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Title: **Modulation / Encoding Techniques for Wireless Infrared Transmission**

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Abstract

A set of two modulation/encoding techniques are proposed for transmission over the wireless infrared channel. The performance of the proposed techniques is evaluated in terms of the required optical power for a specified bit error rate and implementation complexity. For this purpose, a practical channel model, where the most important factors are considered, is described.

This work is being carried out as part of the ESPRIT.6892 - POWER (Portable Workstation for Education in Europe) project comissioned by the CEC.

1. Introduction

The in-door wireless infrared channel exhibits some particular characteristics that must be considered in the design of an infrared transmission system. In this document, a pratical model for the in-door wireless infrared channel is presented and its limitations are identified for future research.

This channel model is then used to evaluate the performance of On-Off Keying (OOK) with Manchester encoding and uncoded Pulse Position Modulation (PPM) as two solutions for infrared transmission. For both techniques, examples of the receiver sensitivity are presented for a 1 Mbps transmission system, taking typical values for the system parameters as the background noise and photodetector active area.

Some aspects related to the implementation complexity are also analysed, in particular those related to the use of these transmission systems in portable and battery operated equipement.

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2. Infrared link reference model

The physical transmission support for the wireless network is based on an optical infrared transmission system. A generic block diagram is presented in figure 1.

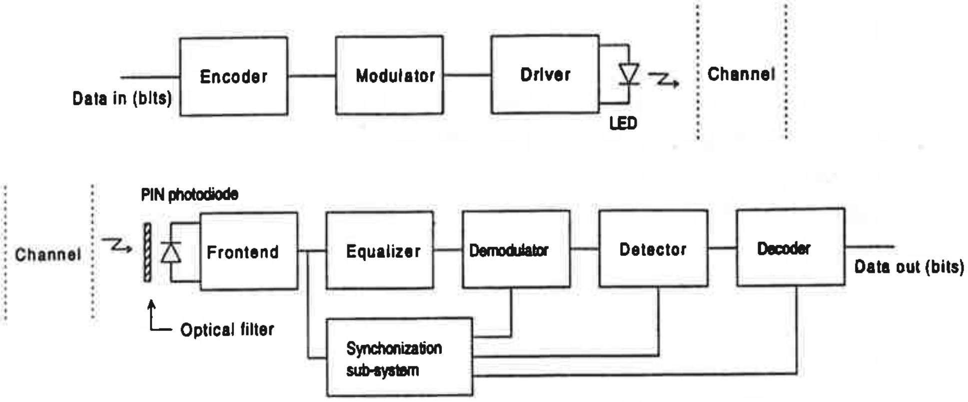

Figure 1. Block diagram of the transmission system.

On the transmitter side, the encoder is responsible for line coding and/or error correction coding. Line coding can be used as a way to shape the power spectral density of the transmitted signal according to the channel characteristics and to ease clock recovery on the receiver side. Error correcting codes may also be included to increase system performance and reduce the optical power requirements.
The optical sources considered are LEDs. Laser diodes are an alternative, but LEDs are preferred for several reasons such as low cost, simple driver circuits (no temperature control is needed) and reduced safety problems.

On the receiver side, the optical front-end is preceded by an optical filter to reduce the amount of ambient light that reaches the photodetector, thus reducing the shot noise on the detector. For this kind of applications, the transimpedance front-end configuration is the most suitable due to its higher dynamic range and wider bandwidth over the high impedance configuration. High dynamic range is required since the signal level is strongly dependent on the infrared transceiver position and orientation within a room, while wide bandwidth may avoid the equalisation, mandatory on the high impedance configuration.
The synchronisation subsystem may be reduced to simple clock recovery circuits in the case where simple coding and modulation techniques are used like OOK Manchester encoded, or it may include bit, word and frame synchronisation circuits if more complex coding and modulation techniques are used.

The most appropriate techniques and the design of the blocks in figure 1, depends on the channel characteristics. In the next section a description of the wireless in-door infrared channel is presented. Then, a simple model is derived for use throughout the rest of the analysis.

