IEEE 802.11
Wireless Access Method and Physical Layer Specification

Title: **Performance Evaluation of the IR PHY Proposal**

Authors: Adriano J. C. Moreira, A. F. de Sousa, Rui Aguiar, Rui T. Valadas,
A. M. de Oliveira Duarte

Integrated Broadband Communications Group
Dept. of Electronics and Telecommunications
University of Aveiro
3800 AVEIRO
PORTUGAL

Tel: +351 34 381937
Fax: +351 34 381941
Email: adriano@ci.ua.pt

Summary

This contribution is part of a set of documents where a baseband IR PHY is proposed and evaluated. These include:

- *IR PHY Template, doc: IEEE P802.11-94/95*
- *IR PHY Proposal, doc: IEEE P802.11-94/96*
- *Performance Evaluation of the IR PHY Proposal, doc: IEEE P802.11-94/97*

A system implementing the proposed specification is being developed by the University of Aveiro as part of the ESPRIT.6892 POWER (Portable Workstation for Education in Europe) project commissioned by the European Community.

This documents evaluates the performance of a system implemented in agreement with specifications proposed in the document IEEE P802.11-94/96 - "IR PHY Proposal". Most of the parameters and proposed solutions are analysed and shown to provide a good compromise between performance and simplicity.

The modulation method to be adopted by the standard, being one of the aspects with most impact in the complete specification, will be treated in first place. A comparison with other modulation methods is presented based on a common set of conditions.

Next the format of each of the frame fields is analysed and the total Frame Error Rate (FER) is calculated taking into account the influence of the several detection processes.

1. Modulation method

The modulation method to be adopted for the standard will take the major role in the IR PHY performance and success. IR coverage area or cell size, data throughput, transmission reliability, transceiver power consumption, cost and other important aspects will all be affected by the modulation method.

The wireless indoor optical channel is power limited. This results from the way optical signal propagate in an unguided channel and also from the noise and interference induced by ambient light. In addition, as the optical power budget increases, the same happens to the number of required LEDs, resulting in larger and more expensive transceivers. Safety levels impose another limit to the maximum transmitted optical power.

The other important aspect to consider on the choice of a modulation method is the available channel bandwidth and the signal spectrum. The IR channel bandwidth is mainly limited by the speed of the emitting devices and by the multi-path dispersion.

The first one is a technological limitation. Currently off-the-shelf low cost LEDs have turn-on and turn-off times in the range 10-40 ns, when operated in non-linear mode.

The second bandwidth limitation is intrinsic of the channel and is highly dependent on the room geometry and the materials used on the wall, ceiling and furniture. For large room the multi-path dispersion should not be higher than about 50 ns.

Considering these two aspects we reach to a bandwidth in the range 10 to 30 MHz, depending on the room we are considering, the quality of the LEDs and without the need to resort to equalisation techniques.

Having a channel that is power limited and with enough bandwidth, the best trade-off is to exchange bandwidth for power, that is, one should explore the bandwidth to reduce the power constrains. These characteristics leads us to the use of Pulse Position Modulation. On the other hand, the availability of bandwidth may lead to the use of carrier modulation schemes, such as FSK or PSK, to provide several simultaneous transmission channels. Latter we will analyse both solutions in terms of their practical implementation feasibility.

In figure 1, several modulation/encoding schemes are compared in terms of the receiver sensitivity, for a 1 Mbps system. The use of a transimpedance front-end is considered. These results show the total difference in performance including the different receiver bandwidths required for each modulation method.

For PPM, two orders are considered, 4-PPM and 16-PPM, since those are the cases of interest. The Manchester encoded scheme assumes optimum detection while PPM assumes the use of a MAP detector. PSK is assumed to be coherently detected.

