MACA-BI (MACA By Invitation)
A Receiver Oriented Access Protocol for Wireless Multihop Networks

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***Abstract*— A novel wireless MAC protocol named MACA-BI (MACA By Invitation) is introduced. MACA-BI is a simplified version of the well known MACA (Multiple Access Collision Avoidance) protocol, which is based on the Request to Send/Clear to Send (RTS/CTS) handshake and which has inspired the IEEE 802.11 wireless LAN standard. In MACA-BI, the RTS part of the RTS/CTS handshake is suppressed, leaving only the Clear to Send control message which can be viewed as an "invitation" by the receiver to transmit. This reduction greatly improves efficiency when radio turn-around time is significant with respect to packet transmission time. Yet, it preserves the "data" collision free property of MACA. Simulation results for various multihop topologies show that, when traffic characteristics are stationary or predictable, MACA-BI outperforms several known multiple access protocols, especially when "hidden terminal" conditions are predominant.**

I. Introduction

An important component of a wireless network design is the MAC (Medium Access Control) layer. CSMA (Carrier Sense Multiple Access) was the MAC layer used in the first generation packet radio networks [8]. CSMA prevents collision by sensing the carrier before transmission. A terminal, however, can sense the carrier only within its transmitting range. Transmissions from terminals out of range cannot be detected. Thus, in spite of carrer sensing a transmission could still collide at the receiver with another transmission from an "out of range" terminal, often referred to as the "hidden terminal".
The Multiple Access with Collision Avoidance protocol (MACA), proposed by Karn [7], solves the hidden terminal problem and outperforms CSMA in a wireless multihop network. Fullmer and Garcia-Luna-Aceves [4] extend MACA by adding carrier sensing. The resulting FAMA-NTR protocol performs almost as well as CSMA in a single-hop wireless network. The same authors propose further improvements (FAMA-PJ [3], CARMA [5]) achieveing even better performance at high loads. In the FAMA-PJ evaluation, an accurate radio model is used to account for the TX-RX turn-around time (the transition time from transmit to receive state). Their study reveals the impact of the turn-around time on performance.
Several modifications of MACA have been proposed which suppress RTS, mostly to transmit multipacket messages or to support real time streams. For example, to increase the channel utilization for multipacket message transmissions, Fullmer and Garcia-Luna-Aceves propose in [6] to replace all RTS packets but the first with a MORE flag in the header of the data packet. In [4], the same authors propose to use FAMA-NTR in bulk mode to maximize the throughput. For a multimedia application, Lin and Gerla propose to use RTS/CTS only for the first packet of a real time stream [9]. Subsequent packets are transmitted with a reservation scheme that relies on the periodic nature of the multimedia traffic.
Yet, other extensions to MACA have added even more overhead to the RTS/CTS exchange, mostly for error recovery purposes. For example, in [10] an "invitation minipacket" is introduced to invite the transmitter to retransmit its last packet, in case it has been lost (Negative Acknowledgment). In another case, the three-way handshake is expanded to a five-way handshake (MACAW) with protected ACKs to guarantee transmission integrity in a multihop "nanocell" environment [2]. 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 useful throughput.
Let us focus for a moment on the TX-RX turn-around time in order to appraise its impact on performance. According to the standard proposed in [1], the TX-RX turn-around time should be less than $25\mu s$ (including radio transients, operating system delays and energy detection). Moreover, every transmission should be delayed by the TX to RX turn-around time (that is, up to $25\mu s$) to give a chance to the previous transmitter to switch to receive mode. This transmit-to-receive transition occurs precisely in the RTS/CTS mechanism of MACA. The higher the channel speed, the higher the turn-around time overhead in terms of bits. Thus, turn-around time will play a key role in future high speed wireless LANs.
To reduce, in part, the turn-around overhead, we propose MACA-BI (Multiple Access with Collision Avoidance By Invitation), a simplified version of MACA with only a "two-way" handshake. A node ready to transmit, instead of "acquiring" the floor (Floor Acquisition Multiple Access, FAMA) using the RTS (Ready to Transmit)

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signal, waits for an "invitation" by the intended receiver in the form of an RTR (Ready to Receive) control packet. This paper extents earlier simulation results presented in [11] for a simple four node "in line" network. Here, different multihop topologies are selected with varying degrees of "hidden terminal" transmissions. Three protocols are evaluated, namely CSMA, MACA and MACA-BI.

