Performance comparison of the IEEE 802.11 and AIr infrared wireless MAC protocols

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Abstract

A performance comparison is made between the IEEE 802.11 Infrared W-LAN and the IrDA Advanced Infrared (AIr) MAC protocols. Both protocols are CSMA/CA based medium access schemes that operate on a similar basis but with certain significant differences. The study uses an existing analytical model of the 802.11 MAC protocol with suitable modifications for the AIr MAC protocol. Verification of the results is provided from simulation modelling using the OPNET Modeler package.

1. Introduction

The Infrared (IR) medium has been shown to be an attractive alternative to RF for short range indoor wireless data communications, with the principle benefit being the use of low-cost components with low power consumption [1]. The Infrared Data Association (IrDA) has produced a set of standards for directed point-to-point links with data rates up to 4 Mbps which have been widely adopted. Devices such as digital cameras, mobile phones and PDAs can communicate using IR in addition to the traditional applications of file transfer and printing [2]. At the heart of the IrDA protocol is the IrLAP data link layer which is HDLC-NRM based. However there are limitations in the IrDA protocol from the point-to-point nature of the links and the IrLAP protocol [3]. Recently IrDA and IBM have produced a draft protocol specification called Advanced Infrared (AIr). The basis of AIr is to provide a robust non-directed multiple access IR medium with a suitable MAC (Medium Access Control) layer [4]. The AIr protocol can be seen as being comparable with that of the IEEE 802.11 protocol. The 802.11 is an international standard for wireless local area networks (W-LANs) which was approved in 1997. The standard allows a number of physical layer options, one of which is Infrared [5].

Both systems use a CSMA/CA (Carrier Sensing Multiple Access with Collision Avoidance) based MAC protocol with RTS/CTS medium reservation that operate in a very similar fashion. However there are subtle but significant differences between the two systems in their collision avoidance and media access methods. This paper compares the performance of the two MAC protocols by examining the throughput performance in relation to network size and collision avoidance parameters.

2. The Advanced Infrared (AIr) protocol

The AIr physical layer uses wide angle transceivers with a robust modulation scheme. The modulation used is 4PPM with variable repetition encoding (4PPM/VR) with a base data rate of 4 Mbps. Variable repetition encoding means repeating each 4PPM symbol a number (1, 2, 4, 8, or 16) of times and using majority voting on valid symbols. There is therefore a trade-off between effective data rate and link quality. By doubling the symbol repetition, the data rate is halved, but the signal-to-noise ratio is improved by a factor of 3dB. This also enables variable data rates without physical changes in transceiver circuitry [6].

The AIr frame structure is as shown in figure 1. The frame consists of preamble and synchronisation fields that indicate the start of the frame, a robust header, and a variable length main body (with PDU data 0 to 2K bytes) which if present is protected by a 32 bit CRC. The robust header contains essential information for MAC operation and is always encoded with the maximum 16 repetition rate (RR). The main body (including the CRC) has a variable RR.

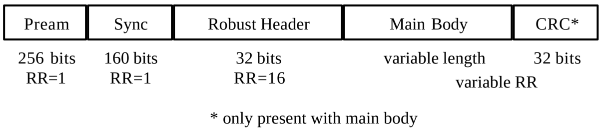

Figure 1. AIr Frame Structure

In the AIr protocol the IrLAP layer is split into three sub-layers of the AIr MAC, the AIr LM (Link Manager) and the AIr LC (Link Controller). The LM layer provides multiplexing for client protocols and the LC layer is a HDLC-ABM (Asynchronous Balanced Mode) based data link layer. The AIr MAC protocol is responsible for establishing access to the IR medium and avoiding packet collision. Access to the medium can be both reserved (using RTS/CTS exchange) or unreserved.

