An Adaptive Medium Access Control (MAC) Protocol for Reliable Broadcast in Wireless Networks

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Abstract— **This paper presents ABROAD, an adaptive medium access control (MAC) protocol for reliable broadcast packet transmission in wireless networks. ABROAD incorporates a collision-avoidance handshake within each slot of a synchronous transmission schedule, allowing nodes to reclaim and/or reuse idle slots while maintaining bounded access delay. Thus, ABROAD provides worst-case performance guarantees while remaining adaptive to local changes in traffic load and node connectivity. We analyze the optimal worst-case performance of ABROAD, and show that there is a strict increase in the number of broadcast packets per second over a pure time division multiple access (TDMA) protocol. Extensive simulation confirms our analysis, and also demonstrates that ABROAD outperforms broadcast protocols based on reliable unicast packet delivery schemes, such as the IEEE 802.11 MAC standard.**

I. Introduction

Ad hoc networks are independent of fixed communications infrastructure. Each node is mobile, and equipped with a wireless communications device with which it exchanges packets with other nodes across one or more shared wireless channels. When direct communication between two nodes is not possible, packets are relayed through intermediate nodes in a multihop fashion to their destination.

There are three types of packet transmissions depending on the number of neighbors in the destination set. A packet destined to a single neighbor, a subset of neighbors, or all neighbors is correspondingly a unicast, multicast, or broadcast transmission. However, the successful delivery of a packet to the destination is not assured with each transmission, regardless of its type. For example, there is the well known hidden terminal problem in which two non-neighboring nodes nodes simultaneously transmit to a common neighbor[1]. Furthermore, the half duplex nature of wireless communication prevents a transmitting node from receiving at the same time. Thus, packet delivery to a transmitting node will always be unsuccessful. Therefore, we define a *reliable packet transmission* as the successful delivery of the same packet from a source node to each neighbor in the destination set.

Medium access control (MAC) protocols coordinate access to a shared communications channel. Consequently, support for *reliable broadcast transmission* is dependent on the MAC protocol used. MAC protocols can be classified according to the access strategy employed. Probabilistic contention protocols utilize direct, asynchronous competition between neighboring nodes to determine which node will transmit next. Early examples, including Aloha and CSMA, were unreliable, best-effort transmission protocols principally designed to support unicast packet transmission [1]. More recent protocols, including the IEEE 802.11 MAC standard, provide reliable unicast services by incorporating channel reservation schemes and acknowledgements [10].

Clearly, a reliable unicast protocol can support reliable broadcast transmissions by simply sending a copy of a packet to each neighbor in the destination set. A drawback of this approach is that MAC protocols typically do not maintain link state information, such as the current neighbors of a node. This requires another protocol to gather and maintain this information. Furthermore, the ability to maintain the link state information is subject to the operation of the MAC protocol itself. Thus using a reliable unicast protocol as a basis for a reliable broadcast protocol hinges on the correct operation of two separate, yet dependent, protocols. Moreover, this approach is not scalable since the time to complete a broadcast increases with the number of neighbors. This may be an issue for time sensitive applications that have stringent packet delivery deadlines.

Deterministic allocation protocols, such as TDMA and TSMA, assign each node a transmission schedule indicating in which of the synchronized slots a node has the right to access the wireless medium [1], [2]. These protocols were primarily designed to support reliable unicast transmissions by guaranteeing that each node is assigned at least one collision-free slot to each of its neighbors. Consequently, allocation protocols can also support reliable broadcast transmission. However, most allocation protocols rely on rigid slot assignments, rendering them insensitive to variations in network load and node connectivity.

The many variants of reuse TDMA protocols, including FPRP, periodically compute TDMA schedules according to the current network topology [9]. This allows nodes to dynamically adapt the length of their transmission schedules, thus improving overall network performance. In order to accomplish this, these protocols rely on a separate contention protocol to recompute the transmission schedules as topology changes occur. If the rate at which the topology changes exceeds the rate at which the schedules can be updated, then the result is an unstable protocol which can lead to network failure.

