Carrier Sense Multiple Access Schemes Utilizing Reservations by Interruptions vs. Ideal MAC Schemes

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***Abstract*—Carrier Sense Multiple Access with Reservations by Interruptions (CSMA / RI) is a medium access discipline with strong inheritance from the 1-persistant CSMA / CD (Collision Detection) used in wireline Ethernet local area networks. This basic form of CSMA / CD deterministically results in a collision and a subsequent back-off procedure every time when several packets arrive in the network during the packet transmission of another terminal. CSMA / RI permits the use of the packet transmission of another terminal as a reservation period.**

CSMA/ARI is a specialized enhancement to CSMA/RI applied to Ethernet, where a part of the CRC of small packets is utilized for reservation purposes. ISMA/P is an access protocol intended to be used in a time division multiple access cellular system with a centralized base station.

The performance of CSMA / RI compares favorably to 1-persistent CSMA / CD, and comes close to the delay performance of a token ring. CSMA/ARI demonstrates a further improvement over CSMA/RI as the reservations do not collide with packet transmissions.

Algorithmic comparison to Inhibit Sense Multiple Access with Polling (ISMA/P) is also made. Even though the operating environments and principles of the protocols are totally different, common targets in optimizing channel users yield similarities in the approaches.

***Index Terms*—Medium Access Control, CSMA/RI, CSMA/ARI, CSMA/CD, ISMA/P**

I. Overview

THE BASIC improvement over CSMA/CD proposed in the CSMA/RI scheme presented in [1,2,3] is to lower the collision probability in a situation where more than one idle stations receive packets during active transmission of another station. The gain in performance is sought by permitting the interruption of an ongoing packet transmission to make a pending reservation. CSMA/ARI, as discussed in [4], builds on this by implementing a special way of substituting a part of the cyclic redundancy check (CRC) code of a packet with reservation minislots.

ISMA/P is a slotted system, where stations transmit access probes during designated access periods to enter a polling list.

A. Execution Environment

Operating conditions for CSMA/RI and CSMA/ARI are almost the same as for CSMA/CD:

1. All stations must be able to sense the channel status at any time and detect the presence of another transmission, also when they are transmitting.
2. Maximum propagation delay τ must be finite and in practice it should be rather low.
3. No exposed or hidden nodes. All stations are expected to be able to hear each other's transmission and all sensed disruptions are expected to be destructive to own transmission.

Additionally, in analyzing the performance it is assumed that all stations are synchronized, thus the system can be slotted with fixed-length intervals. In order to use common mechanisms for detecting collisions and aborting collided transmissions in a slotted channel, the minimum duration of a slot has to be $T = 2\tau$.

Due to 1. and 3. CSMA/RI and CSMA/ARI are mainly targeting a wireline network. In a wireless system carrier sensing during own transmission is challenging, and additionally due to the nature of the radio environment both hidden and exposed nodes can occur at any time.

CSMA/RI sets the new requirement that in addition to sensing busy / idle status of the carrier, stations have to be able to recognize a reservation interrupt. Additionally the received data must be buffered slot by slot so that a fragmented packet (after being interrupted by a reservation) can be recovered.

As a slight different to CSMA/RI, CSMA/ARI is assuming a star topology network. Each station must measure its own propogation delay between the huband itself before CSMA/ARI can be utilized. In CSMA/ARI stations also have to recognize, in which reservation minislot other stations have sent their reservation pulses, setting tight requirements to propagation delays in the system. In simulations the propagation delay between any two stations has been set to τ.

The operating environment in ISMA/P is fundamentally different than in the CSMA-schemes. It has been designed for use over a single slotted channel of a time-division multiple-access (TDMA) cellular system. Carrier sensing is not used, as the target system is wireless. Instead, centralized controller (base station, BS) and an independent downlink (DL) channel are utilized in signalling uplink (UL) reservation status.

B. Definition of CSMA/CD

As CSMA/RI is an extension of CSMA/CD, a brief description of 1-persistent CSMA/CD is given. The notion used by the authors of [1,2,3] to refer to a station that has one or more packets waiting for transmission as a *ready station* is adopted here. CSMA/CD is defined in [1] using the following set of rules:

1. If the channel is sensed idle, a ready station transmits its packet immediately. It is required to monitor the channel status in case of a collision.
2. If the channel is sensed busy, a ready station keeps monitoring the channel status. As soon as the channel becomes idle, the ready station transmits its packet into the next slot with probability one.
3. Upon detection of a successful transmission, each station reads the data from the ongoing packet transmission into its local buffer. Only the station to which the packet is addressed to may use the data, others should discard it.
4. If a collision is detected, each ready station becomes backlogged and reschedules the retransmission individually to some later time based on a collision resolution algorithm. In [1,2,3] Truncated Binary Exponential Backoff (BEB) [5] is utilized.

Describing a transmitting CSMA/CD station in terms of states is relatively straightforward, as shown in Figure 1. When the first packet arrives, an Idle station moves into Ready state. If at any point a collision is detected, the station becomes backlogged. After finishing a backoff procedure, Ready-state is resumed. When all packets are transmitted, the station becomes idle again.

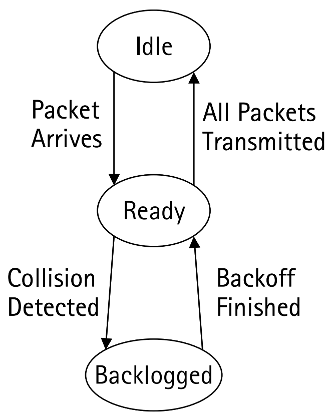

Figure 1: Transmitting CSMA/CD station states

A simplified flowchart representation of CSMA/CD transmission is shown in Figure 2 for comparison with Figure 4, which gives a similar representation for CSMA/RI.