Section 2 introduces MACA-BI for single and multi-hop operation. Section 3 shows that MACA-BI, like MACA, is collision free. An analytical model of MACA-BI for single-hop networks is presented in section 4. Simulation results for multi-hop wireless networks are presented 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

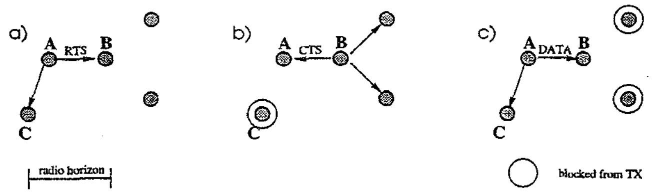

Fig. 1. The three-way handshake of MACA

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).

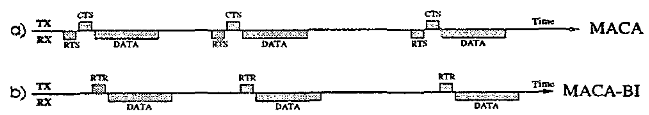

Fig. 2. Two and three-way handshake timing as seen by B

Fig. 2a shows a typical sequence of data packet transmissions as seen by node B, the receiver. 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 as shown in Fig. 2b. 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 suppressed and CTS packets are renamed as RTR (Ready to Receive), indicating the readiness to receive a certain number of packets. The suppression of the CTS packet is the main idea behind MACA-BI. The "two pass" handshake of MACA-BI is shown in Fig. 3.

Note that node B in Fig. 3 does not have the exact knowledge of packet queue at node A. Rather, it must estimate queue and average arrival rate. To make this possible, we assume that each data packet carries the

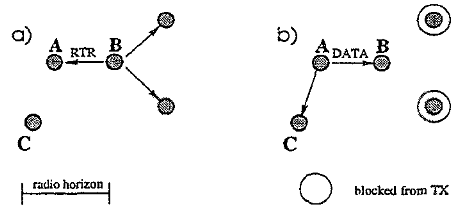

Fig. 3. The two-way handshake of MACA-BI

information about the backlog in the transmitter (A in this case). From the backlog notification and from previous history, B can decide how many packets to invite. Node A replies with the requested packets and with the new backlog information. So, the efficiency of the "invitation" scheme rests on the stationarity of the traffic pattern, which permits to predict which neighbours have (how many) packets to send. Traffic prediction is clearly easier in the case of multimedia traffic, where the periodic rate of real time traffic is declared at call setup (ATM) or can be learned by the node.

To enhance performance in non stationary traffic situations, a node may transmit an explicit RTS if the queue length or delay has exceeded a given threshold before an RTR is received from the intended destination. In the limit, MACA-BI reduces to MACA if traffic burstiness prevents timely invitations.

The reduced "two pass" handshake of MACA-BI exhibits the following features (see Appendix A for formal specifications):

- turn-around time overhead is reduced,
- MACA functionality is preserved in MACA-BI [11],
- MACA-BI is data collision free in the same sense as MACA (as shown in the next section),
- MACA-BI is less vulnerable to control packet corruption than MACA, since it requires half as many control packets,
- the "receiver driven" mechanism of MACA-BI automatically provides traffic regulation, flow control and congestion control (by simply witholding the "invitation").

III. COLLISIONS IN MACA-BI

In this section we show that MACA-BI is "data collision" free, that is, it prevents direct collision among data packets. To this end, consider the 4-node network in Fig. 4. The channel is assumed to be noise free and symmetric. A data collision occurs if node A transmits a data packet to B and simultaneously, node C transmits a data packet to B or to D. This causes a data collision in B. We will show that such collision cannot occur in MACA-BI. Note that other 4-node topologies (with varying degrees of connectivity among nodes) can be examined beside Fig. 4. However, it suffices to prove the property for the linear topology, which provides the maximum degree of "hidden terminal" situations.

These cases must be considered:

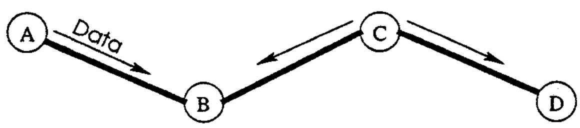

Fig. 4. Collision free property

1. C transmits a data packet to B. This is impossible since node B can invite only one node at a time (either A or C in our case),
2. C transmits a data packet to D. This can happen only if C did not hear the RTR from B to A. Here again, two cases must be considered:
   (a) B transmitted RTR to A while C was transmitting (either RTR or data). This is impossible, since transmission from C would have been heard from B, preventing its RTR transmission to A,
   (b) B transmitted RTR to A while C was receiving an RTR from D. Again, this is impossible because the RTR from D would have conflicted (at node C) with RTR from B, thus preventing the subsequent data transmission from C to D.

