Simulation analysis of advanced infrared (AIr) MAC wireless communications protocol

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Abstract: The paper presents results from a simulation model of the IrDA advanced infrared (AIr) MAC protocol for nondirected multiple access infrared wireless communication. The MAC protocol is CSMA/CA based with robust RTS/CTS medium reservation which deals with 'hidden nodes'. Throughput performance is analysed in relation to protocol parameter settings. In particular, the effect of the CAS (collision avoidance slot) window size parameter is examined in relation to the data burst size and network size. The effect of a proposed CAS window size dynamic adjustment algorithm is also examined. The results are validated by comparison with those from an analytical model.

1 Introduction

Infrared (IR) optical provides an attractive alternative to the radio medium for short range indoor wireless data communications [1]. The Infrared Data Association (IrDA) has produced a set of protocol standards for directed point-to-point IR wireless communication that have been widely adopted. Devices such as digital cameras, mobile phones and PDAs can now communicate through IR with desktop and laptop computers in addition to the traditional IR wireless applications of printing and file transfer [2]. The IrDA SIR (serial infrared) protocol provides data rates up to 115.2 kbit/s using the standard serial interface or 4 Mbit/s with additional hardware [3]. The data link layer, the Infrared Link Access Protocol (IrLAP), is closely based on the HDLC-NRM protocol in which a primary–secondary pair exchange transmission periods with a maximum duration of 500 ms [4]. However, the directed nature of the infrared link and the nature of the protocol mean that only one pair of devices can be connected at a time, and multiplexing must be on an application basis only [5].

IrDA and IBM have developed a new protocol set called advanced infrared (AIr) that aims to overcome the limitations of the IrDA SIR protocol. The basis of AIr is to provide a 'broadcast' medium by using nondirected robust links with a suitable multiple access MAC (medium access control) protocol. This is achieved by lifting the restrictions in the IrDA SIR physical layer, and by splitting the IrLAP layer into three sublayers consisting of a MAC layer, which controls access to the medium and avoids packet collisions, an LM (link management) layer, which provides multiplexing for different client protocols, and an LC (link control) layer which provides reliable data transfer based on balanced HDLC procedures [6]. These are defined in draft specification documents made available from IrDA. The MAC protocol is CSMA/CA (carrier sensing multiple access with collision avoidance) based with media reservation using RTS/CTS exchanges. The RTS/CTS exchange using the robust header of AIr frames effectively deals with the 'hidden node' problem common in wireless networks [7]. Collision avoidance uses a randomly chosen number of time slots before attempting to reserve the media. The AIr MAC protocol acts in a very similar manner to that of the IEEE 802.11 W-LAN standard (which can utilise an IR physical layer) with certain significant differences. The performance of the 802.11 MAC has been analysed by various authors [8–11] using both simulation and analytical methods, while analyses of the AIr protocol by other authors has so far focused on the physical layer [12–14].

This paper presents results from a simulation model of the AIr MAC protocol which was developed using the OPNET Modeler simulation package [Note 1]. Simulation produces throughput performance measures in relation to network size and station parameters settings. In particular we have examined the effect of the collision avoidance slot (CAS) window size (the range from which a random value is chosen), and the use of a dynamic collision avoidance window size adjustment algorithm. Simulation results are validated by comparison with those from a modified analytical model of the IEEE 802.11 MAC protocol.

2 AIr MAC protocol

In contrast to the IrDA SIR optical interface which has a maximum transmission cone angle of ±15° [15], the AIr optical interface specifies a maximum cone angle of ±60°, with a maximum output intensity of 360 mW/Sr for L-class (long range) transceivers. AIr frames employ a robust variable repetition 4PPM (4PPM/VR) encoding scheme at a base data rate of 4 Mbit/s. The scheme uses a variable (1, 2, 4, 8 or 16) number of repetitions of each 4PPM symbol with majority voting on valid symbols. The number of repetitions is called the repetition rate (RR). The basis is to provide a trade-off between data rate and link quality. By doubling the repetition rate, the data rate is effectively halved but the signal-to-noise ratio (SNR) is improved by 3dB [16]. The AIr frame structure is as shown in Fig. 1.