Recent efforts have focused on the combination of the allocation- and contention-based design philosophies to achieve a *hybrid* protocol that shares the properties of both strategies. Protocols, such as HRMA and CATA, use the collision-avoidance schemes of contention protocols to reserve transmission slots [7], [8]. Consequently, both protocols can

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[1] Nodes are neighbors if they are within each others transmission range.

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efficiently manage their slots according to the local topology and traffic load. However, HRMA and CATA are also susceptible to instability as the network load is increased, compromising reliable operation.

In [3], we introduced a new family of hybrid unicast MAC protocols that avoid protocol instability. These new protocols have deterministic access guarantees while providing flexible and efficient bandwidth management by reclaiming unused slots through contention. Essentially, each node is assigned one or more slots for its dedicated use by a *base allocation protocol*, i.e., it has priority to use these slots. However, if a slot remains unused for a specified amount of time, other nodes may then contend to use it rather than wait for their next assigned slot. This improves the performance of the protocol by increasing spatial reuse and reclaiming any idle slots, resulting in improved bandwidth efficiency.

In this paper, we extend our results from [3] and present ABROAD, a hybrid MAC protocol that supports reliable broadcast transmissions in ad hoc networks. The ABROAD protocol incorporates a collision-avoidance contention protocol within each slot of a TDMA transmission schedule. ABROAD permits nodes to reclaim and/or reuse any idle slots while maintaining bounded access delay. We show that the resulting *a*daptive *broad*cast protocol has the following desirable properties:

- ABROAD obtains bounded access delay from its base TDMA allocation protocol, and remains stable for all traffic loads and node topologies.
- ABROAD outperforms a pure TDMA protocol since it can dynamically manage the slots.
- ABROAD does not require link state information.
- ABROAD is scalable since the time to reliably broadcast a packet is not dependent on the number of neighbors.
- ABROAD can also support reliable multicast and unicast transmission services.

The rest of this paper is organized as follows. The basic principles and operation of the ABROAD protocol is detailed in Section II. In Section III, we analyze the throughput performance and reliability of the ABROAD protocol. Through extensive simulation, we validate our analysis and compare the relative performance of ABROAD to other MAC protocols in varying ad hoc network conditions in Section IV, confirming that using a unicast protocol as a basis for a broadcast is impractical. In Section V, we summarize our findings and conclude the paper.

II. The Adaptive Broadcast (ABROAD) Protocol

In this section, we outline the basic principles and operation of the ABROAD protocol. As Fig. 1 illustrates, ABROAD integrates a CSMA/CA based contention protocol [5] within each slot of a TDMA allocation protocol. Each node is assigned a transmission schedule (frame) consisting of N slots, where N is the number of nodes in the network. There is a one-to-one mapping between nodes and slots, and each node has priority to access the channel in its assigned slot. We assume that a node is capable of determining the current channel state, i.e., whether there is currently zero, one, or multiple packet transmissions corresponding to an idle channel, a successful packet transmission, or a packet collision.

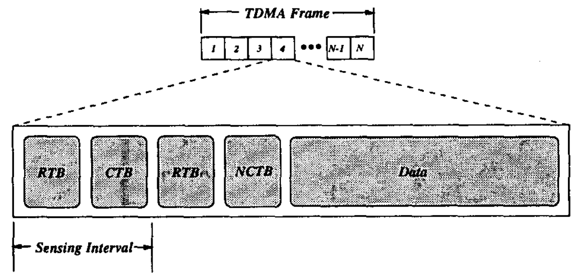

Fig. 1. The ABROAD slot and frame structure.

