IEEE 802.11
Wireless Access Method and Physical Layer Specification

Title: **IR PHY Proposal**

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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.

The IR PHY proposal is based on the use of Pulse Position Modulation (PPM). This method was already suggested and studied by the University of Aveiro in documents 93/79 and 93/154. The present set of documents introduces further detail and covers the main parameters that should be part of the IR PHY standard.

A major feature introduced by this IR PHY proposal is a dual-rate (1/2 Mbps) capability. The main objective is to allow Stations and Access Points to trade-off between power consumption and throughput. The dual-rate capability is mandatory for the receivers while for the emitters only the basic rate (1 Mbps) is mandatory. The same range/performance is provided in both data rates. All MPDU frames are transmitted at the same data rate and therefore the dual-rate capability imposes no requirements on the MAC. The data rate selection will the responsibility of higher layers.

A detailed specification of a PPM based IR PHY was already submitted to the IEEE P802.11 by Photonics Corporation in documents 93/212 and 94/56.

The present IR PHY proposal from the University of Aveiro here described agrees with the previous Photonics proposal in the following features and parameters:

- *Modulation method: PPM (baseband)*

- *Preamble pattern*
- *A common preamble, independent of the data rate*
- *A variable preamble length to support advanced receiver technologies*
- *A fixed and limited transmitter output power and the proposed specification*

It disagrees in the following features and parameters:

- *SFD pattern*
- *The use of an implicit EFD*
- *A fixed and limited receiver sensitivity*
- *Proposed specification of receiver sensitivity*
- *Proposed specification for transmitted Pulse Width, Rise Time, Fall Time and Jitter.*
- *Method of specification of radiation emitter pattern*
- *PPM mapping rule*

It includes the following new features:

- *A higher data-rate mode at 2 Mbps*
- *A data rate (DR) field*
- *An explicit EFD*

IR PHY Specification

1. General Specifications

1.1. Modulation Method

We have studied and compared several candidate modulation methods for a 1 Mbps IR PHY. Based on our own studies [5, 6, 7] and supported by others [3, 9, 10] we concluded that Pulse Position Modulation (PPM) is the best trade-off for a 1 Mbps IR PHY. This is mainly due to the its power efficiency [1, 2] which matches very well the power limited nature of the IR channel.

PPM is also a strong candidate for higher data rates. Its power efficiency advantage over other modulation methods (OOK Manchester encoded, PSK, FSK and others) is still valid for data rates higher than 1 Mbps. As demonstrated in doc. 94/97 "Performance Evaluation of the IR PHY Proposal", the power penalty of 16-PPM at higher data rates due to multipath dispersion and interference can be as high as 8.5 dB and still be superior to coherent PSK.

1.2. Data Rate

We propose to support two non-optional data rates: 1 and 2 Mbps. In order to keep the impact of an higher bit-rate on the transceiver complexity minimal we introduce a novel concept whereby the two data rates are provided by two different PPM orders in such a way that the basic pulse remains the same.

We propose to use 16-PPM for 1 Mbps and 4-PPM for 2 Mbps. Figure 1 shows the PPM signals for both data rates.

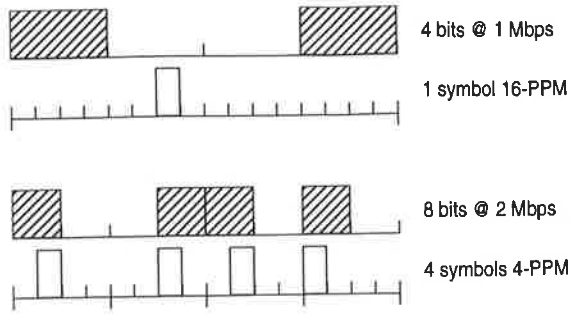


Figure 1. Dual data rate - dual PPM order

When extending the data rate using the previous concept:

- The receiver bandwidth remains the same.
- The pulse shaping filter (equaliser) remains the same.
- The clock recovery circuit remains the same.
- The PPM detector requires a minimal modification because of the different number of slots per symbol: 4 in 4-PPM and 16 in 16-PPM. This is accomplished by simple modifications in the synchronisation sub-circuit as shown in figure 2.
- The frame format remains the same: the same preamble, SFD and EFD are used.

To upgrade the system to the dual rate receiving capability, only the dashed blocks in figure 2 require some modifications: an extra clock divider is implemented to provide the bit clock for 2 Mbps; a multiplexer is added to select the clock signals for each mode; a detector is added to detect the Data Rate (DR) field.

