MOBILITY-INDEPENDENT FLOODING FOR REAL-TIME, MULTIMEDIA APPLICATIONS IN AD HOC NETWORKS*

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Abstract - This paper describes the use of Time-Spread Multiple-Access (TSMA) protocols for realizing the dissemination ("flooding") of data and/or control packets in networks characterized by the lack of a fixed infrastructure (*ad hoc* networks). We show that, due to the unique characteristics of TSMA, namely, that it is independent of the changes in the network topology due to node mobility and it is deterministic, it is effective for implementing and/or supporting those ad hoc networks primitives that are crucial for delay-sensitive applications, such as multimedia. Through the use of simulation, we finally show that the average broadcast delay for TSMA-based flooding remains stable for higher network loads when compared to the average delay of simple TDMA-, Aloha- and Slotted Aloha- based flooding.

I. INTRODUCTION

An ad hoc mobile network is a self-organizing system of wireless mobile nodes requiring no fixed communications infrastructure. In the event any two nodes cannot directly communicate, each node is designed to act as a relay, forwarding packets on the behalf of other nodes. These characteristics make ad hoc networks ideal for situations when the network must be deployed rapidly, such as for supporting emergency services, aiding in disaster recovery, or providing battlefield communications. Moreover, a host of real-time multimedia applications and protocols are emerging for ad hoc networks that anticipates their wide spread commercial use. Examples of these applications include tele-cooperation (e.g., video conferencing, tele-education, collaborative planning), hypermedia (e.g., web-browsing, web-based transactions), and interactive television (ITV) (e.g., video-on-demand) (1).

One of the most basic network operations needed in an ad hoc mobile environment is *flooding*, namely, the dissemination of a packet originating at one node to every other node in the network. For instance, flooding is fundamental in on-demand route discovery, and path-building activities for routing and multicast protocols (for a general discussion and references, see, e.g., (2)). Moreover, flooding is widely used as a failure/recovery method in fault tolerant systems and in routing mechanisms to name a few. In fact, in many of these examples, the existence of a flooding protocol is assumed, and its ability to operate effectively in an ad hoc mobile network is taken for granted (3), (4). Without a stable, dependable flooding protocol, most of these applications, or protocols that run in support of applications, would no longer function effectively (if at all).

In order to flood a packet, a source node must be able to successfully deliver its packet to each of its one-hop neighbors, i.e., nodes that are within its transmission range. Each of these neighbors, in turn, transmits this packet to each of its one-hop neighbors, and so on until each node has successfully received the packet. Of course, if a node has already transmitted the packet successfully it will ignore subsequent copies of the packet.

In order for a node to transmit a packet to each of its one-hop neighbors it must rely on a channel access protocol. Note that, though the transmission medium is broadcast in nature, it is not enough for a node to transmit once in order to successfully reach its one-hop neighborhood. This is due, in part, to the *hidden terminal* problem, the conflict situation that may arise when two or more nodes sharing a common neighbor attempt to transmit a packet at the same time. Thus, the successful transmission of a packet to the one-hop neighbors may require the link between each neighbor to be activated separately (i.e., several point-to-point communications are needed).

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Many of the existing channel access methods, while taking the hidden terminal problem into account, are not suitable for highly mobile environments, or environments with high traffic load. Generally, this is because some protocols require up-to-date knowledge of the network topology, such as in variants of "TDMA re-use" (see, e.g., (5)), and the nodes spend all their time exchanging and processing topology information when highly mobile. Other protocols cannot provide deterministic performance guarantees, namely, probabilistic protocols like Aloha or CSMA and their variants (see, e.g., (6)), as the nodes spend all their time resolving conflicts (overlapping transmissions) under high traffic conditions. These limitations preclude the use of these protocols to support ad hoc mobile networks with real-time constraints, such as that seen in multimedia applications.

In this paper we propose the use of a channel access protocol based on *Time-Spread Multiple-Access* (TSMA) (7) for implementing the flooding of (control and/or data) packets in ad hoc networks. The TSMA family of protocols overcome the problems of the existing channel access protocols in that they are deterministic, thus providing a delivery guarantee even at high traffic loads, yet are *mobility transparent* since each node is assigned a permanent transmission schedule (i.e., the schedule does not change with changes in topology).

