MACA-BI (MACA By Invitation)
A Wireless MAC Protocol for High Speed ad hoc Networking

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Abstract: **This paper introduces a new wireless MAC protocol, MACA-BI (MACA By Invitation). The protocol is a simplified version of the well known MACA (Multiple Access Collision Avoidance) based on the Request to Send/Clear to Send (RTS/CTS) handshake. The Clear to Send (CTS) control message is retained, while the Request to Send (RTS) part of the RTS/CTS handshake is suppressed. MACA-BI, preserving the data collision free property, is more robust than MACA to problems such as protocol failures (control packet collision and corruption) and finite turn-around time. Analytic results for a 1Mbps single-hop far-field wireless network, and simulation results for a 10Mbps multi-hop near-field ATM wireless indoor network, show that MACA-BI outperforms other multiple access protocols in high speed, steady traffic environments (e.g. ATM VBR and CBR) and where the propagation delay can be neglected (typically indoor).**

I. INTRODUCTION

The Multiple Access with Collision Avoidance protocol (MACA), proposed by Karn [6], solves the hidden terminal problem and outperforms CSMA in a wireless multihop network. MACA with carrier sensing (FAMA-NTR) can perform almost as well as CSMA in a single-hop wireless network [4]. Fullmer and Garcia-Luna-Aceves propose improvements (FAMA-PJ [3], CARMA [5]) that achieve even better performance at high load, again for the single-hop case. An accurate radio model is used which takes into account the TX-RX turn-around time (the transition time from transmit to receive state) [3].

Improvements to MACA were also presented by Bharghavan and others in [2] and were validated in a multihop "nanocell" network simulation experiment. In this case, the three-way handshake for collision avoidance (MACA) is expanded to a five-way handshake (MACAW). Unfortunately, each additional pass in the handshake contributes one TX-RX turn-around time plus preamble bits (for synchronization), control bits (e.g. source-destination information) and checksum bits. This overhead clearly reduces the channel utilization.

In order to better appraise the turn-around overhead we recall that, in situations of neglegible propagation delay (indoor), every transmission should be delayed by the TX to RX turn-around time (that is up to 25μs [1]) to give a chance to the previous transmitter to switch to receive mode. Although a station normally doesn't need to receive immediately after its own transmission, this is clearly the case in the RTS/CTS mechanism of MACA. The relative impact of turn-around time becomes even more critical at high channel speeds and low propagation delays. For these reasons, turn-around time will play a key role in future high speed, indoor wireless LANs and, more generally, multihop ad hoc networks.

To reduce, in part, the turn-around overhead, we propose a simpler version of MACA with only a two-way handshake (Multiple Access with Collision Avoidance By Invitation, MACA-BI). A node ready to transmit, instead of "acquiring" the floor (Floor Acquisition Multiple Access, FAMA) [4], waits for a "prepared" floor (Floor Prepared Multiple Access, FPMA). That is, it waits for an "invitation" by the intended receiver in the form of an RTR (Ready to Receive) control packet.

MACA-BI for single and multi-hop operation is presented in section 2. In section 3, we show that MACA-BI, like MACA, is collision free. To compensate in part for the function carried out by the suppressed RTS packet, MACA-BI needs a traffic prediction algorithm at the receiver. This is discussed in section 4. Performance of MACA-BI is evaluated in section 5. Section 6 concludes the paper.

II. MACA-BI ILLUSTRATED

Fig. 1 depicts the three basic cycles of the MACA protocol in a typical multi-hop wireless situation. Node A asks for the floor by sending a Request To Send packet (RTS) (Fig. 1a). Node B replies with a Clear To Send packet (CTS) notifying node A that it has acquired the floor (Fig. 1b). Then, node A sends the Data Packet (Fig. 1c). This sequence is "driven by the transmitter". That is, node A decides when to start each transmit cycle by issuing RTS. The same result, however, can be achieved with a "receive driven" schedule. Namely, we can imagine node B issuing CTS packets at a rate matching the incoming traffic rate, inviting node A to transmit. In this case, RTS packets are omitted. CTS packets are renamed RTR (Ready to Receive) packets since they are issued to declare the readiness to receive a certain number of packets. The "two pass" handshake of MACA-BI is shown in Fig. 2a and 2b. Node B does not have the exact knowledge of packet arrival times at node A. Rather, it estimates the average arrival rate. Assuming that each data packet carries the information about the backlog in the transmitter (A in this case), i.e. number of packets and their lenghts, the average rate and future backlog can be easily estimated at B. Thus, B predicts the backlog in A