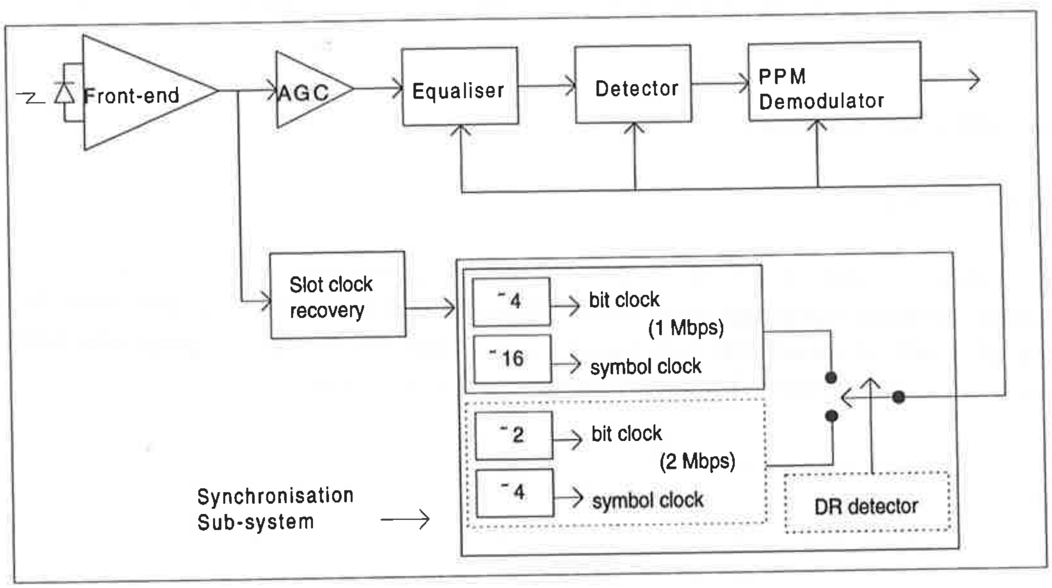


Figure 2. Modifications required for operation at 1 and 2 Mbps.

From the above considerations we conclude that the dual-rate system is only marginally more complex than its single rate equivalent.

In agreement with [9] (see also Appendix A) we believe that the impact of hidden stations on the IR PHY should be kept as low as possible. Therefore, we propose to provide the same coverage area in both rates. In order to accomplish this requirement the same transmitted peak power has to be used in both rates. This means that the average optical power for transmission at 2 Mbps is 6 dB higher than that required for 1 Mbps. Since this requirement may have some impact on the power consumption, size and cost of the transceiver with the present optoelectronic component technology the transmission at 2 Mbps will be optional.

However, reception at 2 Mbps will be mandatory since the impact on receiver complexity of supporting both data rates is minimal.

The main reason for introducing the dual-rate capability is to allow Stations and Access Points to trade-off power consumption for throughput.

The optional transmission capability at 2 Mbps is to be used by any transceiver that has less stringent requirements in terms of power consumption, size and cost. An obvious case for the 2 Mbps transmission capability would be an Access Point (AP): all the transmissions from the AP to the stations could be performed at 2 Mbps with the associated increase in throughput.

It should be noted that the use of the same peak optical power provides the same performance at 1 and 2 Mbps. This means that a station that implements the 2 Mbps transmission capability may transmit all frames at 2 Mbps, including RTS, CTS and ACK.

1.3. Propagation Mode

The propagation mode should be diffuse: no line-of-sight or transceiver aiming required.

2. Transmitter Specifications

2.1. Output Power

The proposed value is 2.0 W ± 20% of peak optical power. This value is a reasonable compromise between coverage area, safety limits and transceiver size and cost. It allows the coverage of a cell of about 100 m^2, based on the receiver sensitivity proposed bellow. Larger coverage areas can be achieved by using more sensitive receivers.

The same peak optical power is used at 1 and 2 Mbps. This requirement is imposed by the necessity to avoid hidden stations as stated above. This means that the 2 Mbps mode requires an extra 6 dB optical power on the limit of an infinite frame. However, due to the doubled transfer rate and to the PHY overhead which is identical in both data rates, the impact on the power consumption will be inferior to 3 dB.

