Direct Detect Modulations of High Speed Indoor Diffused Infrared Wireless Transmission

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Abstract: High speed indoor diffused infrared wireless transmission is greatly needed for data and multimedia applications. We investigated the error rate performance of OOK (on off keying), NRBI (non-return-to zero with bit insersion), M-ary PPM (pulse position modulation), and two novel coded direct detect modulations, DCGPPM (differentially coded and guarded PPM) and MRLC (modified run length code), by adopting representative channel modeling from measurements and simulations. Practical implementation issues have been further considered. From our results, we suggest DCGPPM at 10M bps, 4-ary PPM or DCGPPM at 20M bps, OOK or NRBI at 40M bps, and MRLC at 100M bps, for the baseband direct detect transmission of indoor wireless optical transmission.

I. INTRODUCTION

Wireless data networking has become an emerging technology in computer and communication industries due to recent blooming development of mobile computing and data networking. Under the strong demand of communication bandwidth in multimedia applications, wireless physical transmission to economically support high speed networking much above 10M bps throughput is greatly needed, especially in indoor environments. Under the strict limitation of radio spectrum, optical transmission is an attractive alternative for indoor high speed wireless transmission. To avoid unfriendly line-of-sight propagation, optical transmission which is most likely to be done via infrared due to the current availability of components must rely on diffused or nondirective propagation shown in Figure 1. Since Gfeller and Bapst's pioneer investigation to use diffused infrared transmission for indoor wireless data communication [1], a lot of research has been conducted in this direction [2-11] to meet above demand. Diffused infrared transmission seems to be the best approach to support such a demand with simple implementation. However, not many investigations really presented the efforts toward high speed realizations beyond 10M bps transmission except [2,11]. In this paper, we shall investigate efficient modulation methods for high speed diffused (nondirective) infrared wireless communication, which may be the most fundamental aspect of communication but still not available in this area. This research is based on the channel characterization done by IBM [2,12] and UC Berkeley [5-9] to evaluate possible modulation methods.

Two coded baseband modulations are further proposed to improve error rate performance. They are DCGPPM (differentially coded and guarded pulse position modulation) and MRLC (modified run length codes). Based on the special features of diffused infrared channel characterisitics, we develop DCGPPM based on the concept of trellis coded modulation (TCM) with simple hard decoding, and MRLC based on the concept of run length codes due to partial response property. Both coded modulations are analyzed in this paper. Our investigations target at data rate from 10M bps up to 100M bps. Due to the attraction of baseband direct detect modulations in implementation complexity, modulations with carrier are not within the scope of this paper.

II. DIRECT DETECT MODULATIONS

Traditional modulations associated with economic optical sources are intensity modulation such as on off keying (OOK) and pulse position modulations (PPM) which are all baseband modulations. The data information are embeded in the optical pulses and the receiver noncoherently detect and demodulate the signal under typical noises. In traditional point-to-point optical communication in optical fiber or free space inter-satellite links, we would like to confine the optical beam as narrow as possible to achieve the highest efficiency. On the contrary, to achieve a robust link in indoor diffused optical channels, we would like to spread the optical power into a wide angle [1,2,10]. After diffusion from the surfaces in a room such as walls, the optical power can flood almost everywhere in the room. Once we have a receiver fitting to operate in such a situation, this "line-of-sight" optical communication can work even the direct path is blocked and we achieve wireless communication similar to radio communication cases.

A diffusion model was established to demonstrate the concept of diffused indoor wireless optical channel in [1]. Based on a simulation model of [12], it has been noted that such a channel is a kind of power-limited channel [3] if direct detect modulations are used. To further investigate in this area while statistical model is not available, we adopt two deterministic models based on the measurements done by UC Berkeley [8]. The channel is hereafter modeled as a linear filter with impulse response $h(t)$. In case the direct path is not blocked, $h(t)$ can be in general represented by a superposition of two exponential functions with the second one half of the first one, or a similar superposition with the first one half of the second one, which means the direct path under certain amount of shadowing effects.