3. Channel model

The wireless in-door infrared channel has several particular characteristics that must be taken into account on the system design. The most important are the following:

- **Dynamic range:** the signal irradiance (average optical power per unit area) at the receiver site is very irregular, depending on the receiver position and orientation within a room. The optical power distribution within the room also depends on the infrared cell configuration, propagation modes (line-of-sight, diffuse, etc.) and emitter radiation pattern. These factors result in a wide dynamic range of the infrared cell as discussed in a companion contribution [7].
- **Ambient light noise:** in a typical in-door environment, there are ambient light in the form of natural (solar) light and artificial light produced by incandescent and fluorescent lamps. The ambient light optical power spectrum extend to the infrared region, reaches the receiver and produces shot noise on the photodetector. The power spectral density of this noise is proportional to the average optical power incident on the photodetector and may constitute the major limiting factor on the system performance. Noise reduction can be achieved by optical filtering, cutting off the optical spectral components of ambient light that are outside the signal band.
- **Interference:** Artificial light sources also introduce optical interference due to variations on the emitted optical power. This interference is introduced in the optical channel in the form of harmonics of the mains power supply frequency and exhibits considerable spectral components up to 50 kHz. Fluorescent lamps, in particular those using electronic ballasts which operate at higher frequencies, are the more important sources of this interference. Since this interference is higher at lower frequencies, it is very important to avoid the transmitted signal power spectrum at low frequencies. Here, spectral shaping of the transmitted signal may be performed by resorting to line coding and modulation.
- **Multi-path dispersion:** Another characteristic of the wireless in-door channel is multi-path dispersion produced by multiple reflections of the emitted signal on walls, ceiling, floor, furniture and even moving people. This multi-path dispersion increses with higher room dimensions and its effect also increases with the baud rate.
- Other limitations must be taken into account if we include the optoelectronic devices, emitters (LEDs) and receivers (PIN photodiodes), as part of the channel. LEDs used in this kind of applications, i.e., with high output power, exhibit slow rise and fall times, thus limiting the maximum modulation frequency and baud rate. On the receiver side, large area PIN photodiodes must be used in order to collect as much optical power as possible. However, there is a limit on the maximum active area one can use due to the parasitic capacitance of the photodiode. The higher the capacitance, the lower the maximum baud rate one can achieve.

The characteristics described above, with the appropriate quantifications for each parameter involved, constitute a model for the infrared channel.

Throughout the following analysis of the infrared link performance, a more practical channel model is adopted. Some of the simplifications to the above channel model that are assumed in a first analysis, include:

- the amount of noise due to the ambient light is characterised by the average current on the PIN photodiode (IB). We assume that there are no shot noise introduced prior to the signal detection.
- the interference produced by artificial light sources is neglected. This can be shown not to introduce a significant power penalty when the emitted signal has a convenient power spectral density, as is the case of OOK Manchester encoded signals. However, interference must be included in a future analysis, in order to evaluate the real performance of other coding and modulation techniques.
- multi-path dispersion is not taken into account. It can be shown [1] that for bit rates up to a few Mbps, multi-path dispersion may be neglected.
- we assume that there are no speed limitations imposed by the emitting devices. This is a good approximation if we take good quality LEDs, once again because of the reduced bit rate we are considering on the examples (1 Mbps).

Some of these simplifications are currently being removed and a more complete channel model being considered. The resulting analysis should be included in future documents. However, the results presented in this document for the 1 Mbps system are expected to be suficiently accurate and not to change in future analysis.

4. Line coding and modulation techniques

In this section we are going to present some line coding and modulation techniques for application in the wireless infrared channel. First we describe the technique and then we present some examples of its performance, assuming typical values for the major system parameters. The reference for the performance of the proposed techniques will be the performance of an hypothetical system where the data is transmitted in NRZ format (OOK), e. i., without any prior coding.
The receiver sensitivity was calculated following the receiver model from Personick [2] and some simplifications presented by other authors [3].

4.1. OOK Manchester encoded

Manchester line coding has been used in the physical link of several systems, including those of local area networks like Ethernet. It is characterised by its simplicity of implementation and ease of clock recovery. Figure 2 shows an example of a segment of data bits in NRZ format and the corresponding Manchester encoded signal.

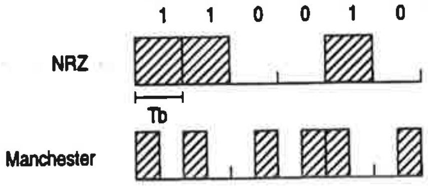

Figure 2. Example of a Manchester coded data segment.

