The Infrared Physical Layer of the IEEE 802.11 Standard for Wireless Local Area Networks

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There is a growing interest in wireless local area networks [1] that is a consequence of the large-scale utilization of personal computers and mobile communications. The portable personal computer integrates computational power and mobility in a single platform and introduces the need for accessing communication networks without the restrictions imposed by cables.

The interest in wireless local area networks (WLANs) has recently found echo in international standardization bodies. In USA, the executive committee of the IEEE 802 project created, in July 1990, the IEEE 802.11 group, to work on the specification of a WLAN for different technologies, including radio and infrared. The standard was approved in June 1997 [3]. An essential characteristic of the IEEE 802.11 specification is that there is a single medium access control (MAC) sub-layer common to all physical (PHY) layers. This feature will allow easier interoperability among the many physical layers that are expected to be defined in the future, driven by the fast technological progresses in this field. There are presently three physical layers in the standard: infrared, frequency hopping spread-spectrum and direct sequence spread-spectrum. Infrared and radio can be considered as complementary technologies for the support of WLANs. Infrared technology [2] is well suited for low-cost low-range applications, such as ad-hoc networks (small area networks that are set-up for a short period only).

IEEE 802.11 NETWORKS

Figure 1 illustrates a scenario, in an educational environment, for the application of an IEEE 802.11 network. In this scenario, still a bit futuristic, each student owns a portable computer that he will use as a notebook and, in general, as a learning tool exploring the applications resident on disk. During classes the portables of the students and of the teacher get interconnected through an IEEE 802.11 network. This will allow for co-operative work within the classroom and for accessing applications and files resident on the school server. Although many of these features are already provided by the school backbone (eventually a cabled network such as Ethernet or Token Ring), the fact that portables are no longer dependent on a cable to access the network enables these facilities to be provided irrespective of the place where the classes take place, allowing for a more flexible and efficient working environment. Moreover, it promotes a better integration of the work performed inside and outside the classroom.

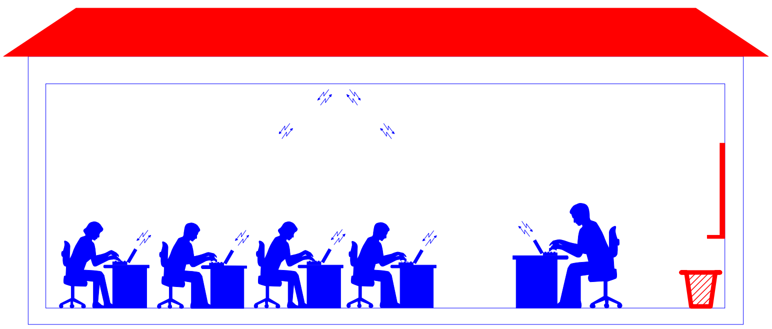

Figure 1. *A scenario for an IEEE802.11 network.*

IEEE 802.11 networks are part of the overall IEEE 802 architecture. An important consequence is that all functions unique to WLANs must be assigned to the physical or medium access control layers. The entities that compose an IEEE 802.11 network are represented in Figure 2. A group of stations associated to establish direct communication form a *Basic Service Set* (BSS). The area occupied by stations from a BSS is the *Basic Service Area* (BSA) or *cell*. Cells can overlap partially, totally or be physically disjoint. The coverage of a cell depends on the propagation environment and the transceiver characteristics. Large areas can be covered using multiple cells, thus, multiple BSSs. The system used for the interconnection of a group of BSSs is the *Distribution System* (DS). The DS can be, for example, an Ethernet or ATM network. The entity that allows stations to access the DS is the *Access Point* (AP). The AP includes all functions of a station. A group of BSSs interconnected by a DS forms an *Extended Service Set* (ESS).