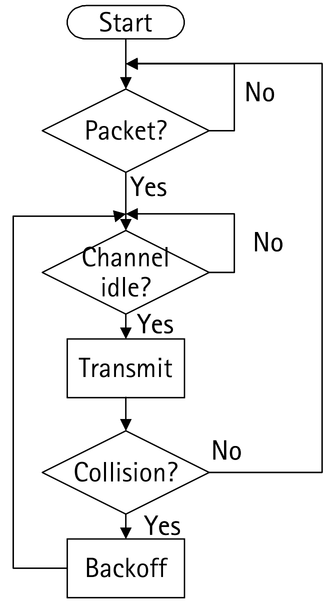

Figure 2: CSMA/CD operation flow

C. *Definition of CSMA/RI*

For a transmitting CSMA/RI station one more state is defined. The stations that have performed reservation by interruption are known as RI stations. The new state adds some new transitions, as illustrated in Figure 3. The RI state should normally guarantee that a station can transmit its data, returning to Idle state. A dashed arrow indicates how to exit the state in the failure case, if several reservations have been placed during the same packet transmission.

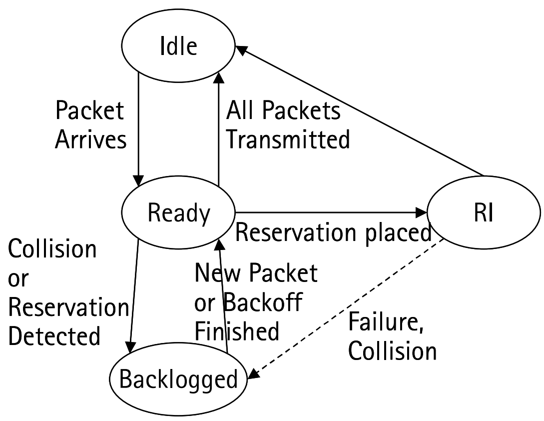

Figure 3: State representation of a transmitting CSMA/RI station

The original set of rules given in [1] contain some ambiguities, described in more detail in section IV DISCUSSION. The modified set of rules to describe CSMA/RI is as follows:

1. If the channel is sensed idle, a ready station transmits its packet immediately. It is required to monitor the channel status in case of a collision.
2. Ready station: If the channel is sensed busy in the case where a successful transmission is detected earlier (the channel is carrying a packet), apply 2a. Otherwise the channel is busy due to collision and

2b applies.

2a. A ready station may interrupt the packet transmission to make a reservation and to become an RI station only if no reservation has been performed during that ongoing paket transmission. Otherwise, it becomes a backlogged station. Upon the completion of the successful packet transmission, only an RI station is allowed to transmit into the next slot. A backlogged station remains silent and continues to monitor the channel.

2b. If a ready station becomes ready during a collision, follow the 1-persistent rule and transmit into the next slot as soon as the channel becomes idle.

3. Upon detection of a successful transmission, each station reads the data from the ongoing packet transmission into its local buffer. Only the station to which the packet is addressed may use the data, others should discard it. At the same time each Ready station chooses a random waiting time not longer than the packet transmission time. During the waiting time, the station is required to monitor the channel to detect if other stations make reservations. If such reservation is made by another station, the station aborts its reservation attempt and becomes a backlogged station. Otherwise, a reservation interrupt signal is sent when waiting time expires.

4. If a collision is detected, each ready station reschedules the retransmission individually to some later time based on a certain collision resolution algorithm (in this case, truncated BEB).

5. For a backlogged station, following the completion of a successful transmission, if the channel remains idle for at least a slot, it becomes a ready station and transmits its packet into the idle channel immediately as in 1.

The random waiting time sets the requirement that the length of the packets has to be either constant, or signalled in a packet header, which is separately decodable. The interruption can occur in any slot of the packet except for the first one, as the first slot is needed for normal collision resolution of the CSMA/CD protocol.

Simplified operation for a transmitting station is shown in flowchart format in Figure 4.

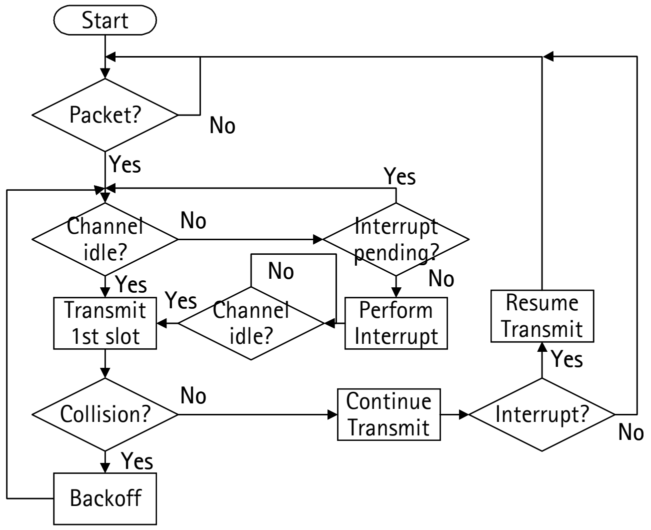

Figure 4: CSMA/RI simplified operation flow

When a packet arrives the station checks whether the channel is idle. If yes, the first slot is transmitted, while sensing the channel. A collision occurring in the first slot cannot be a reservation interrupt, thus it is a genuine collision and the station enters a backoff procedure, after which the transmission attempt resumes.