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Note 1: OPNET is a trademark of OPNET Technologies Inc. (formerly MIL3 Inc.).

Each frame begins with a Pream (preamble) and Sync (synchronise) field that identifies the start of AIr frames and synchronises receiver circuitry. Every frame also has a 'robust header', which contains all essential protocol operation control information and is transmitted using the maximum 16 RR encoding. The main body (including a 32-bit CRC), which is not present in every frame type, can have a variable RR encoding, with a data payload size up to 2 kbytes.

pream	sync	robust header	main body	CRC
256 bits	160 bits	32 bits	variable length, not always present	
RR=1	*RR*=1	*RR*=16	variable *RR*	

Fig. 1 *AIr frame structure*

The AIr MAC protocol can operate in both reserved and unreserved modes. The reserved mode uses an RTS/CTS (request to send/clear to send) exchange to reserve the medium for a specified period (up to 500 ms). Collision avoidance involves waiting a number of empty time slots (each of 800 µs) before transmitting an RTS frame. The number of slots is chosen randomly from a range of values called the CAS (collision avoidance slot) window. Following a set-up reservation request, the station starts the CA (collision avoidance) timer for the chosen number of slots. When the timer reaches zero, an RTS packet is sent. If a packet is received from another station before the timer has reached zero, the timer is paused and restarted when the medium becomes free again. Provided a station can receive either the RTS or CTS robust headers of an exchange, it will know to defer contention, which deals with the 'hidden node' problem where a station is out-of-range of one of the stations involved in an exchange. If the reservation attempt is unsuccessful, which is indicated by the expiration of a wait-for-CTS timer, a new CAS value is chosen and the reservation reattempted. A reservation attempt will fail if there is an RTS packet collision. The CAS window value ideally needs to be set such that it is large enough (in relation to the number of contending stations) that collisions are avoided but not so large as to cause an excessive time overhead which will affect network throughput. A CAS window adjustment algorithm is therefore proposed in the specification which increases the CAS window if there is an unsuccessful reservation attempt and decreases the CAS window for a successful reservation, with upper and lower limits.

Once the medium has been reserved, a 'burst' of data packets is transmitted. The number of packets transmitted is specified by the packets-per-burst (ppb) MAC parameter and must be transmitted within the requested reservation time. Following the final data packet, an end-of-burst (EOB) packet is transmitted to indicate the ending of the reservation. The destination station will reply with an end-of-burst-confirm (EOBC) packet to confirm the ending of the reservation. EXIT1 and EXIT2 timers are used by the source and destination/nonparticipating stations, respectively, to synchronise before contention begins again [17]. As with IrDA SIR, each station must wait a turn-around-time (TAT) delay when moving from receive mode into transmission mode, to cover receiver latency. With AIr this has a fixed value of 200 µs. The procedure for a burst transmission of DATA frames is demonstrated in Fig. 2.

In addition to sending a burst of DATA frames, Acknowledgment Data frames (ADATA) can also be transmitted which are individually acknowledged by the receiving station (Fig. 3*a*). Sequenced Data frames (SDATA) can also be transmitted which can be acknowledged on termination of the reservation (Fig. 3*b*). SDATA frames can also be used in a reliable multicast mode, in which sequenced Acknowledgment frames (SACK) are used in conjunction with sequenced polling (SPOLL) of the relevant station (Fig. 3*c*). With the unreserved mode, the collision avoidance process is still used, but when contention is won a single UDATA frame is transmitted without reservation of the media. It is the responsibility of upper layers in the protocol to provide retransmission if frames are lost due to collision or transmission error (Fig. 3*d*).