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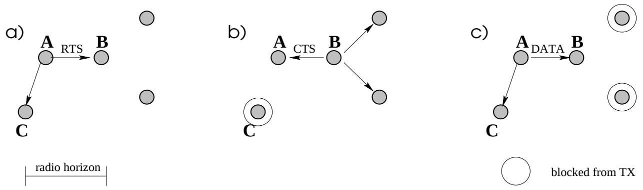

Fig. 1. The three-way handshake of MACA

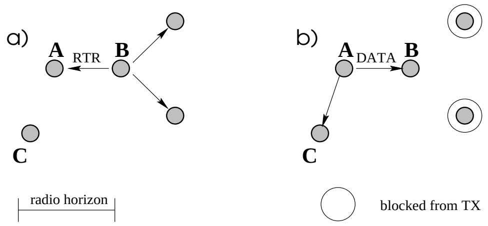

Fig. 2. The two-way handshake of MACA-BI

(from previous history) and "prepares the floor" for the predicted number of packets. Node A replies with the transmission of the requested number of packets and with the new backlog information.

III. COLLISIONS IN MACA-BI

A. Analysis of collision states

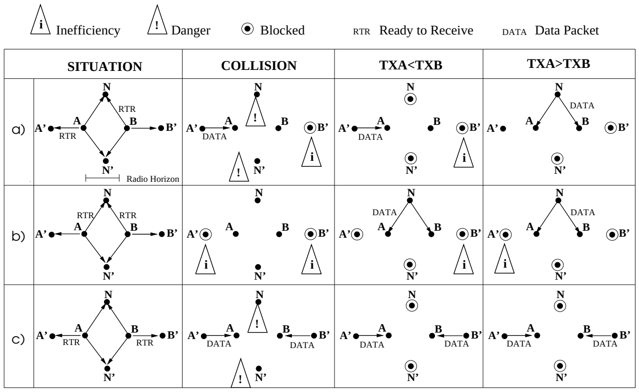

Fig. 3. MACA-BI working with hidden terminals (A and B)

We examine the various MACA-BI protocol states that occur in a simple 6 node hidden terminal configuration, and identify possible collisions. Referring to Fig. 3, node A and B issue RTRs at about the same time to different neighbours. Accounting for simmetry, there are only three possible combinations of neighbours which are represented by each of three rows in Fig. 3. The RTR packets may collide at some nodes. Two types of RTR collision are possible: direct collision between nodes within hearing distance (due to carrier sense failure) and, indirect collision between nodes hidden from each other and transmitting to a common neighbour. In our case, A and B are hidden. Therefore, only indirect collisions can occur (COLLISION column). Another case corresponds to an RTR transmission from A which preceded B's transmission ($TXA < TXB$). A third case corresponds to B preceding A ($TXA > TXB$). These cases account for column 3 and 4 respectively. The "inefficiency" symbol 'i' identifies situations in which some potential transmitter is unnecessarily blocked. The "danger" symbol '!' indicates a potential risk of collision due to the fact that a neighbour of the receiver has not been blocked and may thus interfere with it by issue an RTR. Let us first consider the case in Fig. 3a. By issuing an RTR, node B not only declares that it is ready to receive. It specifically invites one of its neighbours (N) to transmit and at the same time notifies all the other neighbours (N' and B') of the impending transmission, thus preventing collisions. In other words node B "prepares the floor" for one (and only one) of its neighbours (N). In turn, node N upon being invited to transmit (to B), first checks if its transmission will not disturb any of its neighbours (for instance A). Namely, it checks to see if it heard prior RTR packets indicating potential conflicts with its transmission. This is the case depicted in Fig. 3a in the third column $TXA < TXB$. In this case node N defers transmission, waiting for another "floor". Note that in this case node B' was unnecessarily blocked. That is, B' could transmit at the same time as A'. This leads to loss of efficiency.