If the first slot passes without problems, the transmission continues. If an interrupt occurs, transmission is resumed on the previous even slot boundary in the timeslot following the interrupt. With or without an interrupt, the packet transmission will be completed.

If after packet arrival the channel is not idle, the station checks (from memory) whether an interrupt is already pending. If yes, the station becomes backlogged and waits for the next packet interval, when it may attempt an interrupt at a random time during the packet transmission. If there has been no interrupt, the station attempts to interrupt immediately. Note that no random waiting period is required, because the interrupt is randomized by the packet arrival time. After making a successful reservation by interruption the station waits until the end of the packet and begins transmission.

Figure 4 is only intended to illustrate the operation of the protocol. It doesn't take into account e.g. that performing the reservation by interruption may fail, as the timing of the interruption is chosen randomly and there may be other stations, which reserve first.

The reservation interruption is made by transmitting a pseudo-noise signal for a duration of τ. Upon detection of the pseudo-noise, the sender interrupts its packet transmission. All other Ready stations abort their reservation procedures and become backlogged stations. The sender continues packet transmission of the same packet from the point where it was interrupted by the pseudo-noise. Since we assume that the channel is slotted, the fragmented packets can be recovered if the receiver is equipped with memory to buffer the receiving packet slot by slot.

If several stations interrupt a successful transmission at the same time, an interruption collision occurs. As it cannot be reliably detected in the present scheme, several stations can transfer to RI state, leading to packet collision after the transmission of the present packet. However, this probability is small and decreases when the size of the packet increases, as the interruptions are randomized over a longer period.

Successful operation in a three-station network is demonstrated in Figure 5. Slot length is 2τ. First St2 is transmitting a packet to St1. St1 may be either in Ready state if it obtained an idle channel, or in RI state if it used a reservation. A new packet arrives to St3, which becomes Ready and as no reservations have been transmitted yet, transmits a reservation interruption (RI) in the next possible slot. St2 interrupts transmission when it senses the pseudo-noise burst and resumes transmission from the beginning of the next slot. When St2 finishes its packet, St3 begins transmission immediately. Note that if St3 would leave an empty slot, a backlogged station could begin transmission based on rule 5.

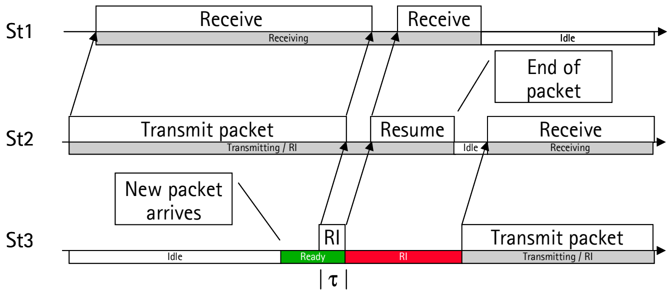

Figure 5: CSMA/RI operation in three-station network

D. Definition of CSMA / ARI

The authors of [4] propose to enhance the original CSMA/RI by adding “adaptiveness” to the reservations. The interruptible region is allocated from the cyclic redundancy check (CRC) field, which is assumed to occur in every frame. The error detection capability of a 32 bit CRC is seen to be excellent for a frame length up to several kilobytes. Therefore it is pointed out that for shorter frames a 16-bit CRC is adequate and therefore two bytes of a CRC-32 can be provided for contending in CSMA/ARI.

Each time a station has sucessfully received a frame for at least one slot time, it will check the length field o this frame and prepare to interrupt the ongoing frame. A CRC Protected Length Threshold (CPLT) is defined by utilizing the probability of undetected error for a 16-bit CRC in a frame of length n (or CPLT) bits. An example given in [4] restricts undetected error probability to $<=10^{-8}$ yielding a CPLT of 8800 bits for $BER=10^{-5}$.

The minimum size of an interruptible frame must also be defined, as for very small frames the pseudo-noise interruption can be mistaken for a collision. Document [4] defines X as the data length, which can be transmitted in a slot time in CSMA/CD (e.g. 512 bits for 10 Mb/s Ethernet). The rule used by the protocol is that the length of an interruptible frame must be larger than X-2 and less than CPLT.

Interruptible frames are denoted as I-frames. Assuming that the propagation delay between the hub and a station can be measured in bits, the 2-byte contention region in each I-frame has 16 independent contention mini-slots. Every station in Ready state can send a pseudo-noise impulse in one of the 16 mini-slots for reservation. The selection of mini-slot follows uniform distribution to achieve fairness. The station detecting that there was no reservation impulse before its transmission, becomes a so-called α-station.

Document [4] further defines two types of I-frames, depending on the frame size, as illustrated in Figure 6. Smaller type-I has one 16-bit interrupt region at the end of the frame, while the larger type-II frame has two 8-bit interrupt regions, permitting two rounds of contention. In this case the winner of the first round becomes an α-station. In the second region, only α-stations may contend and a station sensing no prior reservation pulse becomes a β-station, having permission to transmit after the current packet finishes.

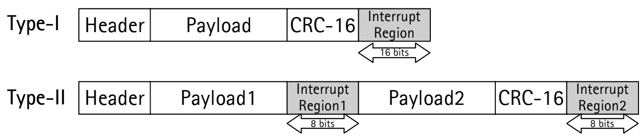

Figure 6: Two types of I-frame format for CSMA/ARI

E. Definition of ISMA/P

ISMA/P, as described in [6,7] stands for Inhibit Sense Multiple Access with Polling. It is a packet-based medium access control scheme for statistical multiplexing of data users over a single slotted channel of a time-division multiple-access (TDMA) cellular system. The presence of a centralized controller and the assumption of wireless connectivity makes the intended operating environment of ISMA/P fundamentally different from the CSMA-based schemes.