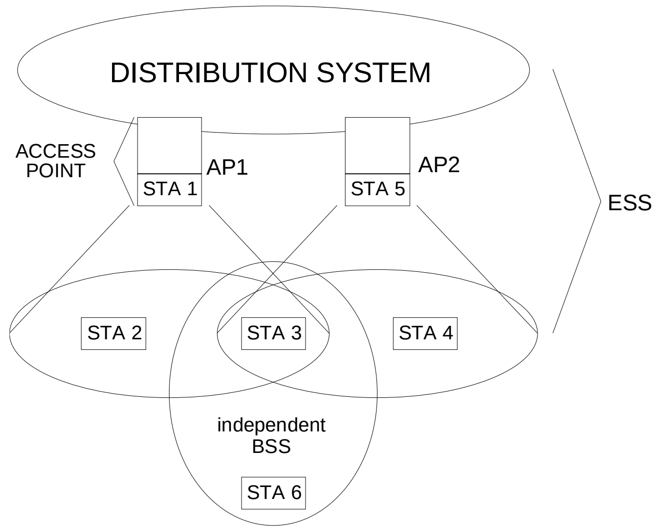

Figure 2. *IEEE 802.11 network components***.**

The simplest IEEE 802.11 network is an independent BSS. This type of network is sometimes called an ad-hoc network. Examples of ad-hoc networks are classrooms (as in Figure 1), small meetings and conference rooms. IEEE 802.11 networks based on infrared technology are well adapted to the requirements of ad-hoc networks.

OVERVIEW OF THE IEEE 802.11 MEDIUM ACCESS PROTOCOL

Wireless networks require several additional functions, when compared to cabled networks, to adapt to the particular characteristics of the transmission channel and to the mobility of the stations. The IEEE 802.11 MAC sub-layer includes, besides the basic medium access control function, additional functions for fragmentation and reassembly of frames when the quality of the transmission channel is poor, association and reassociation of stations with Access Points, temporal synchronization for the support of delay sensitive applications, power management for battery operated stations and data rate adaptation.

Medium access is based on a CSMA/CA (*Carrier Sense Multiple Access with Collision Avoidance*) protocol. According to CSMA/CA, a station that has a packet ready for transmission starts by sensing the channel (*Carrier Sense*). If the channel is free for a period longer than an inter-frame space, denoted by DIFS (*Distributed Inter-Frame Spacing*), the station transmits immediately. If the channel is busy, the station keeps sensing the channel until the channel is free for a period longer than DIFS. When the channel finally becomes free, the station further delays its transmission using a binary backoff algorithm, similar to that of Ethernet, before making another transmission attempt. This is the *collision avoidance* aspect of the protocol. The CSMA/CA protocol is also enhanced with *immediate positive* *acknowledgement* and *reservation* mechanisms. According to the acknowledgement mechanism, when a station receives a valid data packet (DATA) addressed to itself, it must confirm the reception of this packet by sending an ACK (*ACKnowledgement*) mini-packet to the source station. To assure that the destination station do not has to contend for medium access when sending the ACK, the destination station uses an inter-frame space shorter than DIFS, which is called SIFS (*Short Inter-Frame Spacing*). The use of immediate positive acknowledgement as part of medium access allows for error detection by the source station and is required due to high levels of noise and interference impairing the transmission channel. Positive acknowledgement can only be used with directed packets. Therefore, the transmission of multicast and broadcast packets is less robust. The reservation mechanism is based on the exchange of RTS (*Request-To-Send*) and CTS (*Clear-To-Send*) mini-packets between the source and destination stations prior to sending DATA packets. RTS and CTS broadcast information on the time interval the channel will be occupied from RTS (or CTS) ending to ACK ending. Each station maintains a timer, called NAV (*Network Allocation Vector*), that indicates in each instant the remaining channel occupation time. The NAV at all BSS stations must be updated whenever an RTS or CTS packet is received. Stations can only transmit after the NAV countdown has expired. In this way, RTS and CTS mini-packets reserve the channel for data transmission. The medium access mechanism is illustrated in Figure 3.