2.2. Radiation Pattern

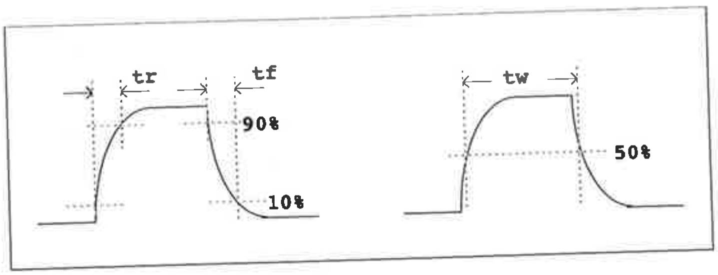
As shown in [4] the emitter radiation pattern has a significant impact on the IR cell range. Vertical orientation of all LEDs is by far not the best solution. Therefore we believe that the specification of the emitter radiation pattern should be based on an optimised array defined using of-the-shelf LEDs.

As referred in [9] excessive tolerance in the emitted peak optical power can lead to hidden stations. We note in addition that excessive tolerance in the specification of the emitter radiation pattern can have a similar effect. Therefore we believe that a more tight specification than the one proposed in [9] should be produced.

This pattern is TBD.

2.3. Pulse Format

The transmitted optical pulse format is shown in figure 3. The parameters that have to be specified are the pulse width (tw), rise (tr) and fall (tf) times and jitter (tj) limit.



tw	250 ns ± 10 ns
tf	≤ 40 ns
tr	≤ 40 ns
|tj|	≤ 10 ns

Figure 3. Transmitted optical pulse format.

For a fixed output peak power, the maximum energy per pulse is achieved at a pulse width equal to the slot period (250 ns). A slightly narrower pulse may be used to reduce the penalty due to channel multipath dispersion.

The optical pulse rise and fall times should be as low as possible within a reasonable cost limit. The poorer these switching times, the higher the penalty due to energy leak from one slot to the next. At the receiver these switching times are added to the channel multipath dispersion further degrading the system performance.

Taking into account the specs of currently available low-cost LEDs, the LED driver technologies and our own experience we believe that 40 ns is a reasonable choice for the optical rise and fall times maximum limit.

The jitter, defined as the deviation in time of a pulse from its correct position, can be kept at very low levels no matter the digital technology used. The proposed value is 10 ns, i.e., the pulse is not allowed to be more than 10 ns away from its correct position, to one side or the other.

2.4. PPM Mapping Table

The mapping between the words to be transmitted and the PPM symbols has no impact on the system performance. Any mapping rule is equally good from the point of view of performance. This fact leaves the choice of a particular mapping rule to be defined by implementation considerations.

The proposed mapping table was adopted because it allows the implementation of both 16-PPM and 4-PPM rules with the same look-up table.

3. Receiver Specifications

3.1. Sensitivity

The receiver sensitivity is defined as the minimum irradiance (in dBm per cm^2) at the photodetector plane required for a specified Bit Error Rate (BER), assuming continuous operation.

The sensitivity is mainly dictated by the target Frame Error Rate (FER) which is assumed to be $\leq 4.0 \times 10^{-5}$ for a MPDU of 512 octets (see section 3.3 below).

The value for the receiver sensitivity can be found by computing the minimum irradiance, for a given set of conditions and taking into account all the error probabilities involved in the detection of a frame, those being the error probabilities in the detection of:

- a valid preamble;
- the SFD;
- the Data Rate field (DR);
- the MAC frame;
- the EFD.

The proposed values, assuming an ambient light level of -10 dBm/cm^2, are shown in table 1.

1 Mbps	-47 dBm/cm^2
2 Mbps	-41 dBm/cm^2

Table 1. Receiver sensitivity.

As discussed in detail in appendix A, we propose not to impose a limit on the maximum receiver sensitivity. This will allow the interoperability with advanced transceivers, e.g., using diversity.

3.2. Dynamic Range

The receiver dynamic range is defined as the ratio between the maximum and minimum irradiance at the photodetector plane that assure a FER $\leq 4.0 \times 10^{-4}$. We note that the dynamic range specification is optical and not electrical.

The proposed value is 30 dB. This value is a reasonable trade-off between the dynamic range of an IR cell and the receiver complexity.

3.3. Frame Error Rate

The PAR [8] specifies a Frame Error Rate (FER) equal or less than 4.0×10^{-5} for a MPDU of 512 octets. In our view this is a MAC FER specification and refers to the frames delivered by the MAC to the upper layers. In the absence of a specification that covers the PHY FER we have adopted the MAC FER target for our IR PHY spec.