In ISMA/P, a central base station (BS) asserts control over the users by polling data in smaller blocks. Protocol operation is illustrated in Figure 7. Uplink (UL) slots are grouped into access periods comprising of *a* slots and polling periods of number of $p*k$ slots occurring cyclically. Here *p* is the number of terminals that are polled during one cycle ($p>=a$) and *k* is the length of one poll in slots. The value of *k* can be fixed to a suitable frame length of the system, such as a retransmission protocol block length. The BS signals the access period and the polling period in the downlink (DL). The DL slots are grouped into control and data slots. A control slot occurs every *k* slots, before every polling period. Assuming that the indications for access and polling periods can be signalled by means of so-called stealing bits (as in Global System for Mobile Communications a.k.a. GSM) or some other similar mechanism not impacting the DL data channel, the rest of the DL data slots are free for other data or broadcast control information transfer applications.

During the access period stations, which do not have an ongoing UL transmission, may attempt to access the cell. If successful, they are placed on the top of a polling list in the order in which they arrive. The BS then starts polling stations, one for each *k* slots, from the top of its polling list. Each polled station may transmit for k slots, indicating whether it has more data to transmit after the current period. If yes, the BS adds the station to the bottom of the polling list. The station will not attempt new access in the next access period(s), as it is already on the polling list. As it was stated that $p>=a$, every successful station from the previous access period will always be polled in the next polling period, eliminating the need for a separate acknowledgement.

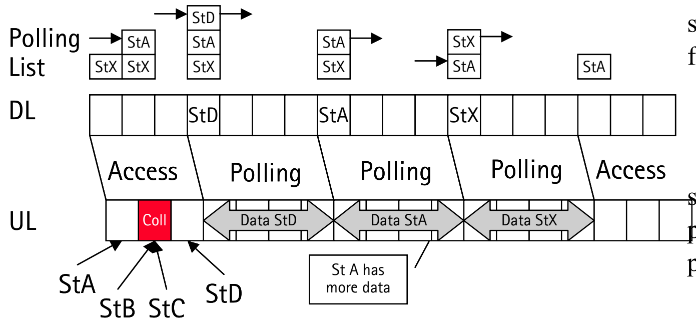

Figure 7: Channel organization in ISMA/P for a = 3; p = 3; k=4

II. Implementation considerations of CSMA/RI

In [1] the authors discuss some issues related to implementing CSMA/RI.

A. Fragmented packets

When a packet is interrupted by a reservation, it will be sent in two parts:

1. The part that was transmitted before the interruption.
2. The "pasted" part, being the remainder of the packet.

If perfect synchronization can be achieved, then the interruption will fit within slot boundaries and the pasted part can begin exactly at the next slot boundary.

In practice some data that were transmitted in the first part should be repeated. In the most straightforward case repetition should start from the beginning of the interrupted slot and the pasted part of the packet may also include a header specifying the exact position of the beginning of the pasted part in the packet to improve robustness of the protocol.

B. Packet size

If variable packet size is used, then the following is needed:

- The packet size should be specified in the header of the packet so that ready stations know how to choose their random waiting time to initiate the reservation procedure. Additionally the ending time of a packet must be known to the RI station to start its transmission immediately after the ongoing packet finishes. Otherwise a delay of a slot can occur, permitting all backlogged stations to transmit.
- There must be a minimum packet size to limit the interruption collision probability, and to guarantee the required performance level.

C. Power Up

A station which is powered up in the middle of an ongoing packet transmission is not allowed to interrupt that packet transmission. It may not be aware of an already existing reservation and it doesn't know the remainder length of the packet currently being transmitted.

This rule improves CSMA/RI efficiency when many stations power up at the same time, which is a scenario often following a network failure.

III. Performance Comparison

The performance of CSMA/RI has been evaluated by simulations in [1,2,3]. The evaluated parameters are delay performance, channel assignment delay and packet collision probability.

Two scenarios are used for the evaluation of delay performance:

1. Disaster Scenario: A power-up situation is assumed, where M stations transmit simultaneously during a slot at a particular instant causing a collision, which needs to be resolved.
2. Saturation Scenario: Probability of new arrival after a transmission is 1, i.e. after completion of each packet, a new packet is immediately generated.

In addition to CSMA/CD, the simulated performance is compared to a token ring protocol. For all the simulation results a noise-free channel is assumed. Synchronization is assumed to be perfect so that there is no extra header overhead for the pasted part of an interrupted packet. Furthermore, a star topology is assumed so that the propagation delay between any two stations is always exactly τ and the duration of a slot is 2τ.

A. CSMA/RI delay vs. throughput

Figure 8 demonstrates the improvement of CSMA/RI over CSMA/CD. The number of stations is infinite, the arrival process is a Poisson process. Packet size is denoted by b [slots]. Packet sizes of 5 and 50 slots have been tested. The normalized mean packet delay is defined as the ratio between the mean packet delay and the packet transmission time. CSMA/RI achieves higher throughput in both cases with maximum throughput with large packets going beyond 0.9.