Each bit of data is transmitted by sending a pulse in the first half slot, of duration Tb/2 (mid-bit), if we are transmitting a binary "1", or in the second half slot if we are transmitting a binary "0", where Tb is the bit period. This coding rule assures that there is at least one transition per transmitted bit which makes the clock recovery operation on the receiver side very easy and also avoids DC-wandering problems. Another important characteristic of the Manchester code is that encoded signal power spectral density shows little power components at low frequencies, making high-pass filtering a possible solution for interference rejection.
The obvious disadvantage of Manchester coding is that the resulting baud rate is the double of the original bit rate. This increase in the baud rate results in an optical power penalty up to 4.5dB, depending on the bit rate and receiver parameters.

For the Manchester encoded signal detection we discuss two different approaches:

a) In the first one, the received pulse assumed rectangular (in agreement with the simplified channel model) is formatted to a full raised cosine output pulse. The detection operation is performed by making a binary decision over each mid-bit. Phase ambiguities are solved by using differential Manchester encoding/decoding.
b) In the second detection technique [4], a partial response detection method is adopted. A "sine shaped" filter is used in addition to the full raised cosine formatter to produce an output pulse with three levels. The resulting eye diagram at the filter output is depicted in figure 3. The detection and decoding operations are performed simultaneously by making a binary decision over the "open" eye. This technique has several advantages over the full response technique: it provides a better receiver sensitivity; the filtered signal has a more convenient power spectral shape with lower power components at low frequencies which makes the system less sensitive to ambient light interference; the 3-level signal provides collision for detection of collisions through monitoring violations to the coding rule [6].

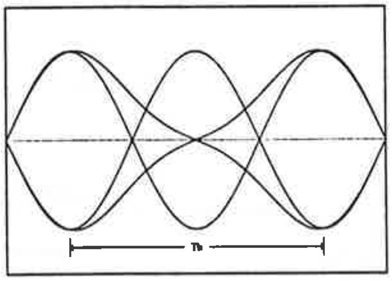

Figure 3. Eye diagram at the partial response detection filter output.

The sensitivity of an optical infrared receiver using Manchester line coding was calculated and is shown in figure 4 where the bit error rate is plotted as a function of the irradiance (optical power per unit area) at the receiver site.
In the calculations we assumed the following values for the most important parameters:

-Bit rate: 1 Mbps
-Photodetector active area : 10 cm^2
-Photodetector parasitic capacitance: 2 nF

-Background noise current (IB): 0.15 mA per cm^2 of active area
The front-end is based on a transimpedance amplifier.

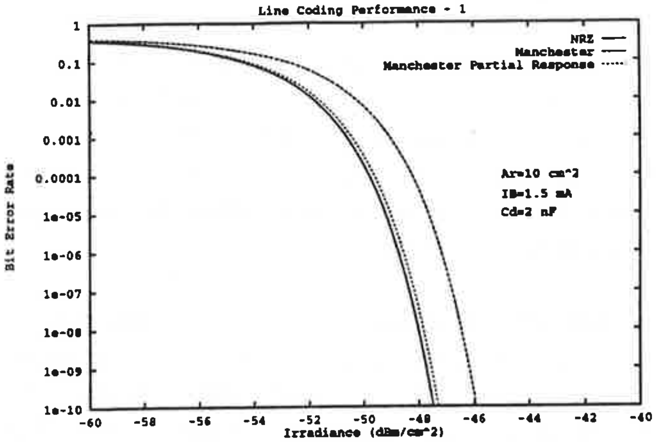

Figure 4. Performance of the OOK Manchester encoded system.

For the NRZ system the receiver sensitivity (required irradiance for a bit error rate of 10^{-9}) was found to be -47.7 dBm/cm^2.
As shown in the figure, the optical power penalty of the Manchester code over the NRZ is about 1.6 dB.
This penalty is substantially reduced if we resort to the detection scheme where a partial response filter is used. The result is also shown in figure 3, showing that in this case the performance of the Manchester code is only slightly worse than that of NRZ. However, this performence gain is achieved at the cost of a slight increase of the complexity at the detection and synchronisation subsystems.

The receiver sensitivity as a function of the photodetector active area was also calculated. The result is shown in figure 5.