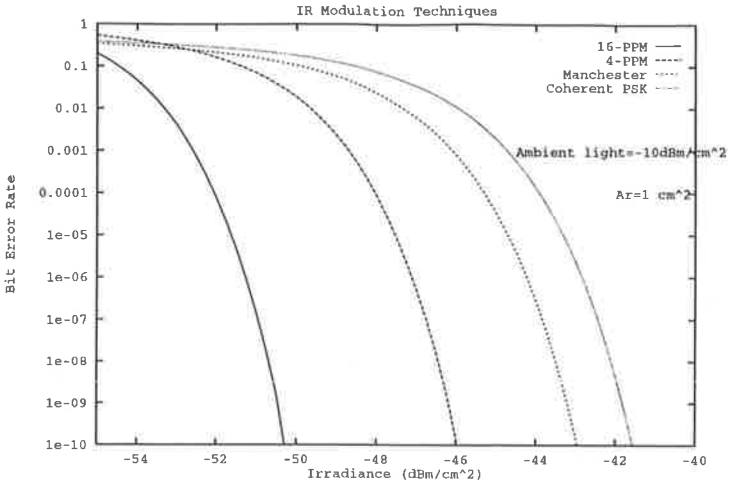

Figure 1. Comparative performance of several modulation methods (1 Mbps).

The results shown in figure 1 are for a data rate of 1 Mbps and assume a 1 cm^2 active area detector and an ambient light level of -10 dBm/cm^2.

It is clear from figure 1 that PPM is by far the most power efficient modulation method. For a BER of 10^{-9}, 16-PPM requires about 7.1 dB less power that OOK Manchester encoded. When compared to coherently detected PSK, PPM requires about 8.3 dB less power. The penalty of 4-PPM over 16-PPM is about 4.1 dB.

The receiver sensitivity value is not the only parameter to consider. Implementation complexity and practical feasibility of the a particular solution have also to be considered. In wireless infrared systems, one such aspect is the optical power budget or, at the end, the number of LEDs required to provide the necessary optical power. The optical power budget is mainly determined by the receiver sensitivity and by the worst case propagation losses.

Table 1 summarises the major parameters of a system for the modulation/encoding methods considered above. In particular, the required number of LEDs is estimated for each case.

	16-PPM	4-PPM	Manchester	Coherent PSK
Receiver sensitivity[1] (BER=10^{-9})	-50.4 dBm/cm^2	-46.3 dBm/cm^2	-43.3 dBm/cm^2	-42.1 dBm/cm^2
Average optical power	125 mW	320 mW	640 mW	845 mW
Number of LEDs	8	20	41	54

Table 1. Example of implementation parameters for different modulation methods (1 Mbps).

---

[1] The presented sensitivity value for 16-PPM differs from the one proposed in document IEEE P802.11-94/96. The value presented here is the theoretical sensitivity while the other is a value where a safeguard margin was considered to take into account for implementation imperfections and effects not considered in the model.

The required average optical power was calculated in order to provide a coverage area of about 100 m^2 and assuming the frame characteristics described in the document "IR PHY Proposal".

The results presented in table 1 shows that, power consumption, cost and transceiver size are determined by the power efficiency of the modulation method.

2. Frame format

The proposed frame format is shown in figure 2. It consists in a preamble, a Start of Frame Delimiter (SFD), a field which purpose is to allow the receiver to stabilise the DC level after the preamble (DC Level Adjustment), a field to convey the Data Rate (DR), the MAC frame and finally an End of Frame Delimiter (EFD).

Preamble	SFD	DR	DC LA	Data	EFD

Figure 2. PHY frame format.

A measure of the system performance is the Frame Error Rate (FER). The FER is affected by several processes involved in the frame detection, namely:

- the preamble detection (carrier sense);
- the probability of error in the SFD detection;
- the probability of error in the DR field detection;
- the probability of error in the MAC frame detection (a function of the frame length);
- the probability of error in the EFD detection.

Each of these processes was modelled and its effect on the FER was equated. For each detection step, two major sub-processes have been considered: the probability of false detection or imitation and the probability of non-detection at the correct position.

Two types of detector have been considered: the MAP detector and the threshold detector. Both can be used, while with different performances. In the MAP detector the energy in all slots of a symbol is measured and the position of the detected pulse is assigned to the slot with higher energy. So only one pulse is detected per symbol. In the threshold detector the presence or absence of a pulse in each slot is determined by comparing the signal level against a preset threshold. More than one pulse can be detected in a symbol and, in that case, a symbol error will be declared.

Extensive analysis and calculations have been performed to find the best formats for each of the frame fields. The error probability associated with each field was calculated and a final value for the receiver sensitivity was estimated in order to provide a FER $\leq 4.0 \times 10^{-5}$ for a 512 octets data field.