In order to support reliable broadcast transmissions, we must alter to point-to-point nature of the collision-avoidance handshake, and ensure that there is only one transmitting node within a two-hop neighborhood. Thus, if node s has a broadcast packet to send in its assigned slot, it immediately transmits a request-to-broadcast (RTB) control packet. Each neighbor of s then responds with a short clear-to-broadcast (CTB) control packet. Thus, all nodes within two hops of node s are informed of its intent to broadcast in its assigned slot, and refrain from accessing the channel for the remainder of the slot. Once the channel becomes idle, node s broadcasts its packet.

If the channel remains idle throughout the *sensing interval* (see Fig. 1), any other node t with a broadcast packet may attempt to claim the slot by sending its own RTB. In this case, a neighbor of t responds with a *negative*-CTB (NCTB) packet if and only if it detects a packet collision. The presence of collision indicates that two or more nodes are contending for the slot. If node t detects no NCTB packets, it then uses the remainder of the slot to broadcast its packet. Otherwise, its contention for the slot was unsuccessful, and t defers transmission until its assigned slot, or some later idle slot in the frame as determined by the backoff scheme (see [3]), whichever comes first.

Since it preserves the properties of its base allocation protocol, ABROAD guarantees each node at least one reliable broadcast packet transmission per frame. Thus, an upper bound on broadcast access delay is automatically given by the underlying TDMA protocol. Moreover, ABROAD can use its contention mechanism to reclaim any idle assigned slots for reliable broadcast except in very rarely occurring scenarios which we will discuss in Section III-B. This increases in the number of broadcasts and reduces packet delay, resulting in improved network performance. Furthermore, each node can dynamically adapt its behavior according to local changes in the network load and node connectivity.

III. Analyses of ABROAD

A. Approximate Throughput Analysis

To simplify the analysis, we consider a network of N identical nodes with a homogeneous load distribution. Let r represent the transmission radius of the nodes, and let A denote a two-dimensional geometric area in which all the nodes move. We assume that A is sufficiently large in both directions.

In order to reliably broadcast a packet in a slot, only one node can access the channel within a two-hop neighborhood. Thus, we first approximate the average number of nodes within a two-hop neighborhood. Geometrically, the probability that two nodes are in each other's transmission radius is $\pi r^2/A$. For any two such connected nodes, the cumulative distribution function of the distance x separating them is given by:

$$F(x) = \frac{\pi x^2/A}{\pi r^2/A} = \frac{x^2}{r^2}, \quad (1)$$

where $0 \leq x \leq r$. The probability distribution function is $f(x) = F(x)dx = 2x/r^2$, thus the expected value of x is:

$$\mathbf{E}[f(x)] = \frac{2}{r^2}\int_0^r x^2 dx = \frac{2}{3}r. \quad (2)$$

Now, the radius of the average two-hop neighborhood is approximately r more than the expected value of x, or $5/3r$. Again geometrically, the probability that there is a node in the two-hop neighborhood is $25\pi r^2/9A$. The number of nodes in a two-hop neighborhood is described by a binomial distribution, thus the average number of nodes β in this area can be approximated by its expected value:

$$\beta = \frac{25\pi r^2 N}{9A}. \quad (3)$$

In ABROAD, there are two distinct cases that need to be analyzed, according to whether or not the slot is assigned to a node. Let α be the probability that a node has a packet to transmit. The probability that a node broadcasts in its assigned TDMA slot is α/N, since there is a $1/N$ probability that a slot is assigned to a particular node. A node may also attempt broadcast in an unassigned slot. The probability that a node contends for an unassigned slot can be expressed as $(1-\alpha/N)^\beta p$, where p is the probability that a node contends for a slot. The probability that such a node is successful in its contention is:

$$\beta\left(1-\left(1-\frac{\alpha}{N}\right)^\beta p\right)^{\beta-1}\left(1-\frac{\alpha}{N}\right)^\beta p. \quad (4)$$