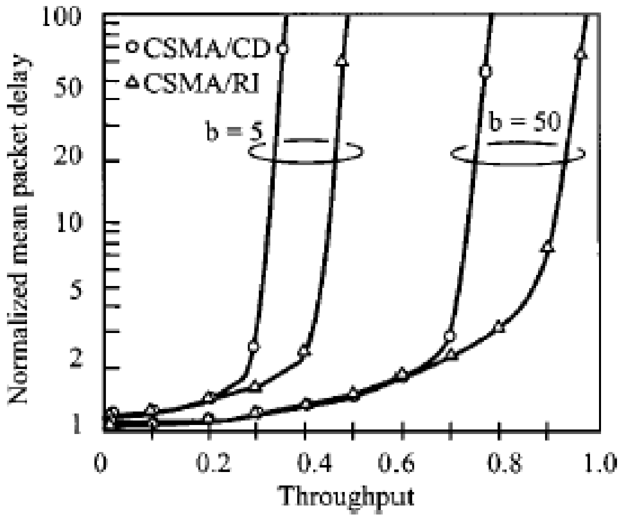

Figure 8: Normalized mean packet delay versus throughput for CSMA/CD and CSMA/RI

B. CSMA/RI Mean Channel Assignment Delay

Mean channel assignment delay (MCAD) describes the number of wasted slots due to packet collisions before a successful packet transmission is obtained. Figure 9 compares this delay to the packet size. M is the number of backlogged stations. This scenario considers a batch of backlogged stations waiting in the beginning of an ongoing packet transmission. In 1-persistent CSMA/CD, if there are two or more backlogged stations waiting in the beginning of an ongoing packet transmission, the packet collision probability immediately after the completion of that packet transmission is equal to one. The MCAD doesn't depend on packet size and is constant for every packet size. In CSMA/RI, as reservations can be made during packet transmission, collision probability is significantly lower. The larger the ongoing packet, the less likely it is for two stations to choose the same slot for signalling a reservation and eventually colliding. With packet size 2 the MCAD for CSMA/CD and CSMA/RI is the same, because slot 2 is the only possibility for a reservation interrupt, and multiple backlogged stations not in backoff will always collide their reservations, as with CSMA/CD. As packet size increases, the choice of slots for interruptions also increases and the number of RI stations is reduced. With larger packet size the situation saturates rather quickly, thus a moderate packet size is enough to collect most of the benefit from CSMA/RI.

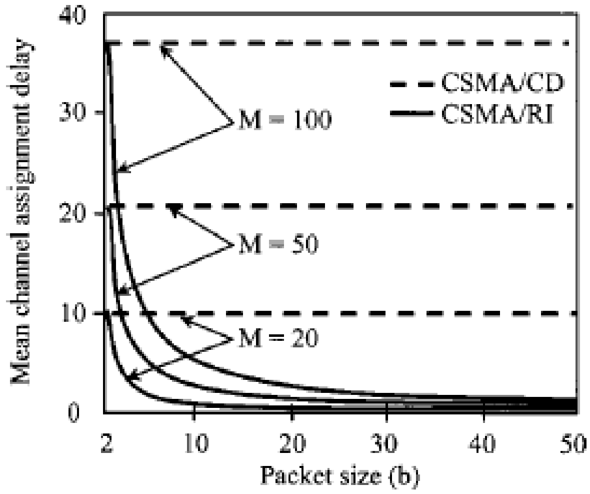

Figure 9: Mean channel assignment delay versus packet size

C. CSMA/RI Disaster Scenario

Using the disaster scenario, Figure 10 shows the normalized mean delay vs. burst size of M stations for a packet size (b) of 50 slots. The G/D/1 queue is used as a benchmark to represent the best delay performance possible to be achieved by a MAC protocol. Where Figure 9 only considers the delay until one packet is transmitted, this simulation observes the mean packet delay throughout the entire period required to transmit the complete batch. Figure 10 demonstrates how the normalized mean packet delay in CSMA/CD increases much faster than that of CSMA/RI and how CSMA/RI stays very close to the G/D/1 benchmark.

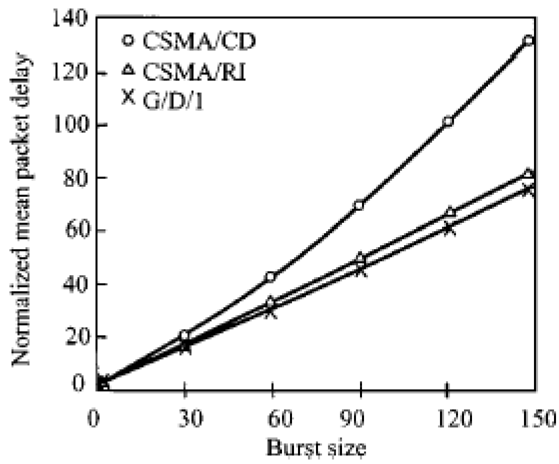

Figure 10: Normalized mean delay vs. burst size for b=50.

D. CSMA/RI Stability

The authors of [1] have also evaluated the stability of CSMA/RI while implemented with the truncated BEB algorithm. A Poisson arrival process and a constant packet size of 50 slots are assumed. System throughput is presented in Figure 11 as a function of the number of backlogged stations.

M is again the total number of stations. A station is either idle or backlogged. If a station is idle, it generates a new packet with probability σ within a time slot. If the packet is successfully transmitted, the station returns to the idle state, otherwise it stays backlogged until the packet is transmitted. Defining *n* as the number of backlogged stations, the Channel Load Line can be defined as $S(n) = (M-n)\sigma$.

S_1 in Figure 11 represents a saturated environment where stations always have a packet to transmit. New packets are generated immediately when old ones are transmitted, i.e. $\sigma = 1$. For S2, all stations equally share the bandwidth, i.e. $\sigma = 1/M$.