Thus, we conclude that collisions among data packets are not possible in MACA-BI.
Note that control packets may still collide with each other, either directly (because of carrier sense failure due to non zero propagation delays) or indirectly (because of hidden terminal transmission). Control packet collisions lead to protocol failures, which in turn cause collisions between data and control packets. A detailed analysis reveals that no MACA protocol is immune from these types of collisions [11]. Recovery from this kind of data loss is possible only by using explicit ACKs [7].

IV. MACA-BI ANALYSIS FOR THE SINGLE-HOP CASE

To evaluate MACA-BI, we first develop an analytic model for the single-hop case, using the same approach and assumptions as in [4]. The analysis (see Appendix B) considers a fully connected single-hop wireless network, which by definition excludes the hidden terminal problem. Briefly, we assume an infinite number of nodes generating Poisson traffic with mean interval δ between packets. Eache node hears all other nodes (error free channel). Turn-around time is neglected. We assume that a floor is suitably prepared when there is a data packet ready to be transmitted. Using data packet length of 296 bytes, control packet length of 20 bytes, a propagation delay of 54 μs (radius 10 miles) and a channel speed of 1Mbps, Fig. 5 reports the normalized throughput for the MACA-BI protocol as well as CSMA non-persistent, FAMA-NTR and MACA protocols taken from [4]. We notice that in a fully connected single hop network MACA-BI performs very well and is comparable with other MACA protocols.

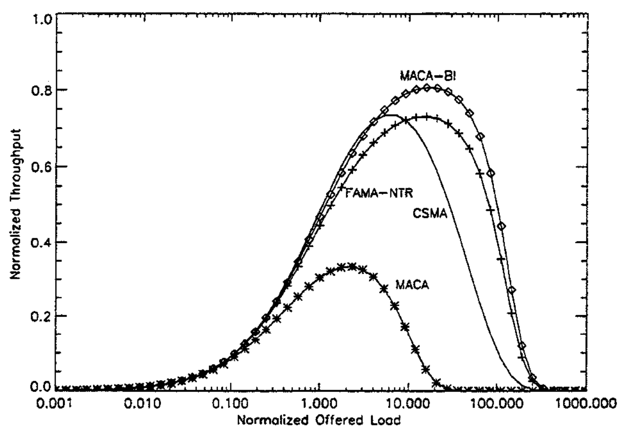

Fig. 5. High Speed channel and SLIP packets

V. MACA-BI PERFORMACE IN A MULTI-HOP NETWORK

Next, we investigate the performance of MACA-BI in a 9-node multi-hop network via simulation. Three topologies are selected. The Dual Ring with Spokes topology is almost like a single-hop fully connected network with minimal "hidden terminal" situations. The 3x3 Grid topology shows considerably more "hidden terminal" situations. Finally, in the Star topology all the neighbours of the central node are hidden from each other. All the links have a capacity of 1Mpbs and are 10 miles long. Channels are considered error free. Turn-around time (values suggested in [1]) and propagation delay are accounted for.
The simulator implements network, data link and MAC layers. In the network layer, all the basic functionalities are supported. In particular, routing is performed with a Bellman-Ford scheme. Each node has a shared buffer pool of 50 packets. Packets are dropped (at the network layer) when the buffers are full. The data link layer uses a sliding window of size 8 with retransmission time-out of 100ms and selective repeat. The link level protocol recovers from data loss caused by collision not prevented by the MAC layer. As earlier discussed, even MACA protocols are not fully protected from packet loss. A separate window is used for each pair of nodes. ACK piggybacking is adopted with a time-out of 20ms.

Separate MAC protocol simulation modules, one for each multiple acces protocol under study, have been developed. CSMA uses a non-persistent access. Our MACA implementation uses the carrier sensing and follows the specifications given in [4], where it is referred to as FAMA-NTR. MACA transmits only one data packet per handshake. MACA-BI follows the specifications defined in the appendix with some semplifications to the `Send_RTR` routine. In particular, nodes reschedule floors (RTR packets) randomly with a Poisson process just to avoid repeated floors conflicts. The average interarrival time is exponentially distributed with mean of $T_s = 2.5$ ms, the same for each node. The function `adjust` T_s has been suppressed. We assume perfect prediction of buffer occupancy. The neighbour with the highest de-