For the system conditions considered in figure 1 and for a 512 octets MAC frame, the following results have been achieved:

	1 Mbps	2 Mbps
Total Frame Error Rate (Target):	4.0×10^{-5}	4.0×10^{-5}
Receiver sensitivity	-50.7 dBm/cm^2	-44.7 dBm/cm^2
Probability of error in the SFD detection:	2.1×10^{-5}	2.1×10^{-5}
Probability of error in the DR detection:	1.6×10^{-5}	1.6×10^{-9}
Probability of error in the payload detection:	3.6×10^{-6}	1.4×10^{-6}
Probability of error in the EFD detection:	2.8×10^{-9}	2.9×10^{-9}

Table 2. Frame Error Rate.

In table 2, the receiver sensitivity is considered to be the minimum irradiance for a FER equal to 4.0×10^{-5}.

The impact of the MAC frame length on the frame error rate was calculated for the MAP detector and the threshold detector. The results for the 1 and 2 Mbps data rates using a MAP are shown in figure 3. The irradiance is that shown in table 2.

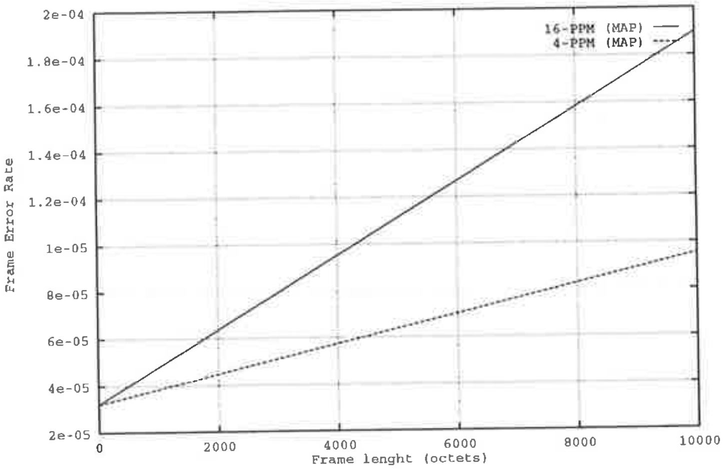

Figure 3. Frame Error Rate vs. MAC frame length.

As expected, the longer the MAC frame the worse the FER. However the FER degradation is not too severe. Note the performance of 4-PPM at 2 Mbps for longer MAC frames when compared to the 1 Mbps mode. This effect is due to the lower Symbol Error Rate of the 4-PPM mode.

Since the FER degradation for long MAC frames is not a serious problem, one might allow the MAC to transmit very long frames for a better system throughput. However there is one other aspect that limits the maximum MAC frame length and that is the stress on the LEDs.

Figure 4 compares the MAP detector to the threshold detector at 1 Mbps. In the threshold detector, optimum threshold level is assumed throughout the frame.

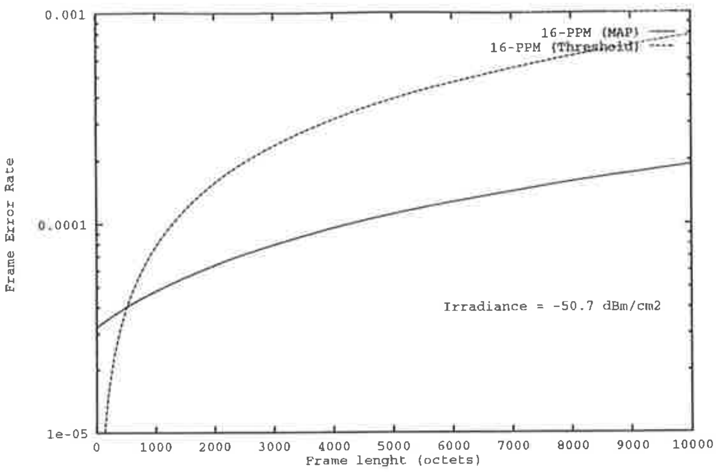

Figure 4. Threshold detector and MAP detector.

The results shown in figure 4 were calculated for the same irradiance. Both systems were designed to provide the same FER for a frame of 512 octets.