2.1 The AIr MAC protocol

Collision avoidance in the AIr MAC protocol involves waiting a randomly chosen set of Collision Avoidance Slots (CAS) each of 800μsecs before transmitting an RTS frame. If another contending station (i.e. with collision avoidance timer running) receives the start of an RTS frame, the collision avoidance (CA) timer is paused, and resumed (from the beginning of the next time slot) when the media becomes free again. The target station replies to the RTS frame with a CTS frame to confirm establishment of the reservation after which the sending station transmits a burst of data packets. The number of packets transmitted is determined by the packets-per-burst (ppb) parameter which must be such that the burst time does not exceed the reservation time, which has an upper limit of 500ms. After the final packet is transmitted, the sending station sends an EOB (End Of Burst) frame. The target station replies with an EOBC (End Of Burst Confirm) frame to complete termination of the reservation. Stations then synchronise before medium contention resumes. Also, each time a station requires to transmit a frame following reception of a frame, the station must wait a turn-around delay time(TAT). This is to cover receiver latency and for AIr has a fixed value of 200 μsecs. The number of CAS slots used is chosen randomly from a 'CAS window'. This normally has a value of 8 by which a CAS value is chosen randomly from 0 to 7. If two or more stations choose the same CAS value, then an RTS collision will occur. This will be detected by the expiration of a Wait-for-CTS timer, after which a new CAS value is chosen and the contention restarted. If the CAS window is small in relation to the number of contending stations then RTS collision can be quite likely [7].

The AIr MAC has a CAS window adjustment algorithm which can be employed to improve contention. If an RTS collision occurs, the CAS window for the RTS retry is increased by an adjustment value. Following a successful transmission, the CAS window is reduced by the adjustment value. The adjustment has a recommended value of 4. There is also an upper and lower limit to the CAS window [8].

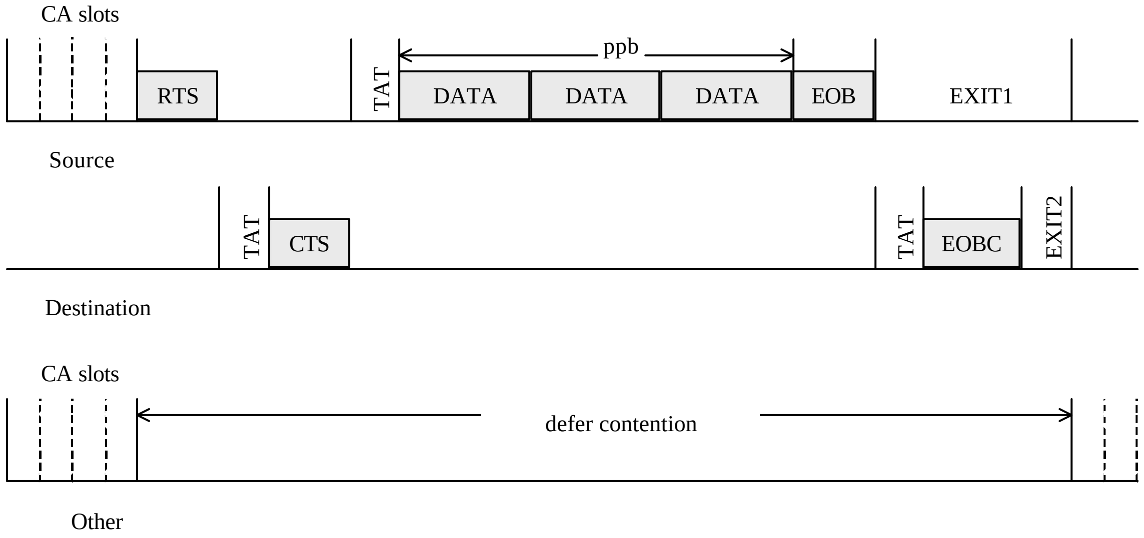

Figure 2. AIr MAC reserved mode data transfer process

3. The IEEE 802.11 W-LAN protocol

The IEEE 802.11 is an international standard for wireless local area networks (W-LANs) that was approved by the IEEE in 1997. The standard specifies a common MAC layer to a number of possible physical layers. The physical layer options include 2.4 GHz RF with direct-sequence or frequency-hopping spread spectrum, or L-PPM diffuse Infrared. All mediums can operate at 1 or 2 Mbps data rates.