If the timing is such that $TXA > TXB$ (fourth column), node N proceeds to transmit. No inefficiency here. Finally, if the RTRs at N and N' collide (as shown in column 2, COLLISION), the transmission N to B is, of course, cancelled. There is, however, the risk that either N or N' may transmit RTRs, thus interfering with the transmission from A to A' (since thay missed the RTR from A). Moreover, node B' is still unnecessarily blocked. The other situations depicted in Fig. 3b and 3c can be analyzed using the same arguments as in 3a.

In general, by simply listening to the RTR packets sent by the neighbours (more precisely, packet number and length information carried in the RTR), a node knows the duration of the impending data packet transmissions by its two-hop neighbours, i.e. its hidden terminals. Taking advantage of this infomation, a node is able to decide if its transmission (control or data) can disturb its neighbours reception.

B. Data collision free property

From the above examples we note that there are no collisions among data packets in MACA-BI (i.e. the protocol is "data" collision free). This property has been verified also for other MACA protocols. For a more general "data" collision free proof in MACA-BI consider the one reported in [7]. Thus, in MACA-BI collisions among data packets are impossible. The hidden terminal problem still plagues the control packets as shown, for instance, in case of Fig. 3a above. In general this results in protocol failures which no longer guarantee a collision free operation. In fact, this may load to an RTR collision with a data packet, as shown by the dangerous states reported in column COLLISION of Fig. 3. Furthermore, the protocol can fail also when control packets collide with each other because of carrier sense failure (non zero propagation delays). Note, however, that the three-way handshake of MACA is not immune from these coontrol packet collisions either.

C. Comparing MACA and MACA-BI protocol states

We carry out a more systematic investigation of collision, both direct and indirect, and compare MACA and MACA-BI with respect to control packet collisions (direct and indirect). We assume that the channel is symmetric (i.e. if A hears B, B hears A) as in all other MACA protocols. Further, we assume that control packets can be corrupted by noise, direct collision between two nodes (due to non zero propagation delays) and indirect collision of two control trasmissions (due to hidden terminals). Collisions (direct and indirect) among three or more nodes are neglected as rare events. We will show that MACA-BI is more robust than MACA to protocol failures. To this end, neglecting noise corruption for the moment, we will split the analysis in two parts: direct collisions and indirect collision. Fig. 4 reports all direct collision situation in a three node configuration with nodes A and B within transmission range of each other. Node C is a common neighbour.