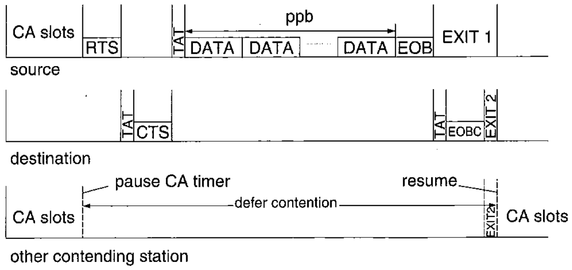

Fig. 2 *Reserved mode medium access and data transfer*

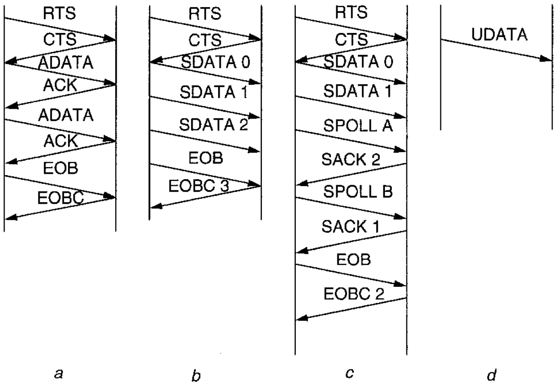

Fig. 3 *AIr MAC data transfer modes*

The principal differences between the AIr protocol and the 802.11 W-LAN protocol can be summarised as follows.

- The 802.11 protocol supports a range of physical layer options, which include infrared. The AIr protocol is specifically designed for infrared.
- The maximum data rate of the 802.11 protocol is 2 Mbit/s. The maximum for the AIr protocol is 4 Mbit/s.
- The 802.11 MAC transmits one data packet in each reservation period. The AIr MAC can transmit a burst of packets up to 500 ms reservation time.
- The 802.11 MAC uses an exponential contention window back-off algorithm. The AIr MAC uses a linear contention (CAS) window adjustment algorithm.
- The 802.11 MAC uses a distributed inter-frame space (DIFS) to determine if the media is busy before beginning contention. The AIr MAC protocol synchronises stations before beginning contention.

3 Simulation model

The AIr MAC simulation model was developed in 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 within each node which are implemented as C coded finite state machines. The implementation of the model was based on the AIr draft specification documents. The specifications use finite state machine diagrams with state transition tables together with primitive specifications to define the operation of the protocol, which makes the specifications particularly suitable for implementation in OPNET. However, as draft specifications, there were a number of errors, inconsistencies and undefined terms in the documents that needed to be addressed. The simulation model was implemented using the 'radio' extension to the OPNET Modeler package, with modifications to the default transmission and reception models to emulate the behaviour of the infrared medium.

The network level is shown in Fig. 4. This represents a 5-station scenario which includes a monitor station for network traffic data collection. Other scenario networks were made for 10, 15, 20 stations, etc. Each station node has a set of attributes representing protocol parameters that can be set individually or promoted to the simulation level where multiple values set can be assigned. We assume in the model that all packets are transmitted error free and there are no 'hidden' stations.

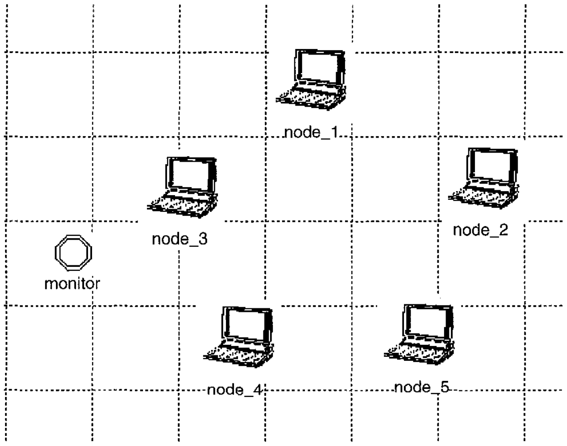

Fig. 4 *AIr 5-station scenario network level*

The node model is shown in Fig. 5, and represents a simplified model of the AIr protocol stack. The LC layer is not implemented in the current model. The link manager (LM) process here constitutes a data packet source and reservation client to the MAC. The LM also controls the assignment of CAS values to the MAC. In the present model the CAS adjustment algorithm uses a single ± CAS adjustment value with a lower limit of 8 and an upper limit of 256. The CAS window is therefore increased by the CAS adjustment value after each failed reservation attempt and decreased after each successful reservation. A CAS adjustment value of 0 indicates a fixed CAS window size which is set by the initial CAS window attribute.