The frame structure for the IR physical layer is shown in figure 3. The 'header' consists a number of fields that indicate the start of the frame and the data rate being used. The header portions are encoding using on-off-keying (OOK) modulation whereas the remainder of the frame uses L-PPM. Specifically, 4-PPM (each symbol is 2 bits) is used for the 2 Mbps data rate and 16-PPM (each symbol is 4 bits) for the 1 Mbps, with the same 'slot' time used for each scheme.

Header	Length	CRC	MPDU
96 to 112 slots	16 bits	16 bits	0 to 1500 bytes

Figure 3. 802.11 IR physical layer frame structure

3.1 The 802.11 MAC protocol

The media access function of the 802.11 MAC protocol is known as the Distributed Co-ordination Function (DCF) but is essentially just a CSMA/CA process. With the DCF, when a station has data to send, it first listens to the media to see if it is busy. If the media is detected free for a period equal to a time period called the Distributed Inter-Frame Space (DIFS) then a packet may be transmitted. If the channel is detected busy within the DIFS, then channel access is deferred until the media is detected free again. The station then uses a contention window procedure in which a random number of contention slots are chosen. If the media is detected busy during the contention backoff period, the contention timer is paused and resumed when the media is detected free again. When the contention timer reaches zero the packet is transmitted. The media can be accessed using either the basic access method or with RTS/CTS media reservation. With the basic access method, a data packet is transmitted and is acknowledged with an ACK frame from the receiving station. With the RTS/CTS method, an RTS/CTS exchange is used to reserve the media, a single data frame is transmitted and is acknowledged with an ACK. Also with the RTS/CTS method, when the link is turned-around, the station must wait a period called the Short Inter-Frame Space (SIFS) before transmitting. Any other station that hears the RTS/CTS exchange updates a Network Allocation Vector (NAV) to determine the period of contention deferral. The process is shown in figure 4.

As with the AIr MAC protocol, the 802.11 DCF uses a contention window (CW) adjustment algorithm. However in this case the adjustment is exponential instead of linear. For an i_{th} successive retry for access to the medium, the contention window becomes $2^{i}CW_{min}$. Upon a successful transmission, the contention window is returned to CW_{min}. The maximum contention window CW_{max} is given by $2^{m}CW_{min}$, where m is the maximum backoff stage. For the IR medium, the specified values are $CW_{min} = 64$ and $CW_{max} = 1024$ [9].

The principle differences between the AIr MAC and the 802.11 MAC can therefore be summarised as follows.

- The maximum data rate of AIr is 4 Mbps. The maximum data rate of 802.11 is 2 Mbps.
- AIr uses non-directed line-of-sight links. 802.11IR uses non-directed non-line-of-sight (diffuse) links.
- A burst of data packets can be transmitted with AIr in each reservation. Only one data packet at a time transmitted with the 802.11 protocol.
- The AIr MAC uses a linear adjustment (both up and down) of the contention window. The 802.11 MAC uses an exponential (up only) adjustment of the contention window.