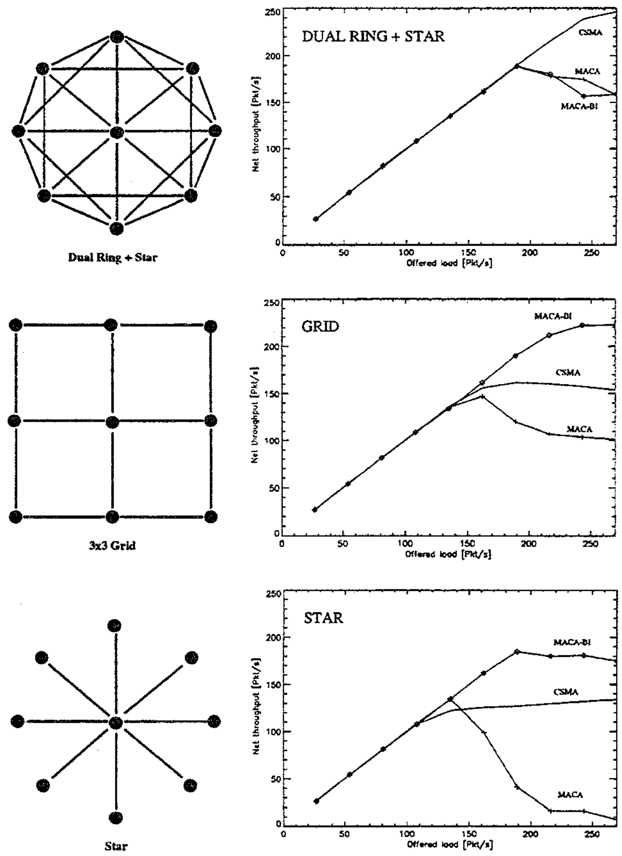

Fig. 6. Network throughput

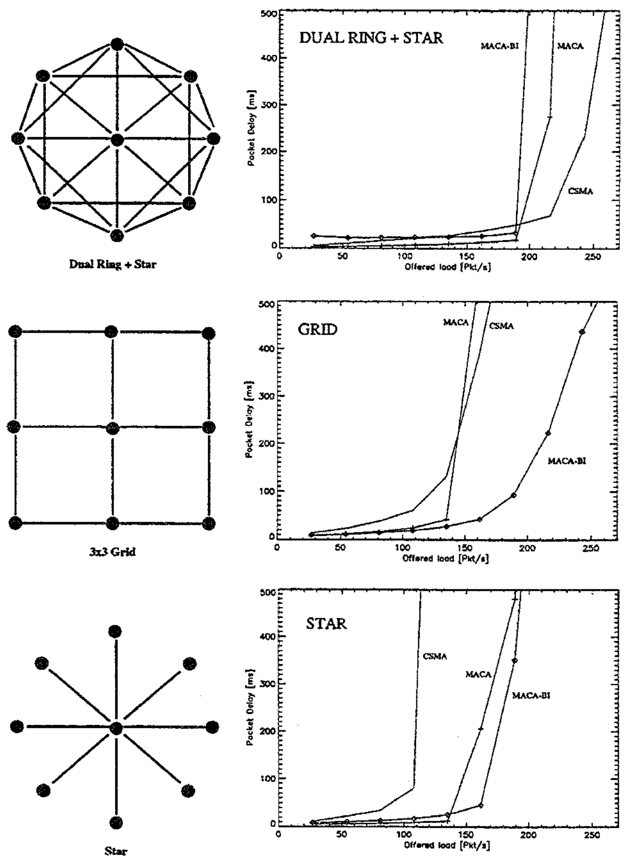

Fig. 7. Network delay

clared backlog is invited to transmit.

Simulation runs are typically 250 seconds long. At heavy load, this corresponds to about 50000 data packets processed in the network. Topology connectivity and routing tables are computed using distributed algorithms during an initial warmup time of 15s. External data packets of fixed size (256 bytes) are generated at every node with a Poisson process to simulate datagram traffic. The destination of each packet is selected at random. The size of the control packets used in MACA and MACA-BI is 20 bytes to accomodate the addresses for destination and source, the information on the impending data transmission and a CRC.

Perfect prediction of backlog is clearly optimistic. However, it can be reasonably justified considering that: (a) for real time traffic, arrival rates are predeclared, (b) for datagram traffic, at heavy load (which is the regime of interest when evaluating performance) the queues tend to be large, thus making backlog info piggybacking effective, (c) the number of store-and-forward neighbours in a multihop topology is generally limited (e.g. six neighbours), for efficiency, thus making the task of "inviting" all the backlogged neighbours manageable. Fig. 6 and Fig. 7 report network throughput and packet delay for the three topologies under study. We note that CSMA outperforms MACA and MACA-BI in the Dual Ring with Spokes topology. This somewhat surprising result is due to the fact that "hidden terminal" effects are minimal in this topology and therefore CSMA is perfectly adequate for it. Besides, the backpressure flow control induced by the link level window mechanism at the entry nodes stabilizes CSMA, eliminating the instability problems exhibited in Fig. 5 (where the model did not include window flow control). MACA and MACA-BI show comparable performance.