It is observed that both S1 and S2 intersect with CSMA/RI around 0.9, which is its maximum throughput. This together with the long distance between the intersections is interpreted to signify efficiency and stability. The result suggests that if the network consists of 100 stations, CSMA/RI can achieve high throughput even under very heavy load conditions and that high throughput can be maintained for a wide range of traffic conditions. CSMA/CD, on the other hand, is observed to have a rather narrow peak and especially for S1 the throughput is relatively low.

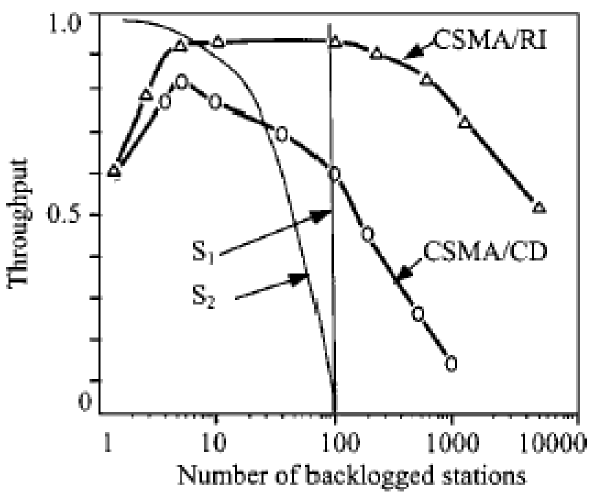

Figure 11: Throughput vs. number of backlogged stations for CSMA/CD and CSMA/RI

E. CSMA/RI comparison with token ring

Comparison of CSMA/RI and CSMA/CD to a contention-free reservation protocol is done in [1] by using the token-ring protocol. Packets are assumed to be generated from 100 identical stations according to a Poisson process. The propagation delay in all cases is 10 µs. The ring latency of the token ring is 1 bit/station. It is further assumed that the *limited-1* service discipline is used for the token-ring protocol to achieve a fair comparison to CSMA/CD and CDMA/RI so that stations in all protocols transmit no more than one packet when they seize the channel. Dual packet sizes (short and long) are used.

Figure 12 shows a performance comparison at 10 Mbit/s, corresponding to a low-rate Ethernet. Short packets, 70% of all packet arrivals, are 250 bytes long corresponding to 10 slots. The rest are long packets of 1.25 kBytes (50 slots).

CSMA/RI demonstrates a clear performance improvement over CSMA/CD. The token ring protocol, which behaves almost like a perfect scheduler, performs better than CSMA/RI.

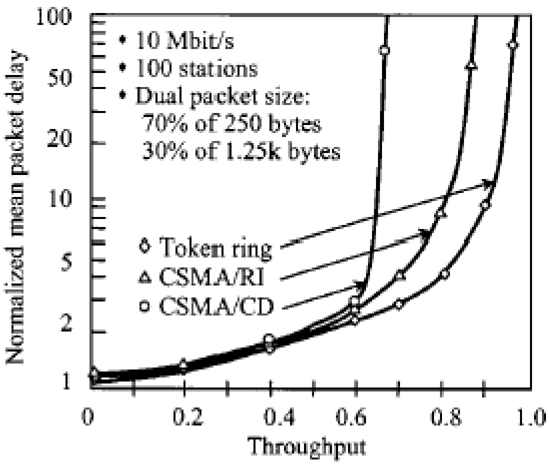

Figure 12: Normalized mean packet delay vs. throughput at bit rate 10 Mbit/s

F. CSMA/ARI Delay

In [4] the performance of CSMA/ARI is compared with CSMA/CD and CDMA/RI. Figure 13 graphs offered network load versus MAC-delay for constant frame size of 1100 bits. MAC-delay is specified as being the average delay after a packet is available at the top of the data buffer until it successfully accesses the channel.

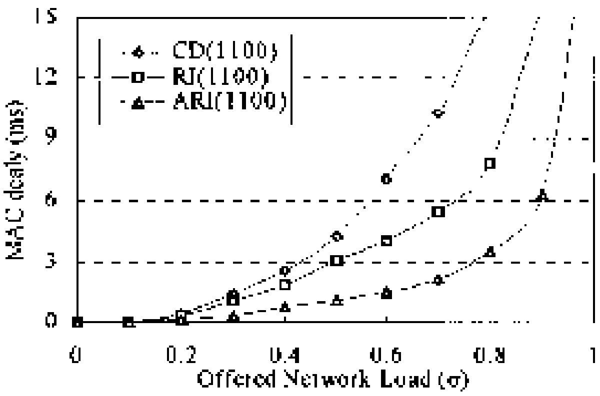

Figure 13: MAC-delay vs. offered load for frame size 1100

As the size of 1100 bits is optimized for CSMA/ARI, it gives the best demonstration of the improvement achieved by the protocol. With variable packet size, as shown in Figure 14, CSMA/ARI still yields best performance, but with somewhat less margin.

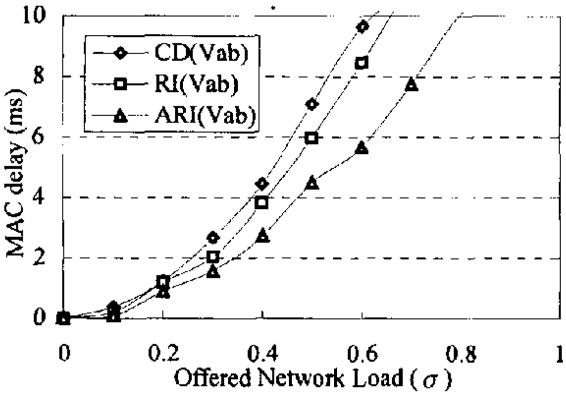

Figure 14: MAC-delay vs. offered load for variable frame size

G. CSMA/ARI Channel Utilization

The benefit of CSMA/ARI in channel utilization is visible only on very high offered network loads, as illustrated in Figure 15, but as improvements in top loading conditions are difficult to achieve, the difference can be considered significant.