3.4. Field-of-View

The Field-of-View (FOV) is defined as twice the angle from the normal of the detector surface to the physical limit direction at which no more optical power impinges on the detector. For a planar detector without package, this value approaches 180°. In practical detectors and depending on the package used by the manufacturer (among other factors) this angle is usually narrower than 180°.

Excessive tolerances in the specification of the receiver (FOV) pattern can also lead to hidden stations. Therefore, a tight specification is also required. We propose that the FOV should be no narrower than 150°.

4. Frame Specifications

4.1. Frame Format

The proposed frame format is shown in figure 4.

Preamble	SFD	DR	DC LA	Data	EFD

Figure 4. Frame format.

The frame is composed of a Preamble, a Start-of-Frame Delimiter (SFD), a data rate field (DR), a DC level adjustment field (DC LA), the MAC frame and an explicit End-of-Frame Delimiter (EFD). For a summary of the frame format see the "IR PHY Template" document.

In agreement with what was proposed in [9], the preamble should be common and independent of the PHY. The use of a common preamble allows for the coexistence of different PHYs in the same BSS.

Preamble

The preamble consists of a sequence of alternated presence and absence of a pulse in consecutive slots. This is a 2 MHz clock signal with 50% duty-cycle.

The transmitted preamble should last for a minimum of 60 slots and a maximum of 76 slots and terminate with an empty slot. The minimum length is determined by the settling times of the clock recovery circuit, AGC, SNR estimator and other receiver sub-circuits. The maximum length is to be limited in order to minimise the PHY overhead, to minimise the probability of imitation of the SFD and to avoid excessive stress on the LEDs.

Start-of-Frame Delimiter (SFD)

A SFD should be transmitted after the Preamble. It allows the receiver to determine the starting point of the MAC frame and to acquire the bit and symbol synchronisation required for PPM detection. As for the preamble, a common SFD should be used. The major reason for this solution is that the use of several different words for the SFD results in a degraded FER due to the imitation of the SFD during the preamble.

The SFD length is 4 slots and consists of the sequence `1001`.

Data Rate Field (DR)

The Data Rate (DR) field serves the purpose of identifying the PHY / DR type.

The proposed format for this field is 3 time slots, which allows for a maximum of 8 different PHY / DR to be specified. For the dual rate PHY being proposed the assigned words are:

- 1 Mbps: `000`
- 2 Mbps: `001`
- other data rates: TBD

DC Level Adjustment

This field is required to allow the receiver to stabilise the DC level after the preamble and SFD. This is because the average power level is higher during the preamble than during the payload section of the frame.

The proposed length for this field is 32 slot times. The format of this field is not critical, provided that the average signal level is made identical to that of the MAC frame. This field should also contain some impulses to keep the clock recovery circuit running properly. The proposed format is:

- 2 × symbol '8' for 1 Mbps (16-PPM);
- 8 × symbol '2' for 2 Mbps (4-PPM)

Since the receiver is adjusting itself during this field, it should not convey any kind of information.

End-of-Frame Delimiter (EFD)

One important aspect of the receiver operation is its ability to detect the end of the MAC frame. This operation has to be highly reliable. Otherwise the frame may be lost due to an advanced or delayed detection of the EFD.

The MAC frame end should be declared after the detection of an EFD, which can be implicit (absence of signal) or explicit (a particular signal). The use of an explicit EFD minimises the error detection probability and speeds-up the detection process.

The correct detection of the EFD, as for the SFD, is affected by the imitation probability during the payload (MAC frame) and by the probability of missing the EFD at its correct position.

For an implicit EFD (absence of signal) to be detected, at least 31 slots have to be detected without a pulse, since 30 slots is the maximum number of empty slots during the payload. This means that a single erasure (non detected pulse) during the payload leads to the imitation of the EFD. To reduce this imitation probability, a longer EFD have to be considered: 46 slots to allow one error, 62 slots to allow 2 errors and so on. Note that an erasure on the EFD detection does not necessarily mean an error on the data if a MAP detector is used.

Also for the implicit EFD, the probability of non-detection at its correct position is very high: a single error on the EFD (a false pulse) means that the EFD is no longer detected. It can be detected latter, but then the frame is already lost, unless the MAC verifies its length.