As the hidden terminal problem becomes more pronounced, in the Grid and Star topologies, MACA-BI clearly outperforms CSMA, as expected since the latter is adversely affected by the hidden terminal problem. The main surprise here is the poor performance of MACA. A careful examination of the simulation results shows that the "sender oriented" approach of MACA causes inbalance of throughputs inside the network and unfair sharing of the medium by different transmitters. The "receiver oriented" approach of MACA-BI, on the other hand, can more evenly arbitrate the transmission among competing senders, achieving a higher throughput. Other causes of performance degradation in MACA are the additional turn-around time for each packet and the single packet transmission (which is consistent with the FAMA-NTR model). MACA-BI, instead, can transmit multiple packets per cycle.

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. Furthermore, it is less sensitive to the TX-RX turn-around time.
An analyic model for MACA-BI in a single-hop configuration was developed, and was applied to a 1 Mbps wireless network example. A simulation model was also developed to evaluate MACA-BI in multihop environments, and was applied to a 9 node multihop wireless operating at 1 Mbps. Both analytic and simulation results confirm the efficiency of MACA-BI in wireless networks with steady (predictable) traffic. Simulation experiments show its superiority to MACA and CSMA in multihop networks especially when hidden terminal problems are critical. Even better results are expected at higher channel speeds where turn-around times will play a key role.

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VII. Appendix A: MACA-BI Specifications

```
Passive : status = PASSIVE
      call Wait(random(Ts)) //Ts = average floor generation intertime
Send'RTR: status = SEND'RTR
        guest neighbour's buffer occupancy
        select neighbour
        adjust Ts
        transmit (RTR)
        call Wait(2*Tp) //Tp = Max propagation time
Receive : receive (PCK)
        if status is REMOTE
         then switch (PCK)
          case: RTR to me
                transmit (DATA)
                call Passive
          case: RTR to others
                status = REMOTE
           call Wait(Td+2*Tp) //Td = Data packet transmission time
          case: DATA
                PCK to upper layers
                call Passive
          case: ERROR
                call Passive
        else switch (PCK)
          case: RTR to others
                call Wait(MAX(Timer,Td+2*Tp))
          case: DATA
                PCK to upper layers
                call Wait (Timer)
          case: DEFAULT
                call Wait (Timer)
Wait (T) : Timer=T
        if (Timer not expired and carrier not detected) wait
        if carrier detected call Receive
        switch (status)
         case: PASSIVE
               call Send'RTR
         case: SEND'RTR
               call Passive
         case: REMOTE
               call Passive
```

VIII. Appendix B: Single-hop analysis

- γ the control packet lenght,
- τ the maximum propagation time,
- δ the average intertime between two floors,
- $\overline{U}$ the average amount of time during which useful data is sent during a successful busy period,
- $\overline{B}$, $\overline{I}$ the expected duration of busy and idle period,
- P_s the probability of success of an RTR transmission,
- $S = \overline{U}/(\overline{B}+\overline{I})$ the normalized throughput.

A successful transmission consists of an RTR (γ) with one propagation delay (τ), a data packet (δ) followed by another propagation delay:

$$T_s = \gamma + 2\tau + \delta \tag{1}$$

An unsuccesful transmission consists of an RTR followed by one or more RTRs within a time Y ($0 \leq Y \leq \tau$) followed by a propagation delay [8]:

$$T_f = \gamma + \tau + Y = \gamma + 2\tau - \frac{1-e^{-\tau\lambda}}{\lambda} \tag{2}$$

An RTR is transmitted with success if no other RTRs are transmitted in a the time interval τ that is:

$$P_s = e^{-\tau\lambda}$$

The average busy period is expressed by:

$$\overline{B} = T_s P_s + T_f(1-P_s) = -1/\lambda - e^{-2\tau\lambda}/\lambda + \gamma + 2\tau + (\delta + 2/\lambda)e^{-\tau\lambda} \tag{3}$$

while the average utilization is:

$$\overline{U} = \delta P_s = \delta e^{-\tau\lambda} \tag{4}$$

Since we have assumed that the floor is ready when the packet arrives, the average idle period $\overline{I}$ for MACA-BI equals the average interarrival time of the floors $1/\lambda$. Finally the normalized throughput is given by:

$$S = \frac{\delta}{\delta + \frac{2-e^{-\tau\lambda}}{\lambda} + (\gamma + 2\tau)e^{\tau\lambda}} \tag{5}$$