One conclusion resulting form figure 4 is that the FER does not degrade dramatically as the frame length increases. While this is true for both systems, it is more clear for the MAP detector.

Figure 4 also shows that for small frames (shorter than 512 octets) the system based on the threshold detector provides lower error rates than the one using the MAP detector. For frames longer than 512 octets, the MAP detector is better. However, the advantage of the threshold detector for short frames can be misleading. In order to provide the same performance for 512 octets, the threshold detector must use a larger area photodetector to achieve a better signal-to-noise ratio. The penalty of the threshold detector over the MAP detector is more clearly seen in figure 5 where, for the sake of comparison, similar receivers with the same photodetector active area were assumed.

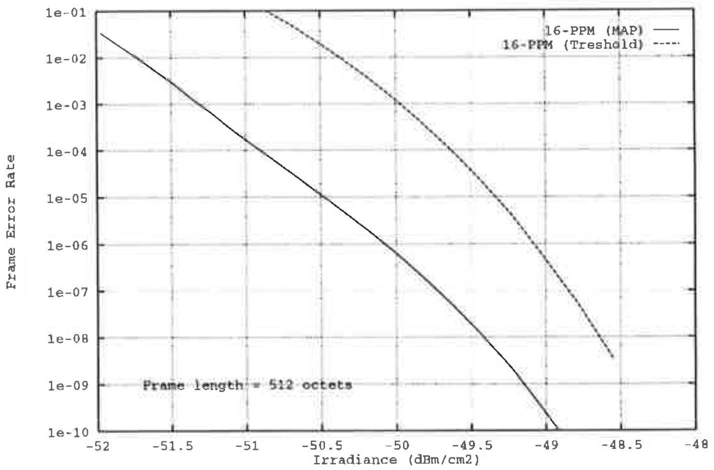

Figure 5. FER vs. irradiance.

Based on this study the following results and conclusions have been attained:

Preamble:

- the preamble length should last between 57 and 73 slot periods; this range should be enough for the receiver to acquire synchronisation, adjust the AGC and perform other measures of the signal quality. The preamble should not be too long in order to limit the PHY overhead and to prevent the LEDs from being over stressed.
- the preamble should terminate with an empty slot in order to minimise the probability of imitation of the SFD.

SFD:

- The SFD length is 4 slots and consists of the sequence `1001`. This word length is the best solution for the SFD: a longer SFD increases the probability of error at the correct position, while a shorter SFD increases the probability of imitation of the SFD during the preamble. Its pattern (`1001`) is also an optimum word for a 4 slot long SFD: it minimises the imitation probability during the preamble.
  The searching process is illustrated in the following sequence:

```
Preamble     |SFD        Number of different slots

1010...101010|1001                  "Good" SFD
        1001 |             2
         1001|             2
          100|1            2
           10|01           2
            1|001          3

1010...101010|0011                  "Bad" SFD
        0011 |             2
         0011|             2
          001|1            3
           00|11           3
            0|011          1      there is only one different slot
```

- For the reasons presented above, the SFD should not be used for other purposes than those of providing a time mark. The use of the SFD to carry information about the data rate (or other information) requires the use of different words (not optimum), one for each data rate. This solution highly degrades the probability of error in the SFD detection, leading to a significant degradation of the FER.

Data Rate:

- a field conveying the data rate information is necessary to provide proper operation of the receiver. In order to provide easy access to other PHYs and minimise the associated overhead we propose this field to consist of 3 time slots allowing for 8 different PHY / DR to be accommodated by the standard.

DC Level Adjustment:

- the proposed length for the DC Level Adjustment field is 32 slots. This seems to be a good trade-off between versatility and PHY overhead. The format of this field is not critical regarding that its DC level being the same as that of the data field.

MAC frame:

- the type of detector used to detect this field has a major impact on the system performance.
- very long data fields may be used, since the FER is not substantially degraded, compared to shorter frames.

EFD:

- an explicit EFD should be transmitted after the data field. The use of an implicit EFD (silence) increases the probability of error in the EFD detection due to imitation during the payload. Its format is not critical, provided that it is composed of several pulses.

Concerning the type of detector, both the MAP or the threshold detector can be used. For very short frames (e.g. RTS, CTS) their performance is very close. For longer frames the MAP detector outperforms the threshold detector by 1 to 2 dB.