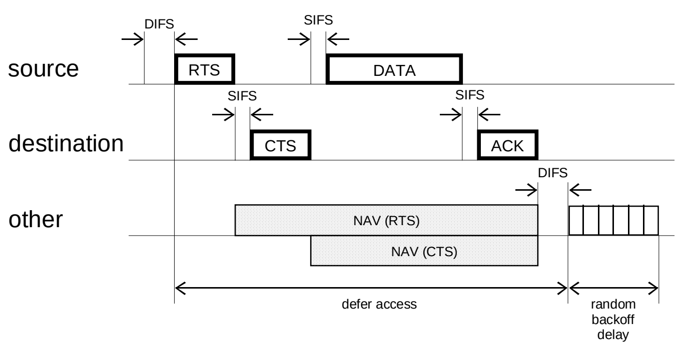

Figure 3. *Medium access protocol.*

The reservation mechanism can be used to combat the hidden station problem. A station A that is not able to sense the activity on the channel produced by a station B is said to be *hidden* from B. In Figure 4 station B is hidden from station A (but not from C). Station A transmits to C but station B will not sense this activity. In this case, station B can transmit freely thus interfering with the transmission from A. However, if A and C exchange mini-packets RTS and CTS with an indication of the time the channel will be occupied, station B, although not sensing directly station A, will be informed through the CTS mini-packet of the time the channel will be occupied by A and C and will not interfere with the transmission of the DATA packet sent by A. Note that this mechanism will not avoid collisions since RTS mini-packet can still be sent simultaneously from A and B. However, RTS collisions are less harmful than DATA collisions in terms of throughput performance since RTS mini-packets are relatively short.

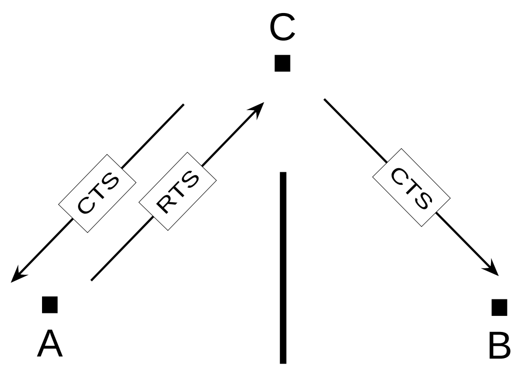

Figure 4. *Use of RTS and CTS mini-packets to combat the hidden station problem.*

INFRARED TECHNOLOGY

Wireless infrared links are based on *intensity modulation* and *direct detection* of the optical carrier. This is similar to many optical fiber links. Intensity modulation is performed by varying the current of a laser diode or an LED. Direct detection is performed by PIN photodiodes or APDs that produce an electrical current proportional to the incident optical power. The optoelectronic components used more frequently are LEDs and PIN photodiodes.

Infrared radiation has properties very similar to visible radiation. Typical surfaces of indoor environments are, in general, good reflectors of infrared radiation (the main exceptions are dark and transparent surfaces). This property has two important consequences. First, infrared radiation can propagate through multiple reflections on the propagation environment. The propagation through multiple paths can provoke time dispersion of the received pulses, which is called *multipath dispersion*. The effects of multipath dispersion are observed as inter-symbol interference. Second, having obstacles between the emitter and the receiver can provoke a significant attenuation of the collected optical power, which is called *shadowing*.

The bandwidth of an infrared link is mainly determined by the multipath dispersion. The inter-symbol interference is not significant for data rates up to approximately 10 Mbps.