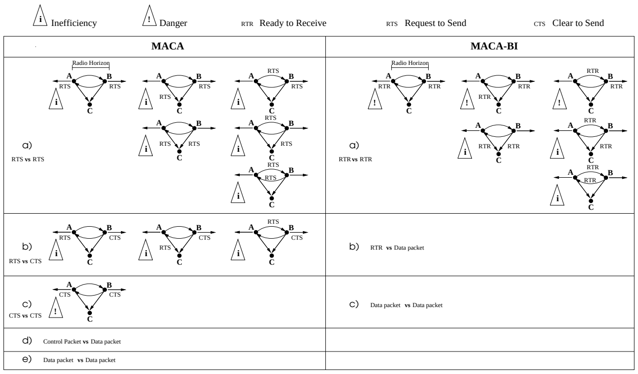

Fig. 4. MACA vs MACA-BI: direct collision

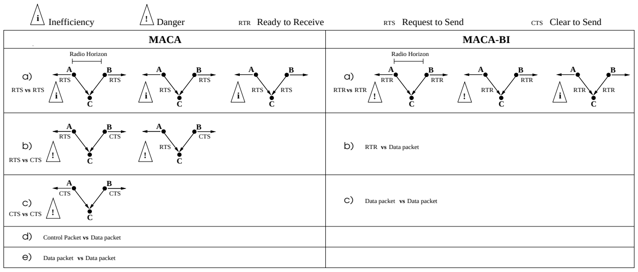

Fig. 5. MACA vs MACA-BI: indirect collisions

We consider all the combinations of transmissions to and from A and B. There are three situations of direct control packet collision in MACA, i.e. RTS vs RTS, CTS vs RTS, CTS vs CTS, versus only one possible direct collision in MACA-BI, i.e. RTR vs RTR. Fig. 4 reports only the starting states. The reader can easily determine how the protocol will evolve thereafter. Similarly, Fig. 5 reports indirect collisions caused by the hidden terminal problem. Here, we use the same three node topology as before, but now A and B are hidden from each other. For completeness, direct and indirect collisions between control and data packets and among data packets are reported. Note, however, that if the protocols work properly, they are data collision free and cases d) and e) for MACA and b) and c) for MACA-BI are empty. Situations not reported in Fig. 4 and Fig. 5 are either not critical or not allowed by the protocol or already reported in a different form (because of symmetry).

We note that in the MACA protocol RTS vs RTS and RTS vs CTS collisions (see Fig. 4) produce only inefficiency (not data failure) in the sense that the protocol must restart the handshake, wasting one or two cycles. CTS vs CTS produces a danger situation: node C does not hear either CTS and may transmit, thus interfering with data receptions at A and B. MACA-BI produces three danger situations of the same type. Nevertheless, it has fewer inefficiency situations. We also note that when MACA-BI restarts the handshake, it wastes only at most one cycle. In the case of indirect control packet collision, MACA-BI has one danger situation less than MACA, and only one situation of inefficiency. We cannot speculate a priori on the probability of each configuration. However, we can qualitatively say that introducing the third pass in the handshake (as MACA does) does not reduce the dangerous situations. At the same time, the added pass (RTS) appears to more than double the inefficiency conditions.

The protocol may fail also because of control packet corruption due to channel noise, fading etc.. In this respect, MACA is more vulnerable than MACA-BI since it requires twice as many control packets. The preliminary conclusion of this qualitative analysis (which will be verified via simulation) is that dropping a pass in the handshake does not increase the number of collision situations and does not affect the functionality of the MACA mechanism. We still have a collison free protocol in the same sense as MACA. But the protocol is simpler, and more efficient.

IV. PREDICTING TRAFFIC

As previously mentioned, the efficiency of the “invitation” scheme rests on the ability to predict when the neighbours have packets to send. For the receiver it is difficult predict exactly, that is deterministically, the moment in which new data packets will be ready at the transmitter. However deterministic prediction is not necessary, and is not required for each packet. The only information needed is the average rate that can be statistically extimated. To this end each data packet has an additional field which carries the backlog of the transmitter. This field provides the basic information to estimate the traffic rate. Of course, other parameters can improve the estimate such as derivatives of buffer occupancy or the declared traffic parameters in the case of ATM connections.

Rate estimation is critical in multimedia traffic support, where the task of the multiple access protocol is not simply minimizing the delivery delay but providing periodically and fairly the “floor” required to carry the requested throughput. The period must be selected to optimize the tradeoff between efficient use of node buffers and delay. Whether the transmitter (like in MACA) or receiver (like in MACA-BI) prepares the “floor” is irrelevant. Our choice is the receiver, because the protocol is simplier. In the case of connectionless bursty traffic, prediction and estimation are not very practical. However, the MACA-BI protocol can be extended by allowing nodes to declare their backlog via an RTS control packet if an RTR was not received within a given time out. Thus, RTS is used only to start the flow on link. Subsequent packets are "invited" using RTR.