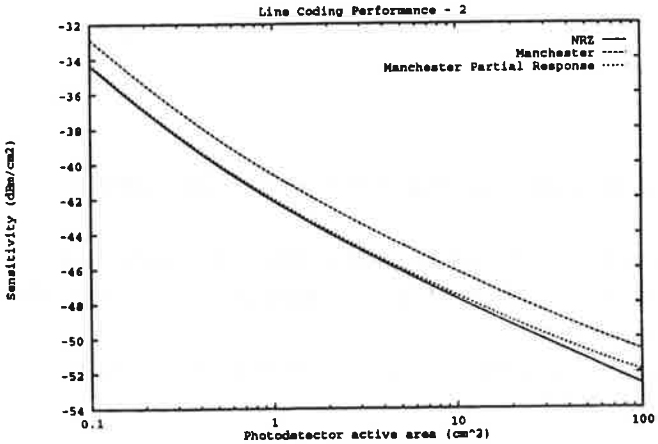

Figure 5. Receiver sensitivity versus photodetector active area.

As expected, the receiver sensitivity improves as we use larger active area photodetectors. However, the rate of the sensitivity gain decreases for larger active areas due to the increased parasitic capacitance of the photodetector. This effect is visible on the plot of figure 5 as the optical power penalty of the Manchester code increases for photodetector areas larger that $10cm^2$. Although this effect is not very pronounced in the example of figure 5 (where 1 Mbps is considered), it may be more severe for higher bit rates.

4.2. Pulse Position Modulation

In the preceding section we introduced line coding to simplify the synchronisation process and also to shape the signal spectrum by reducing the low frequency components of the emitted signal. We saw that Manchester coding provides those functions but at the cost of some optical power penalty over NRZ.
Modulation techniques may also be used to perform some of these tasks. In this section we are going to introduce Pulse Position Modulation (PPM) as a technique to improve the optical link performance by reducing the optical power requirements. This modulation technique has been shown to be very efficient for average power limited optical systems [5].
Figure 6 illustrate the PPM modulation operation for a two bits word (k=2).

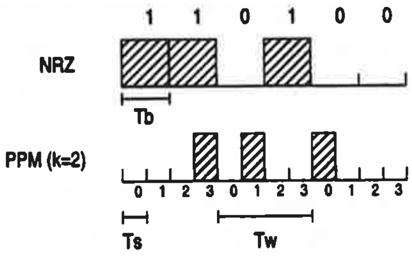

Figure 6. Pulse Position Modulation. Ts is the slot period and Tw is the word period.

In this modulation operation, one pulse is sent in one of the $M=2^k$ time slots contained within a word of length k bits. In the example of figure 6, the word length is two bits (k=2), the number of time slots being M=4. With this modulation scheme an optical power gain is obtained since a single pulse is sent for each k bits. It increases with the word length k (PPM order).
The detection operation is performed by integrating the received signal over the slot period and then taking the correct slot to be the one with the largest integration value.
The immediate disadvantage of PPM is the increased complexity of the optical link. In particular, slot and symbol (word) synchronisation are required. In figure 7, a simplified block diagram of the PPM infrared link is presented.

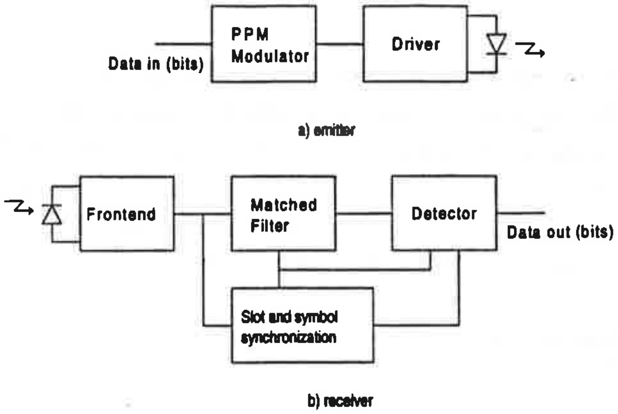

Figure 7. Block diagram of the PPM infrared link: a) emitter, b) receiver.

The matched filter in the receiver should be designed according to the channel characteristics. For the simple channel model we have been considering, this filter reduces to a simple integration over the slot period. In future analysis, multi-path dispersion and the interference produced by the artificial light should be considered and the matched filter adapted accordingly. The detection circuit is responsible for taking the M samples, corresponding to the M time slots, at the filter output and to assign the correct slot to the one with the largest sample value. The implementation of the detection circuit may be full analog or a combined analog/digital approach may be used. The choice is dependent on the complexity involved with each approach and may be implemented using VLSI together with other parts of the receiver circuitry.

In order to evaluate the performance of the PPM when applied to the infrared channel, the receiver sensitivity calculation was performed and the results are shown in figure 8, where the performance of the OOK-NRZ system is used as a reference. In this calculations we assumed the same system parameters we used in the Manchester analysis, including a rectangular input pulse and a full raised cosine output pulse for a more realistic performance comparison with the OOK Manchester encoded approach.