Since one of the primary advantages to apply infrared wireless communication, components used typically introduce large amount of noise such as dark current, shot noise, Gaus-

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sian noise, and so on. Consequently, the overall noise effect before symbol decision can be well approximated by a wideband Gaussian noise. To concentrate on the multipath channel effect in noisy wireless infrared channels, we ignore those factors important in real implementation such as background noise, interference caused by fluorescent lamps, low frequency noise, which can be eliminated by implementation techniques such as precoding [7] and filtering [14].

Traditional low complexity modulations for infrared communication considered for such kind of applications include OOK, PPM (4-ary and 16-ary), non-return-to-zero with bit insertion (NRBI), and Manchester. The primary considerations to choose from them are error rate performance, power consumption, synchronization concern, and implementation complexity. Manchester codes are actually a kind of binary PPM in noncoherent optical communication. Thus, we consider binary PPM which is a more general class of signaling. For high speed communication toward 100M bps, the optical pulses are likely to occupy the whole time slot as the desirability of optical sources such as LEDs and low complexity laser diodes. NRBI is actually a line coding proposed in the IEEE 802.11 standard committee as a candidate of IR PHY. NRBI uses OOK as the fundamental modulation. However, to avoid a run of "0"s to have unfavored impacts on synchronization, an extra "1" is added if there is a run of three "0"s. To fairly compare all kinds of direct detect modulations, signaling is assume to follow the schemes described below.

1. We assume the same rectangular pulses beginning at the instant of a symbol or the corresponding time slot. The duration of the pulses is exactly identical to that of a slot in 16-ary PPM at corresponding data rate.
2. The optical pulses go through the same channel and experience the same system characteristics and noise statistics.
3. All different modulations are direct detected with an appropriate receiving filter. All signal constellations are equally probable.

The error rate calculation of OOK and PPM can be found in literatures. For indoor wireless optical channels, the exact error rate can be calculated as [4] in terms of power leakage fraction f and the ratio between received signal power and r.m.s. noise power, ρ. The power leakage is caused by the multipath effects in diffused channels which spread the received pulse waveform to introduce intersymbol (or interslot) interference by certain amount of power (pulse waveform) "leaking" beyond the symbol/slot boundaries to (most likely) next symbol/slot.

For OOK, NRBI, and MRLC, a scheme such as straightforward decision feedback estimation to compensate power leakage effect is assumed so that the "optimal" threshold decision is used in our error rate evaluation. [13] demonstrated that such an assumption is pretty convincing. Within the data rate of 10M bps to 100M bps, the error rates approximate

$$P_{e,OOK} \cong \frac{P_M + P_F + P_m + P_f}{4} \tag{1}$$

$$P_{e,NRBI} \cong \frac{5}{8}\left(P_M + P_F\right) + \frac{3}{8}\left(P_m + P_f\right) \tag{2}$$

where $P_M = P_F = Q\left(\frac{1-f}{2}\rho\right)$; $P_m = Q\left(\frac{1+f}{2}\rho\right)$; $P_f = Q\left(\frac{1-3f}{2}\rho\right)$; $Q\left(x\right) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-t^2/2} dt$. Please note that P_f is the dominating term in OOK-based modulations.

Under the constraint of identical data rate, power leakage of PPM modulations has to be considered with more time slots. After the channel filtering, we denote f_0 as the fraction of power in the desired time slot; f_1 as the power leakage to the immediately next time slot; f_2 as the power leakage to the second next time slot, and so on. We consider the optimal detection of PPM with upper bounded performance expressions for 4-ary PPM and 16-ary PPM. For binary PPM, the optimal detection is taken as differential detection with zero-level threshold.

$$P_{e,2-PPM} \cong \frac{1}{2}\{Q\left[\frac{(f_0 + f_2 - f_1)}{\sqrt{2}}\rho\right] + Q\left[\frac{(f_0 - f_2)}{\sqrt{2}}\rho\right]\} \tag{3}$$

For general M-ary PPM, the symbol error rate is

$$P_{e,M-PPM} \cong \frac{M+1}{M} Q\left(\frac{f_0 - f_2}{\sqrt{2}}\rho\right) + \frac{M+2}{M} Q\left(\frac{f_0 - f_2}{\sqrt{2}}\rho\right) \tag{4}$$

III. DIFFERENTIALLY CODED AND GUARDED PPM

One important advantage of PPM in optical communication is the ease to implement coded modulation. Although earlier investigations for general cases are not completely successful to reach satisfactory coding gain, we have a better chance to design a specific coded modulation based on PPM to utilize the special feature of diffused channel, uneven intersymbol (or interslot) interference. Furthermore, as the desirable coded modulation(s) should operate in pretty high speed targeting at above 10M bps, simple hard decoding is a must for low complexity implementation which is a competitive edge for nondirective optical wireless communication with distance limitation. We therefore propose a new coded modulation derived from the set partitioning principle in this section.