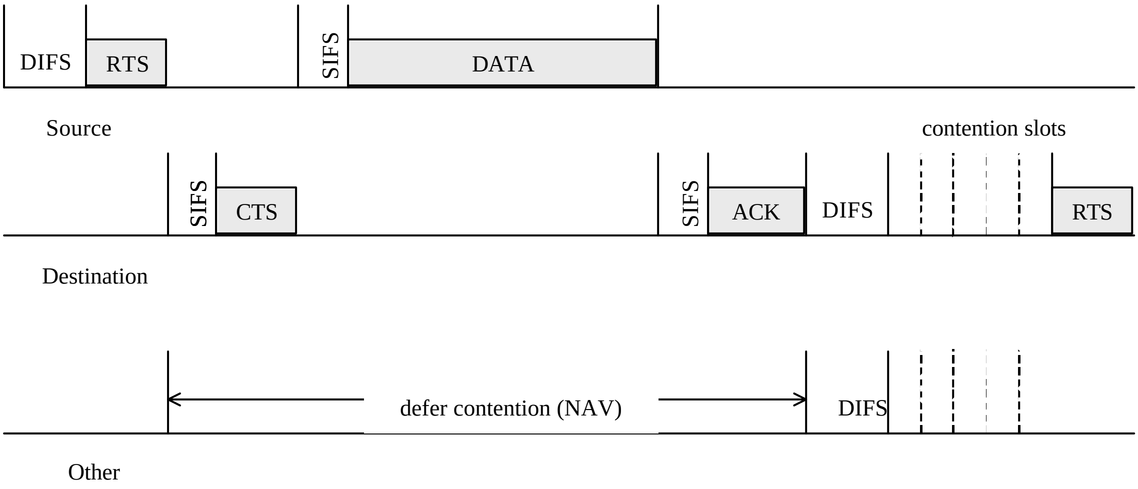

Figure 4. IEEE 802.11 MAC RTS/CTS channel access process

4. Performance Modelling of MAC processes

The analysis used here uses the performance model of the 802.11 MAC process by Bianchi [10] with a modification of the model for the AIr MAC process. In both cases, if we define a transmission slot period in which data is transmitted, the normalised throughput S is determined by:

$$S = \frac{E[\text{data transmitted in slot}]}{E[\text{length of slot}]} \qquad (1)$$

This can therefore be written as:

$$S = \frac{P_S P_{tr} L}{(1 - P_{tr}) s + P_{tr} P_S T_S + P_{tr} (1 - P_S) T_C} \quad (2)$$

where T_S is the average time the channel is sensed busy for a successful transmission, and T_C is the average time the channel is busy if a collision occurs. L is the packet data payload transmission time (we assume constant packet sizes) and s is the contention slot time. P_{tr} is the probability of at least one transmission in the chosen time slot and P_S is the probability of the transmission being successful.

For the 802.11 MAC process, the times T_S and T_C are given by:

$$\begin{aligned} T_S(802.11) &= RTS + SIFS + CTS + SIFS \\ &+ (L + H) + SIFS + ACK + DIFS \end{aligned} \quad (3)$$

$$T_C(802.11) = RTS + DIFS \quad (4)$$

where H is data packet overhead transmission time.

For the AIr MAC process, they are given by:

$$\begin{aligned} T_S(AIr) &= RTS + TTA + CTS + TTA \\ &+ ppb(L + H) + EOB + TAT \\ &+ EOBC + EXIT2 \end{aligned} \quad (5)$$

$$T_C(AIr) = s \quad (6)$$

For both systems, the transmission probability P_{tr} is given by:

$$P_{tr} = 1 - (1 - t)^n \quad (7)$$

where n is the number of stations in the network, and t is probability of transmitting in a chosen time slot. The probability of a successful transmission P_S is the probability of exactly one transmission on the network in the chosen time slot, and is therefore given by:

$$P_S = \frac{nt(1 - t)^{n-1}}{P_{tr}} \quad (8)$$

The probability t is determined by examining the collision avoidance process for both systems. If there is no adjustment of the contention window, then it can be seen that t is simply given by:

$$t = \frac{2}{W + 1} \quad (9)$$

where W is the contention window size. However if the contention window adjustment algorithm is used then we require a Markov model analysis of the process. The Markov model used is different for AIr and 802.11 as AIr uses a linear adjustment and 802.11 uses an exponential backoff adjustment. The analysis relates t to the probability of collision p. This is assumed to be constant and independent for the Markov analysis. However, p is actually dependent on t and the network size n:

$$p = 1 - (1 - t)^{n-1} \quad (10)$$

This produces a non-linear system from which results can be obtained by numerical techniques (e.g. successive approximation).