V. MACA-BI PERFORMACE

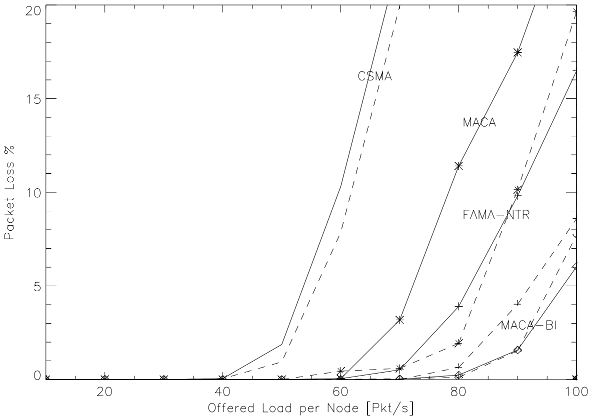

Fig. 6. Packet Loss in a 4 node Network (1Mbps)

Analytical results for a 1Mbps single-hop far-field wireless network are reported in [7]. We investigate performance of MACA-BI in a multi-hop network via simulation. Here, four nodes in line have been considered. A detailed framework of the simulation experiments is reported in [7]. Briefly, all the basic functionalities of the network, data link and MAC layers have been implemented. Routing is performed with a Bellman-Ford scheme. Every node has a shared buffer of size 50. The Data link layer uses a sliding window of size 8 with selective repeat. A separate window is used for each pair of nodes. Flow control is provided by the sliding window mechanism. Separate MAC protocol simulation modules, one for each multiple acces protocol under study, have been developed. FAMA-NTR and MACA implementations follow the specifications given in [4]. In our implementation, FAMA-NTR transmists only one data packet for each handshake. MACA-BI follows the specifications defined in [7]. In particular, nodes reschedule floors (RTR packets) with a Poisson process just to avoid repeated floors conflicts. With perfect prediction of buffer occupancy, the neighbour with the highest buffer occupancy is invited to transmit. Channels are error free, but packet transmissions can collide due to the hidden terminal problem and the non negligible propagation delay. Corrupted packets are retransmitted by the sliding window mechanism until correctly received. Thus, packet loss occurs only at the network level when packets are dropped because the buffer is full. External packets are generated at every node with a Poisson process to simulate datagram traffic.

A first series of simulation experiments uses very short control packets (4 bytes) with data packets of 1000 bits on links of 1Mbps and a null propagation time. The target here is to assess the importance of turn-around time. The average floor generation interval is 2.5ms. Fig. 6 reports the performance of multiple access protocols with a null turn-around time (dashed lines) and with the performace accounting for the turn-around time (continuos lines). Packet loss at network level Fig. 6, show that CSMA and MACA-BI are rather insensitive to turn-around time. FAMA protocols such as FAMA-NTR and MACA on the other hand degrade considerably, especially at high loads. This confirms our intuition about the negative impact of turn-around time on the RTS/CTS mechanism.

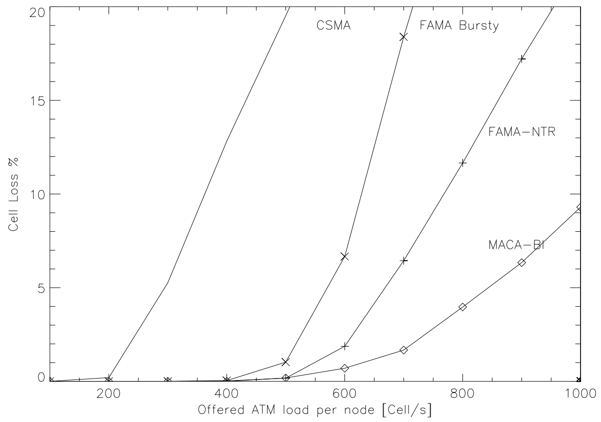

Fig. 7. Cell loss in a 10Mb 4 node ATM Net (10Mbps)

