-9} BER with 95 percent probability as a function of the number of receiver pixels. In this figure we observe that with the imaging receiver, as the number of pixels is increased there is a steady decrease in the transmit power requirement, due to decreases in ambient light noise and preamplifier thermal noise. At large pixel counts, MRC offers a gain of about 2 dB over SB. In Fig. 4b, the transmit power requirement is presented as a function of the transmitter-receiver separation. With a single-element receiver, replacing the single-beam

[3] *Quasi-diffuse transmitters are not much more complex to implement than single-beam transmitters, and provide more improvement in conjunction with imaging receivers. This is due to the fact that when used with imaging receivers, quasi-diffuse transmitters concentrate the signal in a small spot, thus allowing greater noise rejection.*

[4] *We define path loss as the ratio between the transmitted power and the received power, a ratio greater than one.*

[5] *It should be noted that, although the quasi-diffuse transmitter uses narrow beams, eye safety can always be insured by making the beam diameter sufficiently large. Furthermore, the power required in each beam is relatively low (of the order if a few mW), and modest beam divergence is acceptable.*

[6] *Some well-designed practical "diffuse" links employ multiple transmitting beams, typically having had angles of the order of 15°, but they do not explicitly attempt to illuminate a lattice of spots, as in the quasi-diffuse transmitter described here.*



■ **Figure 4.** *Transmitter power required to achieve a BER of 10^{-9} with 95 percent probability in nondirected non-LOS links: a) as a function of J, the number of detector pixels; b) as a function of d_h, the horizontal separation between the transmitter and receiver. Ambient light includes skylight (through a window) and eight 100 W incandescent lamps. All receivers have entrance areas of 9π/4 cm², FOVs of 45° (semiangle), and utilize 83-nm-wide bandpass filters[8].*

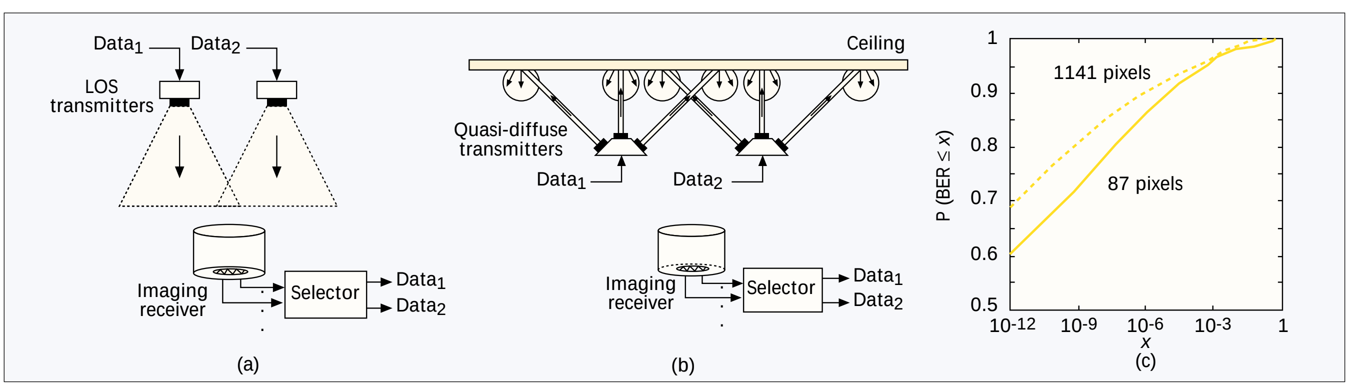
transmitter by its quasi-diffuse counterpart yields a 1 to 7 dB reduction in power requirement, due to a reduction in path loss. When the quasi-diffuse transmitter is employed, exchanging the single-element receiver for a 37-pixel imaging receiver yields a 7–8 dB power reduction, while a 1141-pixel receiver offers a 13 dB reduction.