5. Model verification by simulation

Results from the mathematical analysis are verified by comparison with those from simulation models using the OPNET Modeler package. OPNET uses a set of graphical hierarchical domains that represent the structure of a communications network from the network topology down to specific processes which are implemented as C/C++ coded finite state machines. The IEEE 802.11 OPNET model was initially produced by Baldwin [11] and is now part of the standard OPNET model library.

An OPNET model of the AIr protocol has been produced by the authors [12]. This was based on the state transition tables provided in the AIr specification documentation. As draft documents, these contain certain errors and inconstancies which also needed to be addressed in creating the model. The models use the 'radio' extension to the Modeler package with modifications to emulate the behaviour of the IR medium, which is not inherently supported.

The AIr OPNET model network domain for 5-stations is shown in figure 5. Each 'node' has a set of attributes representing the protocol parameters that can be set at the network level or promoted to the simulation level where a set of values can be assigned. The model also includes a 'monitor' node which collects simulation statistics and compiles results.

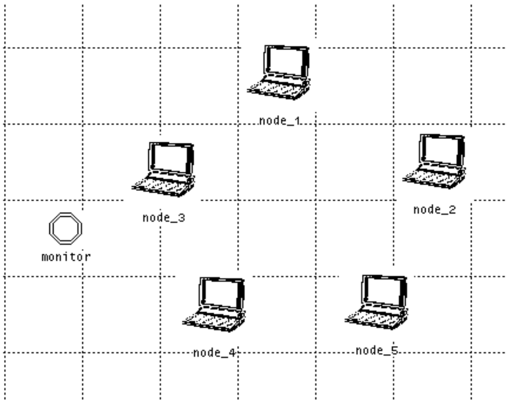

Figure 5. AIr OPNET 5-station model network

6. Analysis Results

The following fixed parameter settings are used for the comparison analysis. To have a valid comparison between the systems, unless otherwise stated, the same data payload size of 2k bytes (16384 bits) is used. One of the more obvious differences between the two systems is the contention slot size. For the AIr MAC, the CA slot is used in carrier sensing, and so must be large enough to cover the RTS transmission and the beginning of the CTS reply to cope with 'hidden nodes'. The 802.11 uses the DIFS for carriers sensing before employing the contention slots. These can therefore be much smaller.

Parameter	Value
Data payload	16384 bits
Data Packet Overhead	250 μs
Data Rate	4 Mbps
RTS	244 μs
CTS	232μs
EOB	232 ms
TAT	200 μs
CA slot	800 μs
EXIT2	200 μs

Table 1. AIr MAC parameter values

Parameter	Value
Data payload	16384 bits
Data Packet Overhead	200 μs
Data Rate	2 Mbps
DIFS	128 μs
SIFS	28 μs
RTS	144 μs
CTS	120 μs
ACK	120 μs
CA slot	8 μs

Table 2. 802.11 MAC parameter values

Figure 5. shows a normalised throughput comparison against fixed contention window size (without any window adjustment), for a network size of 5 stations. The AIr MAC plots are shown for ppb (packets-per-burst) values of 1 (to compare with the single packet 802.11) and with a ppb of 20. This shows that the AIr protocol suffers from a much larger contention overhead from the larger contention slot size.