We may recall that the best performance index of data communication is actually the packet error rate rather than bit error rate. Error propagation in a packet is as harmful as a single bit error. Our purpose is to develop an easy decoding coded modulation by set partitioning being able to correct primary error pattern(s) while packet error is a primary concern here. More precisely, we intend to develop a finite state code based on set partitioning to increase the distance among signal constellations that can be realized by decreasing the observed noise in addition to increasing the separation of signal constellation which is difficult for noncoherent optical PPM. From above rationale, we develop a new coded modulation, differentially coded and guarded PPM (DCGPPM) which can be considered as a special case of general TCM on PPM but the decoding mechanism can be realized by only several logic gates.

Let us start from an M-ary Gray coded PPM. We first expand these slots to $2M$ slots with last bit as the check bit. The check bit is alternating "1" or "0". In other words, each M-ary PPM slot is split into two slots with check bit "1" and "0". If the Gray coded PPM start with slot of even weight, check bit "0" is appended to the first split slot, and *vice versa*. We further append a redundant time slot which does not carry any information at the end of a PPM symbol to form a $(2M+1)$-ary PPM. The encoding and decoding procedures are considered as finite-state machines. Given the parity check of previous symbol formed by information bits only, the optical pulse is placed into the slot according to current information bits with identical check bit. As an example, we consider an original 4-ary PPM since binary PPM and 4-ary PPM have the best spectral efficiency in PPMs. The original slot arrangement (00,01,11,10) of 4-ary PPM is expanded into

$$(00\underline{0}, 00\underline{1}, 01\underline{0}, 01\underline{1}, 11\underline{0}, 11\underline{1}, 10\underline{0}, 10\underline{1}, X)$$

where the underline bit in each time slot represents the check bit and X denotes the redundant slot. Therefore, DCGPPM signal constellations are partitioned to two sets according to the check bit. This redundant slot is actually very useful to alleviate the intersymbol interference leakage, to reduce the noise bandwidth, and can act as a state in decoding process. Suppose the previous symbol has parity "0", that is, 00 or 11. Current optical pulse maps to only those slots with "xx$\underline{0}$" (check bit "0"). Such a differential encoding proceeds for the entire data packet. Acute readers may note that consecutive optical pulses separate 2 empty slots at least. This implies that the receiving filter only has to be an ideal low pass filter with cutoff frequency $3/T$ where T is the symbol period. Noise reduction (thus the increase in the "Euclidean distance" of signal constellations) is achieved, however, the scale must be evaluated more carefully later.

The decoding is extremely simple. The PPM detector decides the slot with the most optical power (equivalently, energy). Then, the decoder examines the check bit of this detected slot being the same as that of previously decoded symbol or not. If yes, the decoding is correct. If not, since the power leakage is most likely into next time slot especially for high data rates, the decoder decides the correct time slot to be the one prior to the detected one. For example, previously transmitted symbol is "00" and correctly decoded. Current symbol "01" is encoded to the slot "010". However, due to the channel multipath effect to spread the received waveform, the detected slot may become "011". At the decoder, it is obvious that the check bit is not correct and the decoder will decode current symbol as previous slot "010". This decoder can be simply implemented by a few logic gates and thus appropriate for high speed communication.

We have to be careful in designing the detector for DCGPPM. The received waveform after the channel effects has been stretched toward delay side. The most reliable timing information is embeded in the rising edge which is also the best for DCGPPM timing. If the receiver derives the timing based on the rising edges of optical pulses, DCGPPM can be robust in timing compared with other direct detect optical modulations, especially toward the delay side around half time slot for most cases of diffused channel characteristics.