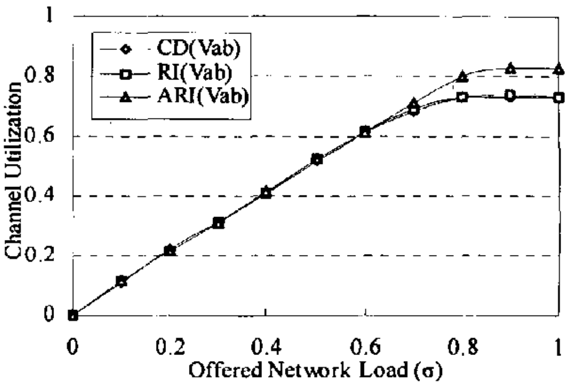

Figure 15: Channel utilization vs. offered load for variable frame size

IV. Discussion

Out of the three protocols presented CSMA/RI is the only one, in which channel capacity is used for reservations only when they are made. In CSMA/ARI the CRC detection capability is always compromised for a certain size of packet, and in ISMA/P the access periods occur cyclically, yielding a fixed overhead, occurring independently of whether there are new reservations or not.

One interesting characteristic is that in both CSMA/RI and CSMA/ARI packet size has a rather dramatic effect on the protocol performance. Small packets in CSMA/RI cause reservation interrupts to collide reducing performance closer to CSMA/CD. In CSMA/ARI too small or too large packets don't have reservation mini-slots, again reducing the protocol to the efficiency of the original Ethernet CSMA/CD. ISMA/P is a slotted system with a reservation mechanism separated from transmission, so packet sizes don't have similar impact. Short packets arriving infrequently will still increase uplink load and collisions during the access period.

The conclusion presented by the authors of [1, 2, 3] is that CSMA/RI performs better than CSMA/CD as demonstrated by simulations based on realistic traffic models and scenarios. It is also stated that for realistically long packets it performs almost as well as a token-ring protocol.

The choice of a 1-persistent scheme for comparison between CSMA/RI and CSMA/CD is undoubtedly good for CSMA/RI, because the spreading of reservations to the whole packet duration results in a very low collision probability and thus low ratio of time spent in backoff-procedures. For CSMA/CD and high load a less aggressive persistence approach might have been more optimal, but this has not been tested by the authors of [1,2,3].

The main benefit of CSMA/RI compared to CSMA/CD comes from reduced collisions in case of several new arriving packets during another station's transmission. The performance tradeoff is the interruption delay of one slot, which is significantly shorter than a backoff procedure based on truncated BEB.

In practical use another benefit of CSMA/RI is in its reaction to noise. In CSMA/CD channel noise causes a station to abort packet transmission and re-schedule, whereas in CSMA/RI as long as the noise occurs after the first slot, the transmitter will only interrupt for the duration of a slot and resume transmission in the next slot.

Reference [1] was not found clear in its definition of the RI state. First it is said that "only the stations that have performed the reservation (by interruption), henceforth called RI stations, are allowed to access the channel." Then the authors go on to state that "…each station, either an RI which failed to obtain a channel or a backlogged station, waits for a randomly chosen waiting time that is not longer than the packet transmission time. During the waiting time, the station is required to monitor the channel to detect if other stations make reservations. If such reservation is made by other stations, the station aborts its reservation attempt and becomes a backlogged station." This brings forth the following questions:

- Why are the authors referring to "RI stations" in plural? The mechanism should, in theory, make sure that there is only one RI at a time.
- What is "an RI which failed to obtain a channel"? The channel for the RI should be guaranteed, because new stations are also required to sense the channel for one packet transmission period.

The most likely interpretation is that there should only be one RI in the system at a given time, but that some of the rules describe error handling in case of colliding reservation interrupts. Otherwise, "an RI which failed to obtain a channel" shouldn't exist. Without collision such a station should be described as being either Ready or Backlogged, depending on why it failed to obtain a channel, eventually contending for the RI status during the next packet transmission.

The explanation of the treatment of fragmented packets for CSMA/RI is in this document somewhat modified from [1], as I do not agree with authors of [1] on how the timing of the interruption is described. In [1] it is stated that: "If perfect synchronization can be achieved, then the interruption will occur at the slot boundary, and the pasted part can begin exactly at that slot boundary. However, to improve CSMA/RI robustness in case of imperfect synchronization, some data that were transmitted in the first part should be repeated."

As the propagation delay from the interrupting station to the transmitting station was not required to be known to the interrupting station in CSMA/RI, it cannot utilize a timing advance. Therefore even with perfect synchronization the interruption will not be detected exactly on the slot boundary, but rather after a propagation delay from the interrupting station to the transmitting station and a measurement delay to detect the presence of the pseudo noise. The transmitting station cannot assume that the receiving station would have received anything during this slot, as the propagation delay from the interrupting station to the receiving station can be shorter as to the transmitting station. Therefore the transmission will have to resume from the beginning of the slot, i.e. some data will always have to be repeated, whether the synchronization is perfect or not.