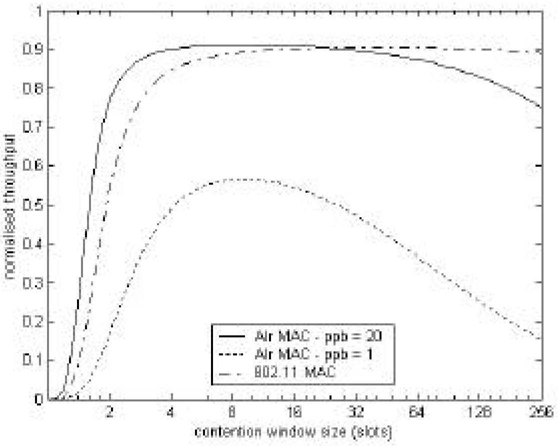

Figure 5. throughput Vs fixed contention window size, n = 5

The remaining figures use the contention adjustment process. For the AIr MAC process, an initial contention window of 8 slots is used with a adjustment of ± 4. For the 802.11 MAC process, an minimum window of 64 slots is used, with a maximum backoff stage of 4. Figure 6 shows normalised throughput against data payload size (bits). For AIr MAC plots are shown for a ppb of 1, 7 and 30 packets. The throughput performance of 802.11 MAC in fact matches almost exactly with the AIr MAC with a ppb of around 20. Again it can be seen that the AIr MAC performance is much worse for a small bust size.

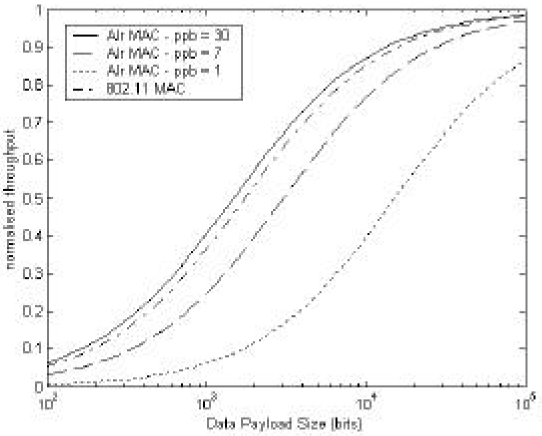

Figure 6. throughput Vs data payload size, n = 5

Figure 7 shows throughput against network size. In general it can be seen that the performance is independent of network size above 2 or 3 stations.

Again the 802.11 performance (relative) matches that of the AIr MAC for a ppb around 20 packets.

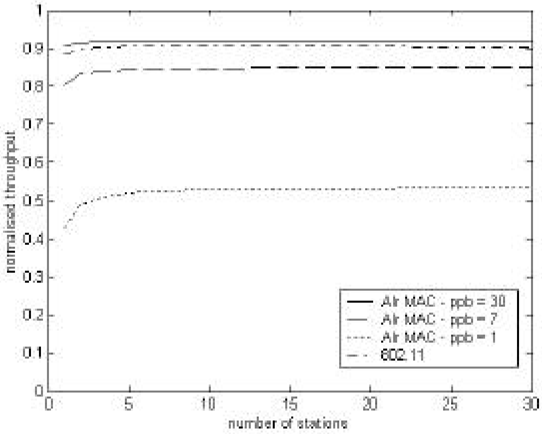

Figure 7. throughput Vs network size using contention window adjustment processes.

7. Conclusions

The IrDA Advanced Infrared (AIr) and IEEE 802.11 W-LAN protocols can be seen as operating on very similar principles and can therefore be favourably compared in their performances. The principle differences are in the maximum available data rate (2 Mbps for 802.11, 4 Mbps for AIr), the number of packets sent after reservation of the medium (1 for 802.11, multiple for AIr) and the method of contention window adjustment (exponential backoff for 802.11, linear ± adjustment for AIr). However a comparison analysis of the protocols has revealed that a further significant difference is the size of the contention window used. For 802.11 the slot size is 8 μsecs for the infrared medium, while AIr has a specified slot size of 800 μsecs. The 802.11 slot can be much smaller because it uses the DIFS in packet sensing. This causes the AIr protocol to suffer when only transmitting 1 packet per reservation making it only slightly better than the 802.11 despite transmitting at twice the data rate. The AIr protocol is therefore only takes advantage of the higher data rate when transmitting a burst of packets in a reservation which reduces the relative effect of the larger contention overhead.

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