For the reasons presented above, the use on an explicit EFD is proposed.

The proposed EFD lasts for 16 slots and consists of the sequence `0000011011011011`. A valid EFD should be declared when the 8 pulses are detected in their correct positions.

This is a much more robust EFD: the probability of imitation during the payload is very low, since at least 8 errors have to occur at particular slots for a false EFD to be declared. Also the probability of non-detection at the correct position is lower since we are only looking for the 8 pulses at particular (and known) positions.

The use of an explicit EFD results in a much faster process than the use of an implicit EFD since only 16 slots are used, compared to a minimum of 31 for the implicit EFD. A faster detection of the EFD has some impact on the throughput.

However there is still a probability that the explicit EFD will not be detected. In case of failure to detect the EFD the Carrier Sense output will be deasserted after no discernible IR traffic is detected for a period of 16 μs.

4.2. MAC Frame

The MAC frame is transmitted using PPM. Each word (2 or 4 bits long) is mapped to the corresponding PPM symbol and transmitted through the channel. The MAC frame length is limited by the FER.

The maximum MAC frame length is TBD.

4.3. TX-RX turnaround time

This parameter is TBD.

4.4. RX-TX turnaround time

This parameter is TBD.

4.5. Carrier Sense

The Carrier Sense (CS) signal form the PHY to the MAC should be asserted no latter that 12 us after the a valid preamble has started to be received. The carrier sense detection method should be left as an implementation choice, not being defined by the standard.

Appendix A - The problem of hidden stations in an IR PHY

In [9, Appendix A] it was argued that there is a requirement for imposing maximum and minimum limits on the radiated optical power and receiver sensitivity.

We agree with [9] in that the number of hidden stations should be kept as low as possible in an IR BSS. However, although it is clear that the presence of hidden stations will effectively degrade the throughput, we feel that not enough data is presently available on the actual throughput degradation associated with a given tolerance on the radiated optical power and receiver sensitivity specs.

In [9] it is clearly demonstrated how an excessive tolerance on the radiated optical power specification may lead to hidden stations. However, the argumentation in [9] considered only desired signal and forgot ambient noise. This is equivalent to assuming an isotropic noise coverage. We strongly believe that in most environments the ambient noise is far from being isotropic (it will be higher near windows or below spot lamps). This was also verified experimentally in [3] and [11].

The ability of a receiver to detect the presence of other stations belonging to its BSS depends on the Signal-to-Noise Ratio (SNR) conditions at the receiver site (and not only on the Signal). Once this is accepted it becomes clear that we may have hidden stations even if the radiated optical power and receiver sensitivity are the same in all BSS stations. For example, a station positioned just below a spot lamp because of its local SNR conditions may not be able to detect the presence of distant stations that belong to its BSS and will collide with them. Although the radiated optical power and receiver sensitivity can be controlled by a specification, we have no control over the ambient noise. Therefore the asymmetry in the IR channel is unavoidable and so it is the presence of hidden stations in an IR BSS.

Having said that we fully agree with [9] in that a maximum and minimum limit should be imposed on the radiated optical power. Both signal and noise tolerances contribute to hidden stations and we should control these factors as much as possible.

However we do not agree with the suggested imposition of a maximum receiver sensitivity. As pointed out in [9] stations with higher than normal receiver sensitivity will not damage the network but will defer their transmissions in an unfair fashion. This is not a problem in a single BSS network where all stations are designed to be within range of each other. Moreover we will argue that higher sensitivity receivers may be not hidden where the lower sensitivity ones could have been. This is because due to the uncontrollable nature of the ambient noise it is not possible to produce a specification assuring operability under all noise conditions. The worst-case noise is always yet to come! Thus it must be accepted that in a given BSS there may be some SNR "holes", where the SNR is lower than the SNR spec. Stations positioned in this "holes" which have higher sensitivity receivers may not be hidden thus contributing effectively to a reduction on the number of hidden stations. However, it is true that in multiple BSS networks higher sensitivity receivers may unnecessarily defer a transmission when they could have transmitted without interfering with transmissions in other BSSs. However, these stations will also have the benefit of being more immune to ambient noise and therefore it is not at all clear if the upgraded sensitivity is a net disadvantage for them. Based on these considerations we conclude that there is no requirement for imposing a maximum limit on the receiver sensitivity. Moreover, removing this constraint will allow interoperability with higher performance stations using for example sectored receivers or more sophisticated detection methods.

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