The authors of [1] continue to state that: "In this case (some data repeated), the pasted part of the packet will also need to include a header which specifies the exact position…" Strictly speaking this is not true either. If the slot synchronization between stations is perfect and known, then even if some data is repeated, resuming transmission from the beginning of the interrupted slot should be adequate to correctly reassemble the packet in the receiver. Therefore the header is not absolutely necessary, even though adding it would certainly improve the robustness of the system.

CSMA/ARI also includes an ambiguous definition in [4]. First the Ethernet minimum frame length X is specified in bits. Then it is stated that an interruptible frame must be larger than "X-2". It is not clear from the description, how does the reduction of two bits in frame size affect the functionality of the protocol, but it would seem that the intention was actually to the define the minimum at X – 16 bits.

It seems that no attention has been paid to power consumption while specifying CSMA/RI. The point that a station becoming ready due to a new packet arrival can interrupt ongoing transmission immediately (without further randomization) means in practice that a powered-on station has to keep sensing the channel all the time, even when it is otherwise idle during the transmission of packets not addressed to it. If instead it would be required for a station receiving a new packet to wait until the end of the present packet transmission (or for the idle period of one slot, as already defined) and always randomize the reservation interrupt, power saving possibilities would be similar to CSMA/CD with only a slight increase of delay occurring only in loaded situations. CSMA/ARI is slightly better in this aspect. Packet headers need to be read, but that would be necessary anyway to distinguish packets addressed to the station itself. After reading the packet header, the placements of interruption periods are known and the next such period can be utilized in case of a new packet arrival. Otherwise the receiver can be switched off when packets are addressed to others.

CSMA/ARI is a very detailed access protocol making precise assumptions about the network topology, operation, transmitted data and original protocol. The target application is exclusively Ethernet and even though the scheme could probably be adapted for other systems as well, major modifications will be required. The central idea of utilizing the extra CRC-space of a short frame for contention is in principle good, as long as the assumption that short frames occur adequately frequently holds. It is, however, also a trick which probably finds little application in any newly specified system. If shorter packets can manage with shorter CRC, then wouldn't the two CRC-lengths be defined already in the protocol? It is also difficult to find technical reasoning for why short packets should have reservation minislots while long packets don't have them. The practical approach to optimization would be to define a proper CRC size for all expected packet sizes and define the existence of reservation mini-slots independently. After that, the reservation mini-slots would represent reservation overhead, and the access scheme reduces to a normal mini-slot based reservation protocol, of which ample examples have been presented. From this point-of-view CSMA/ARI seems to be little more than a trick utilizing an unused optimization point in the Ethernet protocol.

Another potential shortcoming in CSMA/ARI is that the mini-slots have been made extremely short. Simulations use the assumption that the propagation delay between any two stations is always τ. From the protocol definition it seems to be even a system requirement; how else could a station transmitting it's pseudo-random impulse in one slot determine, in which (one bit long) mini-slots all other contending stations transmitted their impulses? This precise control of propagation delays doesn't seem viable in practice.

V. CONCLUSIONS

The design characteristics of an ideal MAC-scheme as defined by [7] are:

1. Maximum throughput as close to unity as possible
2. Reach maximum attainable throughput close to unity load;
3. Stabilize at maximum throughput over a fairly large variation of load;
4. Fair to both short and long messages;
5. Easy to implement.

CSMA/RI, CSMA/ARI and ISMA/P all score favorably in points 1.-3. The maximum simulated throughputs indicated are excellent, with all three protocols achieving relative throughput values of around 0.9 in favorable conditions. These maximum throughputs are reached on high offered loads, as appropriate. Also the stabilization of all three protocols should be fairly straightforward, as all of them have relatively wide stable operating areas where the channel is fully utilized but throughput has not yet began to deteriorate.

On the 4. criteria CSMA/RI and CSMA/ARI are not entirely fair due to their unslotted nature. The channel is occupied for a longer time by a station having longer packets to send. ISMA/P, on the other hand, is scheduling channel usage in fixed-size timeslots and implements a First-In-First-

Out queue for a polling list, which results in fairness for packets of almost all sizes. Single packets small enough to be transmitted during one poll are still favored, as new accesses take precedence on the polling list.

On the ease of implementation none of the protocols get a very high score, as this is where compromises are made. It is difficult to compare the implementation challenge of ISMA/P to CSMA-based protocols, because the two are intended for entirely different network topologies and types of systems. ISMA/P and CSMA/RI appear implementable with reasonable complexity, whereas CSMA/ARI would appear to have significant challenges in a real system due to difficulties in propagation delay management.

I would propose also a 6. characteristic, which is to "Minimize the packet transmission delay". In a situation with low loading CSMA/RI and CSMA/ARI are practically ideal, as the protocols have a built-in requirement for continuous idle channel sensing. If the channel is idle, it is known already when the packet arrives, and transmission can commence immediately. In both low and high loading situations, when a packet transmission has started, it will be finished, which is good from packet delay point of view. In ISMA/P, the station will always have to wait for the next access period to be able to start transmission. In a low-loading scenario the access period repeatedly reserves uplink capacity and in a high-loading scenario packet completion can take indefinite time because new entries always take precedence, unless the polling list size is limited.

As transmission errors have not been considered, none of these schemes currently offer a possibility to prioritize retransmissions. In ISMA/P a priority mechanism could be built into the access probes, and in CSMA/RI and CSMA/ARI priority could influence the timing of the reservation interrupt, pushing it earlier.

For practical applications to portable devices also power-saving is important. ISMA/P gives some possibilities for this, whereas CSMA/RI and CSMA/ARI are extremely power-hungry. The assumption seems to be that if there's a wire for transmission, there's also a wire for power.

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