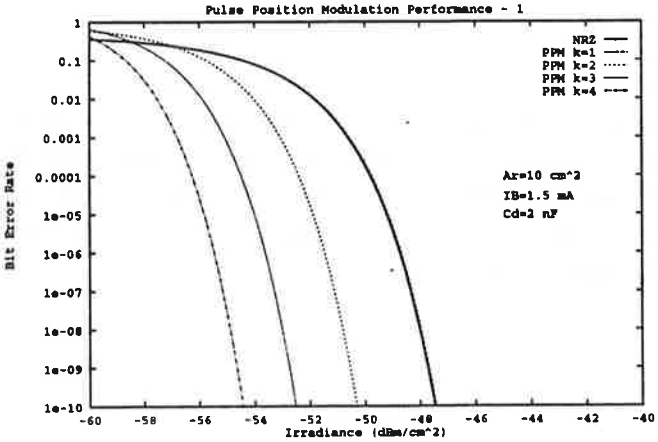

Figure 8. PPM performance: bit error rate versus irradiance.

Form the figure, we see that the required irradiance for the PPM receiver is much lower than that required for the NRZ system, except for k=1, which has a performance similar to the Manchester with partial response detection scheme. For k=4, the PPM receiver sensitivity (-54.6 dBm/cm^2) is about 8.5 dB better than the Manchester receiver with full response detection.

As for the Manchester system, we have also calculated the receiver sensitivity as a function of the photodetector active area. The result is shown in figure 9. The effect of the photodetector active area on the receiver sensitivity is similar to that observed with the Manchester line code. However, note the sensitivity degradation for PPM with k=4 when the active area approaches 100 cm^2. This effect is due to the larger receiver bandwidth required for higher order PPM.

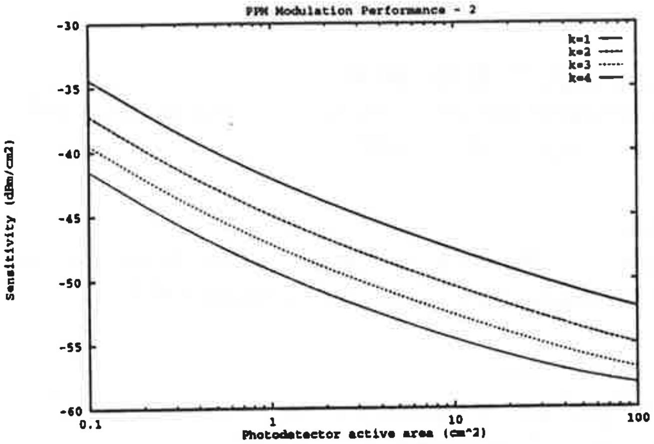

Figure 9. PPM receiver sensitivity versus photodetector active area.

When PPM is used, the required channel bandwidth is higher than that required for transmission using OOK. This may be a limiting problem for high bit rate systems since the emitting devices (LEDs) are speed limited. However, note that for PPM k=2 the signal bandwidth is about the same as that of OOK Manchester encoded signals, with a receiver sensitivity about 3dB better.
The improved performance of the PPM technique is achieved at the cost of an increased complexity. In particular, slot and word synchronisation are required.

5. Conclusions

The results presented above show that both OOK Manchester encoded and PPM techniques are appropriate for transmission over the wireless infrared channel.
The Manchester line code provides good spectral shape and clock information to the encoded signal at a low implementation complexity. The price to pay for that simplicity is the poor sensitivity of the receiver.
For an improved receiver sensitivity and lower optical power budget, PPM can be used at the expense of an increased complexity. In particular, the detection and slot clock recovery circuits are quite more complex than those used for OOK detection and Manchester decoding.

Other aspects that must be taken into account on the choice of the modulation/encoding technique are the electrical consumption and space occupied by the circuitry. This is of particular importance for portable and hand held equipment which is usually battery powered and exigous in terms of space. One possible solution for this problem can be found by resorting to VLSI techniques, integrating most of the emitter/receiver functions on a single chip.
Before a final decision is made, more work has to be done in channel characterisation. The effect of the artificial light interference must be modelled and taken into account on the performance of the proposed techniques. The multi-path dispersion must also be evaluated for typical environments and included in the channel model. Experimental data on those aspects is then required.

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