The illumination sources of indoor environments (sunlight and artificial light generated by incandescent and fluorescent lamps) radiate in the same wavelengths as the infrared data signal. Also, typical intensity levels of the ambient light collected at the photodetector are usually much higher than data signal intensity levels. The ambient light provokes shot noise, due to the random nature of the photodetection process. Moreover, the artificial light provokes interference due to the periodic variations of the light intensity [4]. These variations can occur at the double of the mains frequency or at the switching frequency of the electronic ballasts of the fluorescent lamps. In general, for low and moderate data rates, the ambient noise is the main factor degrading the performance of wireless infrared links [5].

Besides ambient noise, wireless infrared links can also be affected by the front-end noise and by non-optical electromagnetic interference of various types, such as the one provoked by power supplies. In general, non-optical electromagnetic interference can be significantly reduced by properly shielding the front-end and the photodetectors, filtering the power supply and using differential configurations at the front-end pre-amplifier. The front-end noise has two components: (i) thermal noise associated to the photodetector bias resistor and (ii) thermal noise associated to the channel impedance, in case of a FET based front-end, or shot noise associated to the base current, in case of a BJT based front-end. In general, these two degrading factors can be made insignificant relative to ambient noise.

When operating an infrared wireless system, users become directly exposed to IR radiation. Excessive exposure to IR radiation may originate ocular lesions. The extension of these injuries depends on several factors: the intensity and duration of the exposure, the wavelength of the radiation and the dimensions of the emitting area. There are international safety regulations that define the maximum levels a user can be exposed without suffering any lesion. In practice, these standards limit the average optical power emitted by the source to a few hundreds of mW. Other factors pushing for the use of low levels of emitted optical power are the power consumption of battery-operated stations and the poor conversion efficiency of LEDs.

Shadowing and ambient noise drive the need for emitting high levels of optical power. However, as discussed before, the optical power level is restricted a priori by international safety regulations and by the power consumption of the stations. Therefore, the transmitted signal must be processed to allow its detection with the lowest possible signal-to-noise ratio. Pulse Position Modulation (PPM) is generally accepted as the technique that offers the best characteristics for transmission in this type of transmission channel [2]. PPM maps binary words into pulse positions. In L-PPM, a word with *k* bits is coded into one of the $L = 2^k$ positions of an L-PPM symbol.

Infrared systems can be classified according to the way stations establish an optical path between themselves. There are three types of systems: point-to-point, quasi-diffuse and diffuse [2]. The IEEE 802.11 specification was developed for diffuse systems. In a diffuse system the optical path between emitter and receiver is established through multiple reflections in the surfaces of the propagation environment. Both emitter and receiver are non-directive and have arbitrary orientation. Ideally, the received optical level must be independent of the position and orientation of the receiver.

INFRARED PHYSICAL LAYER SPECIFICATION

The infrared physical layer supports two data rates: 1 and 2 Mbps. The specification of two data rates aimed at allowing (i) a smooth migration to higher data rates and (ii) an asymmetric operation of the BSS. There is a different PPM scheme for each data rate: 16-PPM for 1 Mbps and 4-PPM for 2 Mbps. The purpose of this feature is to assure that the basic pulse is the same at both data rates which minimizes the additional complexity introduced by the 2 Mbps data rate. The emitter and receiver circuits can be almost identical (in particular, the same front-end can be used at both data rates) and the most significant enhancements are required on the synchronization circuits [6]. The PPM signals at 1 and 2 Mbps are represented in Figure 5. The duration of each pulse is 250 ns and the peak optical power is 2 W. Therefore, the average optical power is 250 mW at 2 Mbps and 125 mW at 1 Mbps.

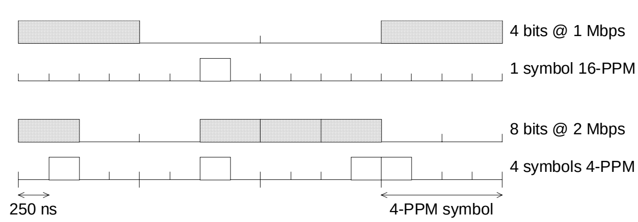

Figure 5. *PPM signals at 1 and 2 Mbps.*

FRAME FORMAT

The main function of the physical layer frame is to carry the MAC Protocol Data Unit (MPDU) while supporting the various features of the physical layer. When developing the infrared physical layer frame format, several aspects were taken into account. The frame format should (i) allow interoperability with future infrared physical layers (most probably at higher data rates), (ii) support multiple data rates, and (iii) be optimized for performance through minimization of the frame error rate (FER).