The process level finite state machine for the AIr MAC protocol is shown in Fig. 6. The IDLE state is used when there is no detected media activity and the station has no data to send. The CONTEND state is used with the contention timer before transmitting an RTS or UDATA frame. The WF_CTS (wait for CTS) state is used following RTS transmission to wait for a CTS reply and the XMIT state is used when transmitting the data 'burst'. The IDLE_WT (IDLE wait) state is used to synchronise stations before returning to the IDLE state. The WF_DATA (wait for data) is used to wait for the first data packet after receiving an RTS frame from another station. The RECV state is used when receiving data transmissions from another station and to wait for transmission completion if the station is a nonparticipant in the reservation. The transition labels represent conditional macros defining the transition conditions between states. These are closely based on the AIr MAC specification.

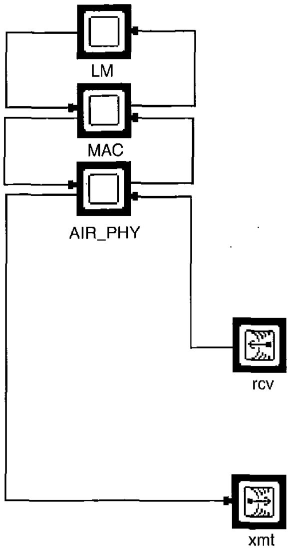

Fig. 5 *AIr node protocol stack model*

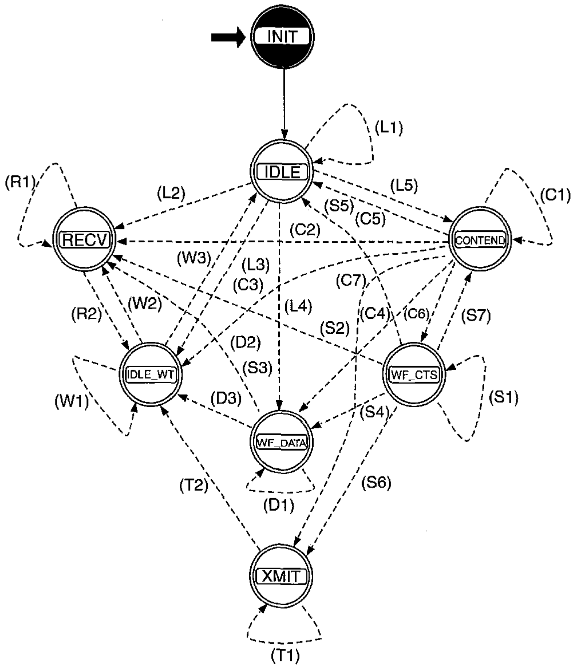

Fig. 6 *AIr MAC finite state machine process level*

4 Validation of simulation model

Validation of the simulation results has been achieved through modification of a performance model of the IEEE

802.11 wireless protocol by Bianchi [18]. In this the normalised throughput, S is given by

$$S = \frac{P_S P_{tr} L}{(1 - P_{tr})\sigma + P_{tr} P_S T_S + P_{tr}(1 - P_S) T_C} \tag{1}$$

where L is the data payload transmission time (we assume fixed packet sizes) and σ is the collision avoidance slot time. P_{tr} is the probability of transmitting at least one frame in a chosen transmission slot and P_S is the probability that the transmission is error free (i.e. exactly one station transmits in the slot). These are given by:

$$P_{tr} = 1 - (1 - \tau)^n \tag{2}$$

$$P_S = \frac{n\tau(1 - \tau)^{n-1}}{P_{tr}} \tag{3}$$

where τ is the probability that a station transmits in a particular time slot and n is the network size. The principal difference in the AIr and 802.11 models is in the calculation of the time taken on the network for a successful transmission T_S and the time taken for a collision T_C. For the AIr MAC model, these are given by:

$$\begin{aligned} T_S = {} & RTS + TTA + CTS + TTA + ppb(L + H) \\ & + EOB + TAT + EOBC + EXIT2 \end{aligned} \tag{4}$$

$$T_C = \sigma \tag{5}$$

where ppb is the packet burst size parameter and H is the DATA packet overhead transmission time. The other terms are time values for packet transmissions and delays. A Markov analysis is used where the contention window adjustment process is implemented that relates τ to a constant collision probability p. If no contention window adjustment process is used so that the contention window size W is constant, the probability τ is simply given by

$$\tau = \frac{2}{(W + 1)} \tag{6}$$

The value for p is actually dependent on τ and the network size n by

$$p = 1 - (1 - \tau)^{n-1} \tag{7}$$

This results in a nonlinear system in p and τ from which results are produced numerically.

5 Simulation results

The following presents results from simulation runs of the AIr model. In all cases a main body RR of 1 was used with a packet data size of the maximum 2 kbytes (16 384 bits). The model assumes a saturated condition in which data packets are continuously available for transmission at every station. In this condition RTS packet collisions will occur when two or more stations choose the same CAS slot time. It is then the station with the next lowest noncolliding CAS slot that will succeed.

The plot in Fig. 7 shows normalised throughput against burst size for different network sizes and a fixed CAS window value of 8. This was produced to determine the burst size to be used for further simulation results. It can be seen that for a network size of 5 nodes the throughput reaches a maximum of just over 0.9 at around 20 packets. A throughput of just over 0.9 is the maximum that can be reached because of the collision avoidance, RTS/CTS exchange and turnaround delay overheads. For larger network sizes, the throughput is reduced and reaches a maximum at higher burst sizes. This is because the network is larger than the CAS window size, thus causing increased RTS collisions. A burst size of 20 packets is therefore chosen for further results.

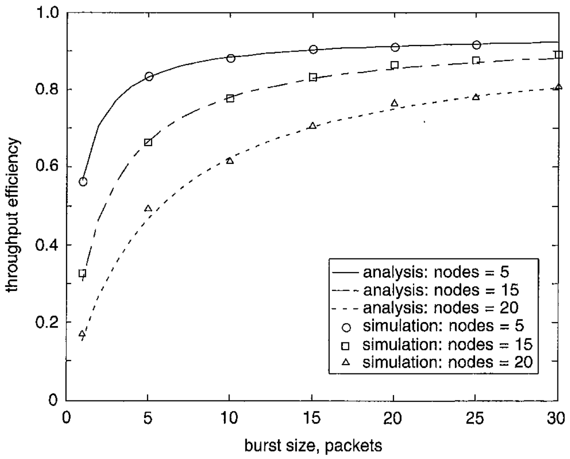

Fig. 7 *Throughput efficiency against burst size*

The plot in Fig. 8, shows normalised throughput against fixed CAS window size (i.e. with CAS adjustment value of 0) for network sizes of 5, 15 and 25 stations. CAS window values of 8, 16, 32, 64, 128 and 256 are used. It can be seen that, for the 5-station network, the throughput decreases with increasing CAS window size as the increased number of empty CAS slots creates an extra overhead. The small number of stations means that the lowest chosen CAS value (which 'wins' the contention) is relatively high. However, with a larger network size, there is an increased probability of collision with a small CAS window but the lowest chosen CAS value for higher CAS window sizes will be lower. In a similar way, Fig. 9 shows throughput against network size for different fixed CAS window sizes. It can be seen that the throughput falls off rapidly for the small CAS window size of 8 once the network size is bigger than the CAS window, but initially it produces the highest throughput. For higher CAS window values, the performance improves with network size as the probability of collision is reduced. Fig. 9 also reveals that the maximum throughput is independent of network size if an appropriate CAS window size is employed.