Space-Division Multiplexing

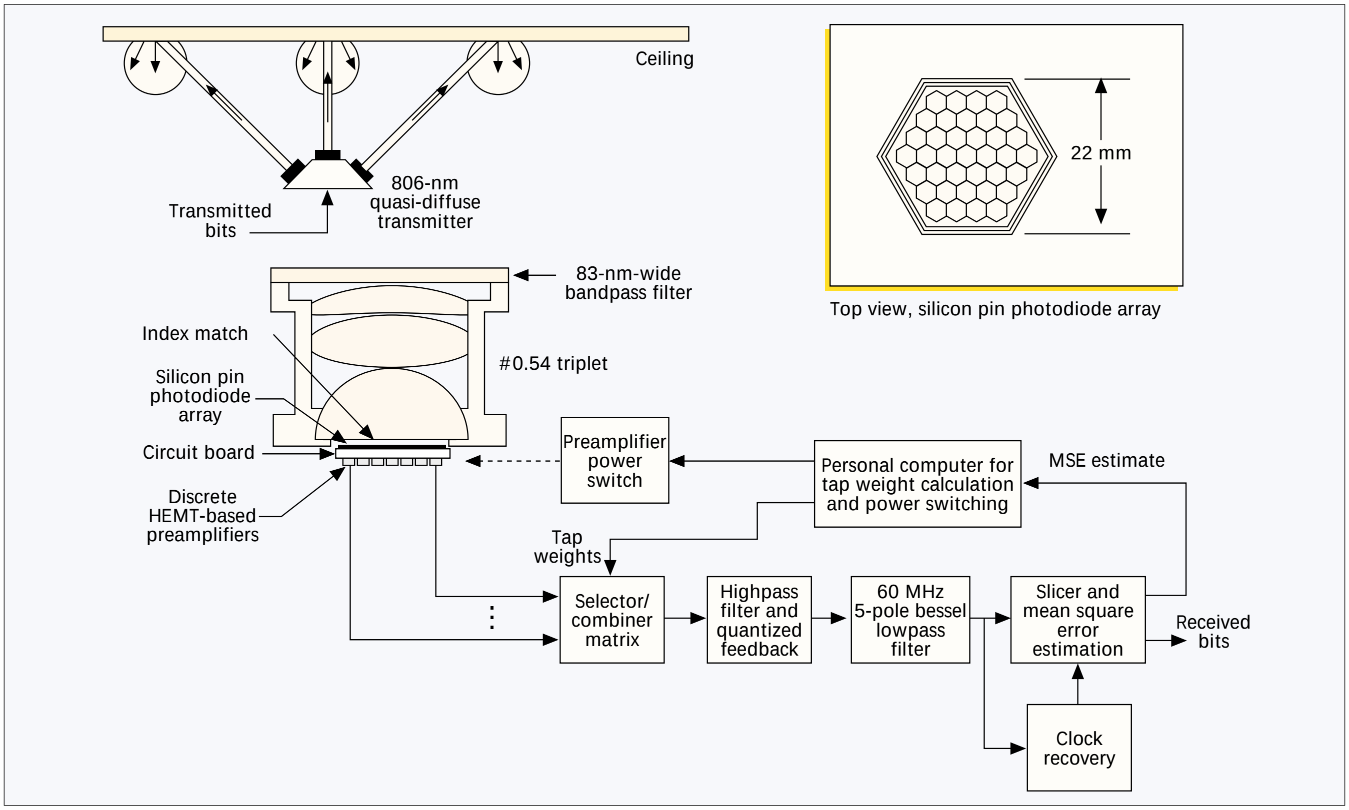
Techniques for multiplexing the transmissions of different users can be classified as electrical or optical [2]. Electrical multiplexing techniques include time-, code-, and subcarrier frequency-division multiplexing. While electrical multiplexing techniques are easy to implement, because they require all users to share a single channel, they necessarily entail a loss of per-user capacity. Optical multiplexing techniques, which include wavelength- and space-division multiplexing (SDM), do not necessarily require a loss of capacity per user. In wavelength-division multiplexing, if all terminals are to be able to communicate with each other, each may need to be equipped with multiple receivers, each tuned permanently to a different wavelength, because of the difficulty in fabricating compact large-area tunable optical filters.

In SDM, different users located in close proximity to each other transmit using the same wavelength at the same time. Using an angle-diversity receiver, which is able to separate signals depending on their direction of arrival, it is hoped that these multiple transmissions can be received with acceptably small mutual interference.

Figure 5a shows schematically how SDM might be implemented using LOS transmitters and an imaging receiver. For example, one might employ this scheme in building a hub capable of establishing simultaneous point-to-point links with terminals equipped with IrDA transceivers, thereby giving such terminals access to a wired backbone network and permitting them to communicate with each other in a multiple-access network. Equipping the hub with an imaging receiver would permit the hub to receive multiple inbound transmissions with tolerably small co-channel interference. SDM infrared systems employing steerable LOS beams and imaging receivers have been proposed recently in [9, 10].



■ **Figure 5.** *Space-division multiplexing: a) with LOS transmitters and imaging receivers; b) with quasi-diffuse transmitters and imaging receivers; c) cumulative distribution function of the BER in a system using two quasi-diffuse tranmsitters and an imaging receiver. The transmitter–receiver horizontal separation d_h ranges from 0 to 5 m. Each transmitter emits an average power sufficient to achieve a BER of 10^{-9} with 95 percent probability in the absence of co-channel interference. The receiver employs maximal-ratio combining [8].*



■ **Figure 6.** *100 Mb/s nondirected non-LOS infrared wireless link.*

SDM might also be employed in non-LOS systems using quasi-diffuse transmitters and imaging receivers, as shown in Fig. 5b. Such an arrangement creates a shared-bus physical topology, which is well-suited to random access LANs. If at least one spot from the desired transmission lies within the receiver FOV and is not overlapped by spots from other transmissions, it can be detected successfully. Figure 5c illustrates the performance of this SDM scheme in a two-transmitter scenario. Each transmitter emits a lattice of spots capable of covering a 5-m range, and at an average power sufficient to achieve 10^{-9} BER with 95 percent probability in the absence of co-channel interference. The positions and orientations of the two receivers are random. Figure 5c presents the cumulative distribution function (CDF) of the BER.[7] It can be seen that 10^{-9} BER is achieved with probabilities of 73 and 81 percent when the receiver employs 37 and 1141 pixels, respectively. The BERs achieved with 95 percent probability are 1.6×10^{-4} and 7×10^{-5} for 37 and 1141 pixels, respectively. These results indicate that the particular non-LOS SDM scheme evaluated would probably not allow implementation of a reliable, random access LAN. To achieve reliable operation, the LAN might be designed to resort to using an electrical multiplexing technique when SDM fails to achieve the desired BER.