Three infrared physical layer frame formats were submitted to the IEEE 802.11 working group [6] [7] [8]. The format that was finally adopted is shown in Figure 6.

SYNC	SFD	DR	DCLA	LENGTH	CRC	MPDU
57-73 slots	4 slots	3 slots	32 slots	16 bits	16 bits	0 to 1500 bytes

Figure 6. *Infrared physical layer frame format.*

Only the shadowed fields in Figure 6 are transmitted using L-PPM. The first three fields are transmitted as OOK signals but using the same 250 ns pulse as the shadowed fields. Although this solution penalizes the FER performance it minimizes the overhead introduced by the PHY header. In addition, this feature enables interoperability with future physical layers if they choose to adhere to the format of the first three fields. The *Direct Current Level Adjustment* (DCLA) field is used to allow the receiver circuits to adjust to the difference between the average signal level of the OOK and L-PPM fields. A different DCLA format is specified for each data rate.

The SYNC field is used for clock recovery (i.e. slot synchronization), for carrier sense and to allow stabilization of the receiver circuits (e.g. the AGC). Its format corresponds to a 2 MHz clock signal. The *Start of Frame Delimiter* (SFD) field performs frame alignment, i.e., it delimits the beginning of subsequent fields. The *Data Rate* (DR) field is used to identify the type of physical layer that transmitted the frame. In the current standard, there are two types, corresponding to the 1 and 2 Mbps data rates. Since different orders of PPM are used for each data rate, this field implicitly carries synchronization information for decoding the PPM symbols. The DR field is 3 slots long allowing for the specification of 6 additional physical layers.

At the receiver, carrier sense declaration requires the detection of a signal with a pre-defined power level and the detection of a valid SYNC pattern. The SYNC pattern is a fragment of the overall SYNC field sequence. After a signal with a pre-defined power level is detected in the medium and slot synchronization is acquired, the receiver starts searching for a valid SYNC pattern. This function can be implemented by digital correlation of the received signal with the SYNC pattern. The pattern can be imitated by noise, which may result in frame misalignment. The longer the pattern the lower will be the probability of false

SYNC detection but the higher will be the probability of no SYNC detection due to errors. The probability that a valid SYNC is not detected is negligible, if a short pattern is used (8 slots) [9].

The SFD pattern required a careful design due to its strong impact on the FER. The search for a valid SFD field follows carrier sense declaration and should start during the SYNC field. During the search process, the SFD can be imitated due to errors in the SYNC field. Also, the SFD will not be detected if it suffers from errors. Thus, the probability that the SFD is correctly detected depends on (i) the probability of imitation and (ii) the probability of error of the SFD. The format that maximizes the probability that this field is correctly detected can be one of the words "1001" or "1100" [9]. The "1001" word was adopted in the standard.

Previous solution for the SFD format, although optimized in terms of FER, still does not comply with one of the basic rules of IEEE 802 networks, which imposes that the Hamming distance of the word used for frame alignment purposes should be at least 4. The adopted SFD pattern has a Hamming distance of only 2. For a Hamming distance of 4, the SFD should be at least 9 slots long, which would increase significantly the FER. In order to comply with this rule without degrading the FER, it was decided to include a frame length field (LENGTH) protected by an error detection field (CRC). If a false SFD is declared, the LENGTH and CRC fields will have incorrect values with very high probability, which will be detected by the CRC. If the declaration of a valid frame is delayed until these two fields are correctly detected, the misalignment probability is very low, while keeping the FER at a minimum. The LENGTH field is also used to delimit the end of the frame.