With properly deriving the timing from the rising edges of pulses, the symbol error rate of DCGPPM can be approximated as

$$P_{e,DCGPPM} \cong \frac{M+1}{M} Q\left[\frac{\max(f_0, f_1) - \max(f_2, \cdots)}{\sqrt{2}}\rho\right] \tag{5}$$

while such performance is pretty robust to inaccurate timing recovery, a feature of DCGPPM since two correct time slots are available for decoding. From Table 1 of Section V, 4-ary PPM provides the best spectral efficiency which corresponds to a 9-ary DCGPPM. DCGPPM shown in Figures 1 and 2 can provide 1-3 dB coding gain with simple hardware decoding by a few logic gates is very satisfactory if we consider TCM with soft decision can provides 1-2 dB gain by one expansion of signal constellation in optical communication links.

IV. MODIFIED RUN LENGTH CODES

Although DCGPPM can provide effective signaling for moderately high speed diffused infrared transmission, it is practically difficult toward very high speed transmission such as 100M bps due to low spectral efficiency (see Table 1 in Section V). As high speed decision feedback equalizer is pretty much realizable for OOK based modulation to deliver reasonable performance, coded modulation based on OOK is also desirable. TCM is generally not appropriate in this situation. However, we looked into the feature of direct detect modulation [4] in diffused channels, run length codes should be a good candidate. Adopting the uneven intersymbol interference feature, we modify the run length codes for our direct detect optical wireless communication and call this set of codes as MRLC (modified run length codes). Suppose "1" represents on for OOK. MRLC, a sort of coded modulation, maps every two bits ("00". "01", "11", "10") as a symbol into different code words which are "01", "001", "0001", and "00001". Since power efficient modulation is very much desired, only one bit of "1" in each code word. The decoding rule is also very simple for high speed hard decision. After the OOK detection, the demodulator basically count the number of "0"s prior to "1" for decoding and no two consecutive "1"s case is allowed (thus corrected).

The symbol error rate of MRLC is approximately

$$P_{e,MRLC} = \frac{3}{2} P_F + P_M \tag{6}$$

V. PERFORMANCE COMPARISONS

(1)-(6) presented the theoretical approximations of error rate performance for various direct detect modulations, OOK, NRBI, binary PPM, 4-ary PPM, 16-ary PPM, 9-ary DCGPPM, and MRLC, which contain most interesting candidates in wireless diffused infrared communications. Figures 1-7 summarize numerical results of interesting cases with the same optical pulses into the same channel. Two kinds of channels are considered. The first one is the direct path with a secondary propagation path separated by 10 nsec. The second one is the direct path under shadowing and thus a relatively large "secondary" propagation while the communication link actually relies on the secondary propagation, diffused communication.

The choice of modulation is not decided only by the bit error rate, especially when the error rate around the same order and being acceptable. We summarize several important factors in Table 1. Spectral efficiency has two major implications in complexity and multipath barrier. Lower spectral efficiency implies that the receiver has to operate at higher clock rate with the price of implementation complexity, and that the whole system has to combat the multipath barrier at lower information rate. That is why 16-ary PPM is not a good choice at high speeds. Even DCGPPM designed for such a channel has speed limitation as lower spectral efficiency is easier to approach bandwidth limited situation. MRLC is a kind of modulation with high spectral efficiency and resistance to multipath and therefore is the only candidate being able to work in the range of 50-100M bps or higher, where just high spectral efficiency is not enough. Another critical consideration in practical applications is power efficiency, which can be evaluated by average number of pulses per bit that is better to be a small number. 16-ary PPM provides the best power efficiency. Consequently, once the spectral efficiency is not a concern, say a moderate speed at 1M bps, 16-ary PPM should be one of the best candidates since power efficiency is a dominating factor. Estimation of decision threshold has implications on complexity while OOK based modulations are unfavored. On the other hand, a pulse in each symbol without a run of pulses is favored for synchronization. That is another reason to append "1" after a run of three "1"s for NRBI. Again, OOK and NRBI are unfavored in terms of this consideration.