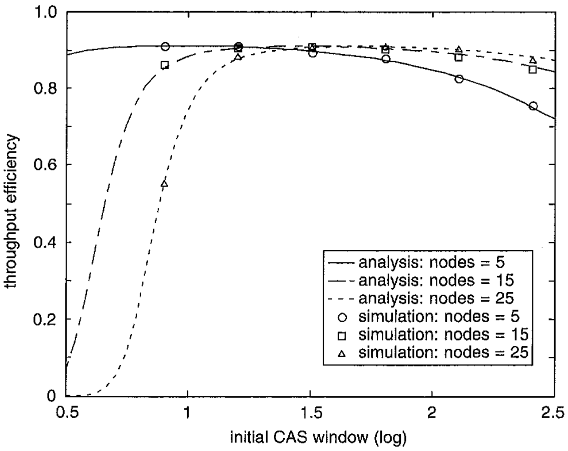

Fig. 8 *Throughput efficiency against initial fixed CAS window*

From Figs. 8 and 9 it can be seen that a dynamically adjustable CAS window size could be beneficial. Therefore Fig. 10 shows throughput against network size for different

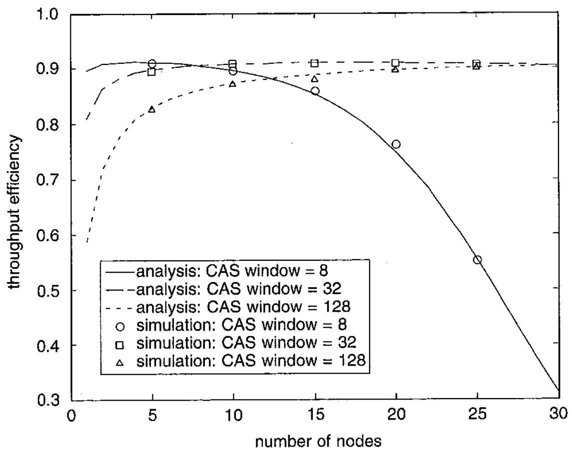

Fig. 9 *Throughput efficiency against network size for fixed CAS window*

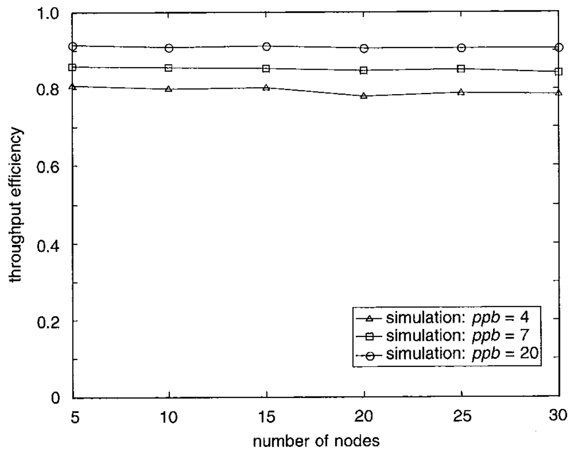

Fig. 10 *Throughput efficiency against network size using CAS window adjustment algorithm with $m = 4$*

burst sizes using the CAS window adjustment algorithm with the adjustment value set to 4. Therefore, for each failed reservation attempt, the CAS window for the next reservation is increased by 4 (with an upper limit of 256), and for each successful reservation it is decreased by 4 (with a lower limit of 8). The result seen in Fig. 10 is that the throughput becomes effectively independent of network size when the dynamic CAS window adjustment is utilised. By comparing Figs. 9 and 10 we can conclude that, for every network size, the CAS window adjustment algorithm 'tunes' the CAS window size to its optimum value for maximum throughput.

6 Conclusions

We have presented a simulation model of the advanced infrared (AIr) MAC protocol using the OPNET Modeler package. The model provides throughput performance evaluation of the MAC protocol in terms of network size and parameter settings. Results from the model have been validated using a modification of an analytical model of the IEEE 802.11 wireless LAN protocol. It was found that the CAS window size, the range from which a random number of collision avoidance slots was chosen, is a significant parameter in relation to the network size. In particular it could be seen that the CAS window size should be bigger than the number of stations in the network to effectively avoid collision but that too large a value would cause an excessive delays which would affect throughput. By using a dynamic CAS window size adjustment algorithm, it was found that the throughput could be made effectively independent of network size.

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