Combining the two probabilities, we get an approximation of a node's average throughput, T_{node}:

$$T_{node} = \frac{\alpha}{N} + \beta\left(1-\left(1-\frac{\alpha}{N}\right)^\beta p\right)^{\beta-1}\left(1-\frac{\alpha}{N}\right)^\beta p. \quad (5)$$

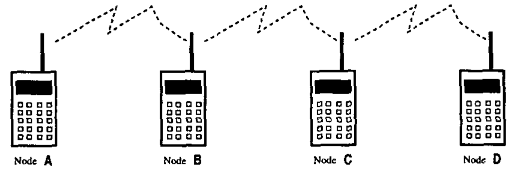

Fig. 2. Simple example of ABROAD reliability failure.

Assuming that the backoff scheme is optimal for all network loads, we can find the optimal value p_{opt} for the variable p through differentiation. Thus we find that:

$$p_{opt} = \frac{1}{\beta\left(1-\frac{\alpha}{N}\right)^\beta}. \quad (6)$$

Substituting (6) into (5) we find:

$$T_{node} = \frac{\alpha}{N} + \left(1-\frac{1}{\beta}\right)^{\beta-1}. \quad (7)$$

Notice that the term involving β in this equation converges to $1/e$ as the size of the two-hop neighborhood approaches infinity. This means that we can match the best throughput of a pure contention based protocol at high loads when reusing the unassigned slots [1].

By computing the average number of distinct two-hop neighborhoods, N/β, we can finally estimate the total network throughput, T_{total}, as:

$$T_{total} = \frac{\alpha}{\beta} + \frac{N}{\beta}\left(1-\frac{1}{\beta}\right)^{\beta-1}. \quad (8)$$

Substituting β from (3), we can estimate the optimal worst-case throughput as function of r, A, N, and α:

$$T_{total} \approx \frac{9A}{25\pi r^2}\left(\frac{\alpha}{N} + \frac{1}{e}\right). \quad (9)$$

Thus, the total network throughput we achieve depends on the two hop neighborhoods since this is the area "locked up" by a broadcast transmission.

B. Reliability Analysis

There are some special cases in using ABROAD in which all of the neighbors will not receive a packet that has been broadcast. Note that because of the properties of the underlying TDMA protocol, these cases only arise when nodes are competing for an unassigned slot, and are due to the fact that the radios are assumed to be half duplex in nature. These cases are not unique to the ABROAD protocol, as the same situations arise in both CATA and FPRP [8], [9]. Due to limitations of space, we only present an example illustrating the limitations of ABROAD, and show that the probability of such a scenario arising is almost negligible. The interested reader is directed to [4] for a more detailed analysis.

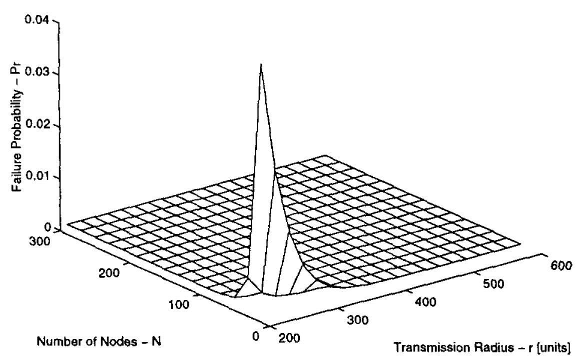

Fig. 3. Probability that ABROAD is unreliable.

Consider the network topology in Fig. 2. Here, we find nodes A, B, C, and D arranged in a line. Assume that nodes B and C contend for an unassigned slot, and transmit their RTB packets simultaneously. Since B and C are transmitting they cannot detect the collision of their RTB packets. Nodes A and D successfully receive a RTB packet and do not respond with a NCTB packet. Therefore, both B and C incorrectly conclude that have successfully reclaimed the idle slot, and broadcast their packets. Clearly, neither B nor C will receive each others broadcast packet and ABROAD fails to deliver these packets reliably.