RECEIVER SENSITIVITY AND PERFORMANCE ISSUES

The performance of the infrared physical layer can be estimated through the calculation of the FER of the adopted frame format. Simple calculation of the bit error rate can lead to erroneous conclusions. For the frame format shown in Figure 6, the FER is given by [9]:

$$FER = 1 - P_{SYNC} \cdot P_{SFD} \cdot P_{DR} \cdot P_{LENGTH} \cdot P_{CRC} \cdot P_{MPDU}$$

where P_{SYNC}, P_{SFD}, P_{DR}, P_{LENGTH}, P_{CRC} and P_{MPDU} are the probabilities that the fields SYNC, SFD, DR, LENGTH, CRC and MPDU are correctly detected.

The basic requirements of IEEE 802.11 networks mandate that the FER should be lower than 4×10^{-5}, for frames with 512 bytes of data. In the infrared physical layer, the receiver sensitivity is defined as the minimum irradiance (optical power per unit area) required to achieve this FER specification, under a stationary ambient light irradiance level of 0.1 mW/cm^2. This FER value is achieved at a signal-to-noise ratio of 2.66 dB, assuming an active area of 1 cm^2 and the use of a maximum likelihood PPM receiver. The resulting error probabilities of the frame fields are presented in Table 1. The results show that the FER is dominated by the probabilities of error of the SFD and DR fields and not of the MPDU field, even after the optimization of the SFD field. The receiver sensitivity was specified at 2×10^{-5} mW/cm^2 for 1 Mbps and 8×10^{-5} mW/cm^2 for 2 Mbps. These values include a margin for implementation imperfections and factors not included in the calculations.

Probabilities	**ML receiver** (SNR=2.66 dB)
$1 - P_{SYNC}$	5.76×10^{-14}
$1 - P_{SFD}$	1.93×10^{-5} •
$1 - P_{DR}$	1.45×10^{-5} •
$1 - P_{LENGTH}$	2.43×10^{-8}
$1 - P_{CRC}$	2.43×10^{-8}
$1 - P_{MPDU}$	6.22×10^{-6}
FER	4.00×10^{-5}

Table 1. *Probabilities of error in the detection of the frame fields***.**

The receiver sensitivity specification considers only stationary ambient noise and not the interference produced by artificial light. This results from the need of producing a specification where the ambient light conditions could be easily reproduced for conformance testing purposes. Clearly, the definition and reproduction of interference light conditions would be a difficult task. However, an optical receiver developed with little or no attention to the optical interference problem may be a conformant receiver but with a very degraded performance if operating under artificial light.

There is no maximum receiver sensitivity value specified in the standard, opening the possibility for competition among different manufacturers. There are several options for increasing the link performance while maintaining conformance with the IEEE 802.11 specification: (i) increase the receiver active area, (ii) use of angular diversity at both the emitter and the receiver [2] and (iii) use of interference cancellation techniques [10].

EMITTER RADIATION PATTERN

The specification of an emitter radiation pattern [11] had in view (i) to minimize the propagation losses, (ii) to allow system operation in a large set of dissimilar propagation environments and (iii) to assure its conformance with the safety standards for infrared radiation [12]. The low cost requirement restricted attention to the use of LEDs on the emitter array. An array with all LEDs oriented vertically would result in an excess of irradiance around the source position. Clearly, the number, orientation, radiation pattern and emitted power of each LED in the array are parameters that can be optimized to make the power distribution as uniform as possible, thus minimizing the channel propagation losses. Ideally, the irradiance should have a constant value slightly higher than the receiver sensitivity, over the whole cell area. The emitter radiation pattern was specified assuming that stations would be moving on a plane parallel to the ceiling.