The Prototype 100 Mb/s Link

We are constructing an infrared wireless link using a quasi-diffuse transmitter and an imaging angle-diversity receiver, as shown in Fig. 6. This link is expected to achieve a BER on the order of 10^{-9} at a bit rate of 100 Mb/s, over a horizontal transmission range of at least 4.5 m, in the presence of bright sunlight. Because of the imaging receiver's excellent rejection of delayed multipath components (see the "Angle-Diversity Reception" section), this link should not require any channel equalization (e.g., decision-feedback equalization) in order to achieve this bit rate. The link employs a quasi-diffuse transmitter [6] that emits eight eye-safe beams at a wavelength of 806 nm. When modulated by an OOK bitstream, each beam has an average power of about 75 mW.

In order to reject ambient light noise, the receiver utilizes a bandpass filter having an 83-nm-wide passband centered at 833 nm. With this choice of bandwidth and center wavelength, the filter achieves a signal transmission of 80 percent, even as the passband shifts to shorter wavelengths at oblique angles of incidence. Imaging is performed by a custom-designed *f*/0.54 triplet. This lens has an entrance aperture diameter of 3 cm, and achieves an FOV close to 45° (semi-angle). On the image plane of 2.3 cm diameter, the image spot diameter increases from 1.4 mm to 6.6 mm as the angle of incidence ranges from 0° to 45°.

The lens output is index-matched directly to an anti-reflection-coated, custom silicon pin photodiode array. As shown in the inset of Fig. 6, this array comprises 37 hexagonal pixels. Each pixel has a capacitance of about 6 pF. The array achieves a transit-time-limited cutoff frequency exceeding 100 MHz. The detector array is flip-chip bonded to a circuit board, on the back of which 37 discrete preamplifiers are mounted. Each high-impedance preamplifier employs a load resistance of 30 kΩ and a common-source high-electron-mobility transistor amplifier. An R-C equalizer compensates for the high-impedance preamplifier pole near 600 kHz. The equalized receiver achieves an overall cutoff frequency of about 100 MHz. The input-referred noise PSD (one-sided) is flat near 1×10^{-24} A^2/Hz below 10 MHz, above which it increases quadratically to approximately 4×10^{-24} A^2/Hz at 50 MHz.

The 37 preamplifier outputs are passed to a circuit that selects the three outputs having the strongest signal components (since the signal spot usually overlaps with no more than three hexagonal pixels), and sums these with variable

[7] *Because the BER depends on both the SNR and signal-to-interference ratio (SIR), neither the CDF of the SNR, nor that of the SIR, is sufficient to characterize the link BER.*

weights. These weights are adjusted adaptively to implement MRC, as described shortly. A highpass filter having a cutoff frequency of 2.2 MHz removes any residual near-d.c. fluorescent light noise [2], and quantized feedback is employed to remove the resulting baseline wander. A five-pole, 60-MHz Bessel filter is used to attenuate wideband noise sources. Clock recovery is performed by a second-order phase-locked loop. A decision circuit estimates the received bits and subtracts the result from the Bessel-filter output. This difference signal is sampled to yield an estimate of the error, which consists, in general, of noise and intersymbol interference. A personal computer takes a moving average of the error samples to estimate the mean square error (MSE), and adjusts the combiner weights to minimize the MSE, using an iterative algorithm described in [6]. Assuming that intersymbol interference is small, minimum MSE combining is approximately equivalent to MRC. In order to minimize receiver power consumption, the computer powers down all preamplifiers, except those in a cluster centered around the desired signal spot.

As of this writing, we have constructed the quasi-diffuse transmitter. The receiving lens and filter have been constructed, and we have tested a single-photodetector version of the receiver. The variable-gain combiner and all following components have been built and tested.

CONCLUSIONS

Imaging receivers are a promising means to improve the performance of infrared wireless links. In both LOS and non-LOS links, they reduce ambient light noise, receiver thermal noise, and multipath distortion, enabling higher bit rates to be achieved with reduced transmitter power. Imaging receivers also reduce co-channel interference, and may enable SDM to be employed in multi-user systems. In non-LOS links, quasi-diffuse transmitters reduce path loss as compared to diffuse transmitters, thereby providing a further reduction of the transmit power requirement. While these components are promising, further research and development is needed before they can become a commercial reality. In the imaging receiver, work is required to reduce the lens size, to integrate the detector and preamplifier arrays, and to minimize preamplifier power consumption. Eye-safe quasi-diffuse transmitters must be implemented in a highly integrated form (e.g., using computer-generated holograms for beam-shaping). Further research is needed to identify viable designs for multiple-access networks using SDM with non-LOS links.

ACKNOWLEDGMENTS

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