Fig. 3 shows the probability that ABROAD fails to deliver a broadcast packet in an area of one million square units, with varying numbers of nodes and transmission radii [4]. Notice that the probability is less than 4%, even when the number of nodes and transmission radius is small. Thus, the chances of failure are negligible.

IV. Performance of ABROAD

Using a discrete event simulator, we modeled an ad hoc network consisting of 100 mobile nodes operating within a two-dimensional plane that measured $10,000$ meters per side. Each simulated node was equipped with a wireless communications device capable of transmitting at a data rate of 1Mbps to a distance of 1000 meters.

Node movement was simulated using the random walk-based mobility model developed in [6]. Briefly, a node's movement is described by a sequence of random length *mobility epochs*. During an epoch, a node moves in a constant direction with a constant speed. At the end of an epoch, a node randomly chooses an new direction and a new speed. The epoch lengths are exponentially distributed with mean $1/\lambda$. The speed of a node during an epoch is an independent, identically distributed, and uniform random variable with mean μ and variance τ^2. Node direction is uniformly distributed over the range $(0, 2\pi)$. The mobility parameters chosen for this study were $\lambda = 1/60\text{s}^{-1}$, $\mu = 5\text{m/s}$, and $\tau^2 \approx 8.33\text{m/s}$, which model pedestrian movement characteristics.

In our simulations, we measured the average number of successful broadcasts per second (throughput). In the case of ABROAD, we also measured the average access delay for a single broadcast packet. The results are shown in Fig. 4 through Fig. 8, and depict each metric as a function of both traffic load and average node degree.

When the node density of the network is low, the contention mechanism of ABROAD is able to reclaim and reuse the large number of idle TDMA slots. When comparing the throughput of ABROAD in Fig. 4 to that of TDMA in Fig. 6, the impact of the contention mechanism is dramatic. At the lowest node degree, the throughput of ABROAD is six times that of TDMA. More interesting is the fact that, even at the highest loads and node degrees, the throughput of ABROAD remains above TDMA by a factor of approximately $9A/(25\pi r^2 e)$ broadcast packets per second, confirming our analytical results presented in Section III. As expected, the access delay of ABROAD in Fig. 5 remains asymptotically bounded.

In order to demonstrate the drawback of using a reliable unicast protocol as a basis for a reliable broadcast protocol, we also simulated the ADAPT protocol from [3] and the IEEE 802.11 MAC standard. To broadcast a packet, a source node simply unicasts a copy of the packet to each of its neighbors. For both protocols this requires that all the neighbors of a receiver must be silent while a node is transmitting a packet. As the average node degree is increased, the number of unicast transmissions per broadcast increases while the number of concurrent transmissions is decreased. This potent combination reduces the overall performance of the protocol, rapidly reducing throughput to the point of instability. This phenomenon can be seen in the throughput performance of both ADAPT and the IEEE 802.11 MAC standard shown in Fig. 7 and Fig. 8, respectively.

V. Conclusions

In this paper we presented an adaptive medium access control (MAC) protocol, ABROAD, for the reliable broadcast of packets in wireless networks. We demonstrated that ABROAD preserves the properties of its underlying "base" TDMA protocol, and thus provides deterministic access delay bounds. Examining the performance of ABROAD, we showed that, even under the worst-case load and node density conditions, our protocol increases the number of reliable broadcast packets per second over a pure TDMA protocol. Through simulation we validated our performance analysis, and demonstrated that ABROAD outperforms TDMA, ADAPT, and IEEE 802.11 under the simulated network conditions. Moreover, we confirmed that using a reliable unicast protocol, such as ADAPT or IEEE 802.11, as a basis for a reliable broadcast protocol is infeasible for all but sparse networks.