The goal of a second series of simulations is to compare MACA-BI performance with other multiple access protocols in a wireless ATM LAN situation. We choose almost the same indoor environment depicted in [2], that is a near-field signal strength with a range of transmission of 3 meters (with a finite propagation time). In this case, the same four node configuration is considered but with a 10Mbps channel speed. The average floor generation interval is 0.3ms. Data packet length has been reduced to 53 bytes (ATM cells) while control packets length remains 4 bytes. A short

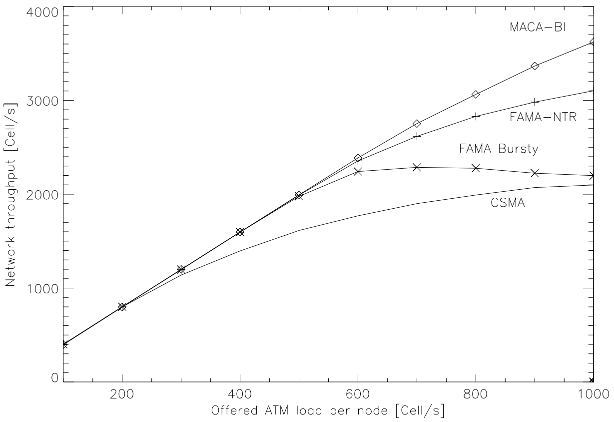

Fig. 8. Throughput in a 10Mb 4 node ATM Net (10Mbps)

data packet favours protocols that transmit more than one packet for each handshake, such as MACA-BI. Since FAMA-NTR transmits only one packet per handshake, for completeness we also consider FAMA Bursty, a version of FAMA-NTR which transmits a burst of two packets for each handshake. MACA is not considered here since it is outperformed by FAMA-NTR.

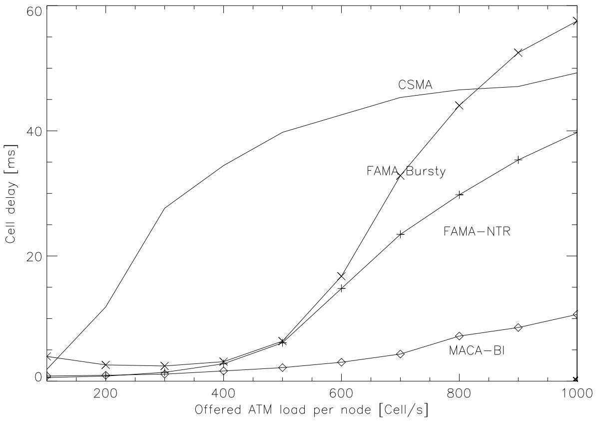

Fig. 9. Cell delay in a 10Mb 4 node ATM Net (10Mbps)

Figg. 7, 8, 9, report cell loss, throughput and delay respectively. Surprisingly, FAMA Bursty performs worse than FAMA-NTR with datagram traffic. Actually, the delay experienced by the two-packet assembly operation, turns out to be larger than the delay introduced by an individual handshake for every packet. FAMA Bursty performance worsens if more than two packets are sent per burst. Both FAMA Bursty and FAMA-NTR show unfairness and instability symptoms. As result, performance of FAMA Bursty and FAMA-NTR degrades sharply at high loads; performance of MACA-BI, instead, degrades gracefully. Assuming maximum acceptable cell loss of 10%, MACA-BI can support a load of 1000 Cell/s per node, FAMA-NTR almost 750 Cell/s per node. At very low loads MACA-BI performs a little bit worse than FAMA-NTR. We recall, however, that in this simulation the average floor generation intertime has not been optimized.

VI. CONCLUSION

A new multiple access protocol for wireless networks called MACA-BI has been presented. MACA-BI eliminates the need for the RTS packet, thus reducing the overhead for each packet transmission and simplifying the implementation, yet preserving the data collision free property of MACA. As a result, MACA-BI is more robust to failures such as hidden terminal collision, direct collision or noise corruption and it is not very sensitive to the TX-RX turn-around time.

Both analytic and simulation results confirm the efficiency of MACA-BI in high speed wireless networks with steady (predictable) traffic, and show its superiority to existing MACA type schemes.

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