	Spect. Eff.	Pulse per Bit	Channel Est.	Pulse in Each Sym.
OOK	1	0.5	Yes	No
NRBI	0.96	0.625	Yes	No
2-PPM	0.5	1	No	Yes
4-PPM	0.5	0.5	No	Yes
16-PPM	0.25	0.25	No	Yes
DCGPPM	0.22	0.5	No	Yes
MRLC	0.57	0.5	Yes	Yes

Table 1 Comparisons of Implementation Factors

Generally speaking, the choice of modulation depends heavily on the speed. For moderate speed like 1M bps, power efficiency is most important factor while multipath plays very limited role. At moderate high speeds around 10M bps, multipath effects caused by the channel become a factor while spectral efficiency is still not critical to prohibit practical applications. Performance with power efficiency concern is the selection criterion. When the transmission speed going higher and higher, modulation(s) being able to resist multipath effects with reasonable spectral efficiency decides our choice.

VI. CONCLUSIONS

We demonstrated the error rate performance of all possible direct detect modulations including two novel coded modulations designed for such channels. By taking more implementation issues into consideration, various modulations based on different speed were suggested. It is good to use DCGPPM at 10M bps, 4-ary PPM or DCGPPM at 20M bps, OOK/NRBI at 40M bps, and MRLC is the only possible direct detect modulation toward 100M bps transmission. Two novel coded modulations associated with OOK and PPM both shows great value for moderately high speed transmission (DCGPPM) with up to 3 dB coding gain by a few logic gates for decoding and very high speed transmission (MRLC) without massive signal processing.

As a matter of fact, to pick up a modulation is an integrated consideration of modulation error rate, synchronization, and equalization that is very helpful in direct detect modulations in wireless indoor optical channels and can be realized by simple decision feedback structure. However, the conclusion of this paper defines the fundamental limiting performance of high speed indoor optical wireless transmission by direct detect modulations.

References

[1] F. Gfeller, U. Bapst, "Wireless In-House Data Communication via Diffused Infrared Radiations", *IEEE Proceeding*, vol.67, no.11, pp.1471-1486, Nov. 1979.

[2] K.C. Chen, *et al.*, "Indoor High Speed Wireless Networks via Optical Transmission", *Records of the International Telecommunication Union TELECOM'91 Technical Forum*, vol.2, pp.211-215, 1991.

[3] K.C. Chen, "On Off Keying Optical Transmission and Channel Capacity for Indoor Wireless High Rate Data Networks", *Proceeding IEEE Globecom*, Phoenix, 1991.

[4] K.C. Chen, C.H. Lee, "Capture in Multiple Access Lightwave Networks Employing Direct Detect Modulations", *Proceeding IEEE Globecom*, Orlando, 1992.

[5] J.R. Barry, *et al.*, "High Speed Nondirective Optical Communication for Wireless Networks", *IEEE Networks Magazine*, pp.44-54, Nov. 1991.

[6] J.R. Barry, *et al.*, "Simulation of Multipath Impulse Response for Indoor Wireless Optical Channels", *IEEE Journal on Selected Areas in Communications*, vol.11, no.3, Apr. 1993.

[7] J.M. Kahn, W.J. Krause, J.B. Carruthers, "Experimental Characterization of Non-Directed Indoor Infrared Channels", submitted to the *IEEE Trans. on Communications.*

[8] A.J. Moreira, *et al.*, "Modulation/Encoding Techniques for Wireless Infrared transmission", *IEEE P802.11/93-79.*

[9] C.R. Lomba, *et al.*, "Update of Propagation Losses and Impulse Response of the Indoor Optical Channel", *IEEE P802.11/93-142.*

[10] R. Samdahl, "PPM Infrared PHY Strawman Proposal", *IEEE P802.11/93-212.*

[11] M.D. Audeh, J.M. Kahn, "Performance Evaluation of L-Pulse-Position Modulation on Nondirective Indoor Infrared Channels", *Proc. IEEE ICC'94.*

[12] P.D. Hortensius, private communication.

[13] K.C. Chen, "On Optical OOK Transmission in Indoor Wireless Time Varying Environments", *Proc. International Symposium on Information Theory and Applications*, Hawaii, 1990.

[14] T.H. Tsaur, K.C. Chen, *et al.*, "A Nondirective Infrared Transceiver for Indoor High Speed Wireless Data Communication", *IEEE Tr. on Consumer Electronics*, Feb. 1994.