The emitter radiation pattern is specified in terms of a mask that defines the irradiance bounds as measured by a test receiver. The algorithm used to define the mask [11] searched for an optimized radiation pattern, while accounting (i) for manufacturing tolerances on the orientation and optical characteristics of the LEDs and (ii) for the diversity of propagation environments. The diversity of propagation environments was considered by restricting to two extreme cases in terms of propagation losses: large open plants and walled rooms.

The emitter radiation pattern mask is shown in Figure 7. The mask is defined by lower and upper irradiance limits, for each angle between the emitter axis and the axis of a test receiver, positioned 1 meter away from the emitter. The irradiance is normalized to the optical peak power.

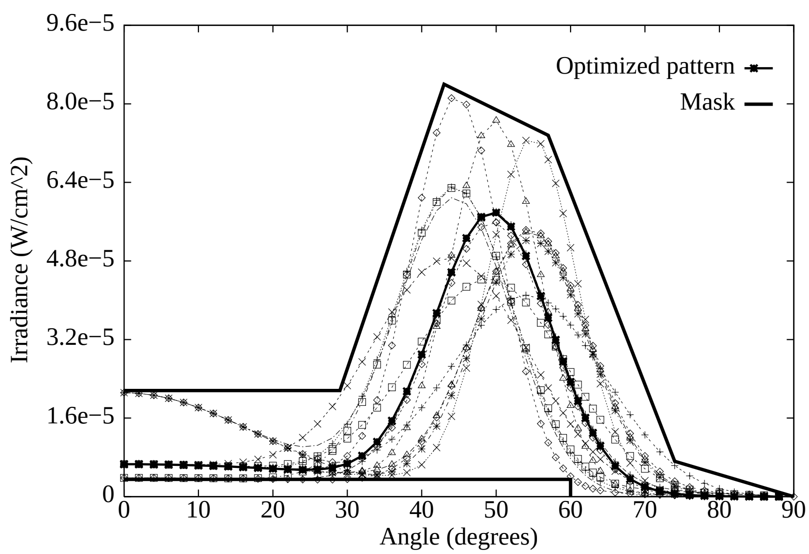

Figure 7: *Mask of the emitter radiation pattern.*

The optimized emitter radiation pattern corresponds to an array of 11 commercially available LEDs: 1 LED, with half-power angle (*hpa*) = 41° and 15 mW of total optical power, vertically oriented, and 10 LEDs, with *hpa* = 9° and 11 mW of total optical power, oriented at 50° with the vertical. Figure 7 shows also several radiation patterns corresponding to different tolerances: 10% for the angle of the LEDs with the vertical, 25% for the *hpa* of the narrower LEDs and 50% for the *hpa* of the larger LEDs.

SUPPORT OF OPTIONAL DATA RATE

With the purpose of minimizing the hidden station problem the same cell coverage is specified for 1 and 2 Mbps. This requires approximately the same energy per symbol at 1 and 2 Mbps. Since the pulse density of a 4-PPM signal is four times that of a 16-PPM signal, the average optical power emitted at 2 Mbps is approximately 6 dB higher than the average optical power emitted at 1 Mbps. However, since frames at 2 Mbps require half the time to be transmitted the penalty in terms of optical energy per frame is approximately 3 dB. Nonetheless, the additional power consumption associated with the transmission at 2 Mbps lead to specify this data rate as optional. In summary, transmission at 2 Mbps is optional while transmission at 1 Mbps and reception at both rates is mandatory.

CONCLUSIONS

The new IEEE 802.11 standard for wireless local area networks defines a specification for an infrared physical layer. We have described this specification in detail, giving an historical perspective of its development and providing some background on infrared technology specific issues. The infrared physical layer was designed for diffuse systems supporting two data rates (1 and 2 Mbps) and includes provisions for a smooth migration to higher data rates. The specification is suitable for low-cost transceivers but allows interoperability with higher performance systems. The main application envisaged for IEEE 802.11 infrared wireless local area networks is ad-hoc networks.

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