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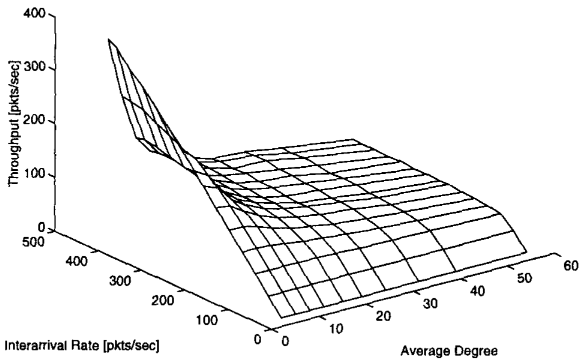

Fig. 4. ABROAD throughput versus interarrival rate and average degree.

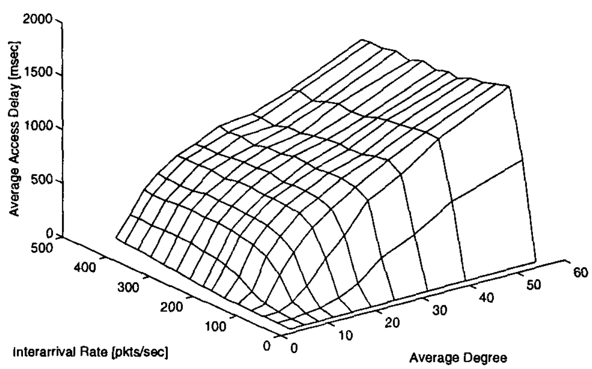

Fig. 5. ABROAD access delay versus interarrival rate and average degree.

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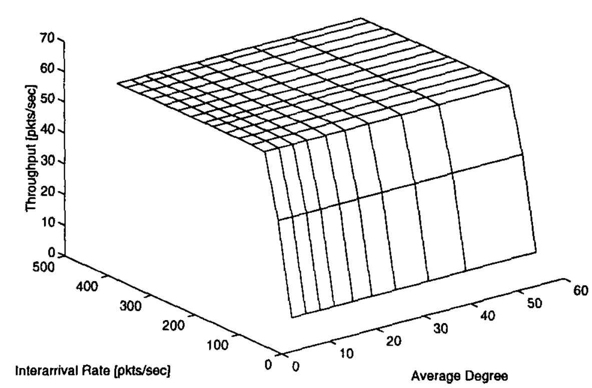

Fig. 6. TDMA throughput versus interarrival rate and average degree.

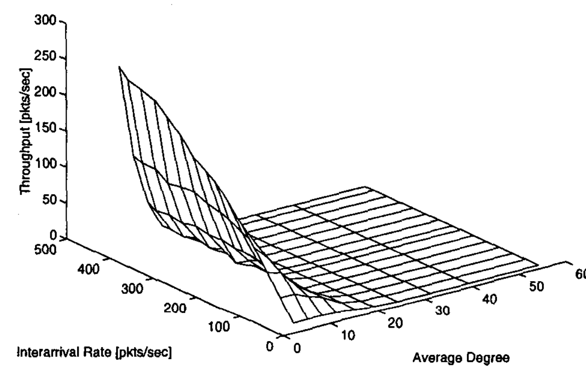

Fig. 7. ADAPT throughput versus interarrival rate and average degree.

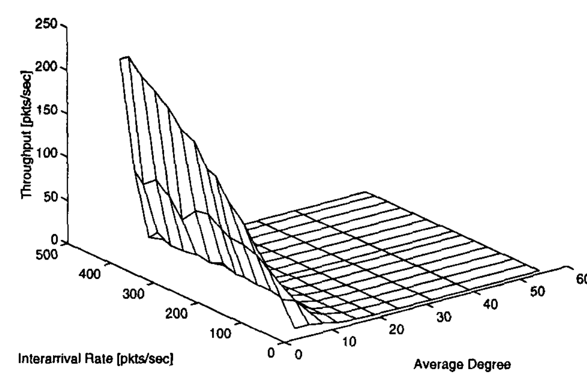

Fig. 8. IEEE 802.11 throughput versus interarrival rate and average degree.