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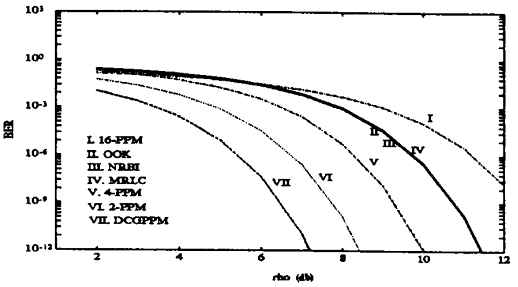

Figure 1: Direct path at 10M bps.

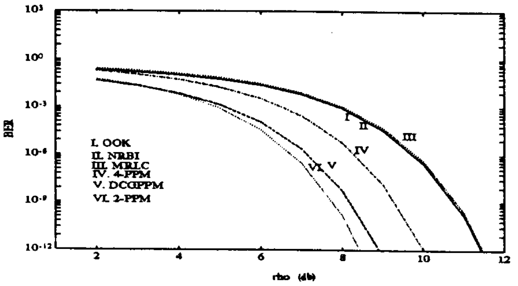

Figure 2: Shadowing at 10M bps.

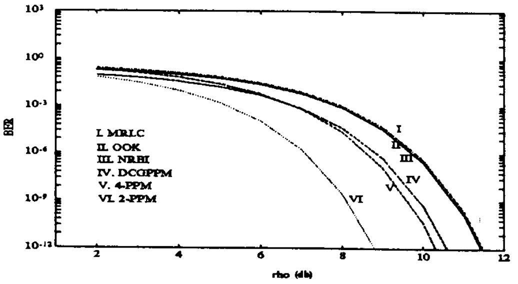

Figure 3: Direct path at 20M bps.

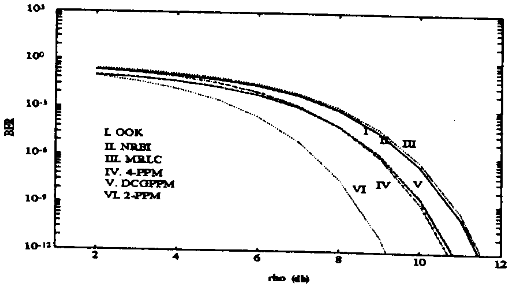

Figure 4: Shadowing at 20M bps.

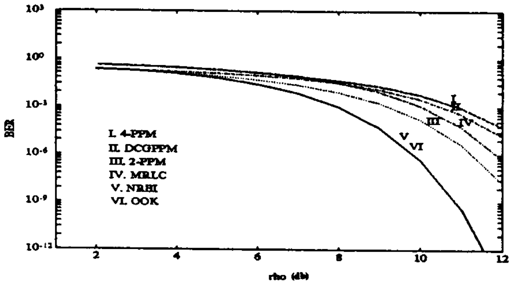

Figure 5: Direct path at 40M bps.

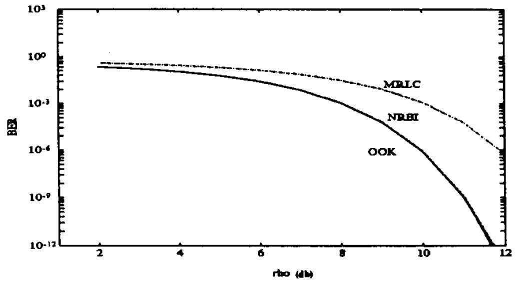

Figure 6: Shadowing at 40M bps.

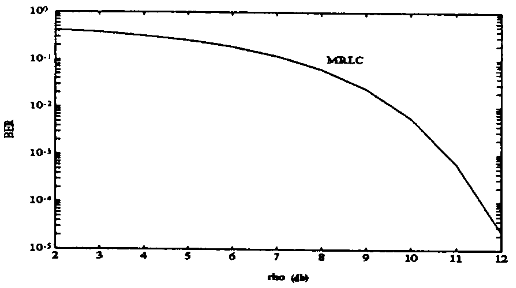

Figure 7: Direct path at 100M bps.