Due to the unique characteristics of TSMA protocols we obtain, for our flooding protocol, the following properties:

1. It is distributed, in the sense that the protocol is executed at every node without a priori knowledge, not only of the global network topology, but also of the identity of its neighbors.
2. It does not assume any underlying network infrastructure, thus being deployable, for instance, in emergency situations or when the nodes' mobility rate exceeds the rate at which topology information can be exchanged.
3. It is deterministic, and thus suitable for supporting delay sensitive applications, i.e., those applications that cannot tolerate the unbounded delays possible in probabilistic solutions, which include real-time, multimedia applications.
4. It is mobility transparent, in that the correct forwarding of a packet at a node is always guaranteed independently of the identity and mobility rate of its current neighbors.
5. It is simple and easy to implement, i.e., no computational overhead is associated with the transmission of a packet since no periodic recomputation of the transmission schedule is needed to avoid conflicts.
6. It is guaranteed to be completed in time proportional to the current network *diameter* (maximum "hop distance" between any pair of nodes) and the squared logarithm of the number of the nodes, under specific traffic patterns.
7. It allows "parallel flooding," in that more than one packet can be flooded through the network at the same time.

Through the use of simulation, we also demonstrate the effectiveness of TSMA-based flooding by showing that the average broadcast (one-hop) delay for flooding a packet is always less than the average delay of simple TDMA-based flooding, and outperforms Aloha- and Slotted Aloha-based flooding at higher network loads.

The rest of the paper is organized as follows. In section II, we overview the limitations of existing protocols for supporting flooding and we describe the TSMA principle that realizes a deterministic, mobility transparent channel access mechanism. Following that, Section III briefly describes the flooding protocol and some of its basic properties. Section IV shows the simulation results, and finally, Section V concludes the paper.

II. CHANNEL ACCESS PROTOCOLS IN SUPPORT OF MULTIMEDIA

Channel access protocols are generally classified according to how conflicts are resolved. In *probabilistic* solutions the conflict is resolved by randomized retransmissions, whereas in *deterministic* protocols, conflicts are instead avoided or limited by distributing transmission rights in a predefined way.

Probabilistic protocols, such as Aloha or CSMA (6), have the advantage of being mobility transparent and therefore do not incur any overhead as a result of topology changes. However, such protocols do not provide guaranteed delay, and are susceptible to the fundamental problem of instability (i.e., essentially no throughput), at high load. With the emergence of multimedia communication in wireless networks, protocols that can provide a guaranteed delay are becoming of paramount importance.

Deterministic protocols, such as TDMA (6), can provide such guarantees on delay. However, simple TDMA provides unacceptably low throughput as there is no spatial re-use. Variants on TDMA re-use (5) attempt to capitalize on re-using the spectrum by computing schedules for the current two-hop neighborhood. Although these protocols can avoid the stability problem, and provide guaranteed access by deterministic scheduling of transmissions, the scheduling depends critically on the actual network topology. In a highly mobile environment, these protocols may require prohibitive overhead associated with the constant updating of schedules.

The Time-Spread Multiple-Access (TSMA) Principle

Recently, it has been shown that coding theory can be exploited in ways other than for error control. A new family of synchronous protocols, called the *Time-Spread Multiple-Access* (TSMA) protocols, use algebraic Galois (finite) field theory to limit the number of conflicts in the shared channel (7), (8). As expected in deterministic protocols, each node is assigned a unique schedule (code) that deterministically specifies in which time slots the node is assigned transmission rights.

Conflicts in the scheduling are not excluded but, due to the coding method, each node is guaranteed a successful transmission to every neighbor by the end of the schedule. Since the position of the successful transmission among the attempts in the schedule is not known in advance (but its existence is guaranteed!), the success is therefore "spread over time," giving the name of the protocol family. The transmission schedule for every node is *permanent* and, therefore, no scheduling updates are needed as the network topology changes. TSMA thus brings together the mobility independence of probabilistic protocols with the guaranteed delivery of deterministic classes of protocols.

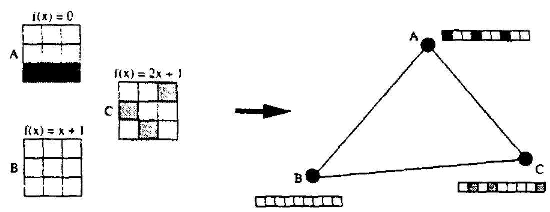

Figure 1. The finite polynomial graphs (left) are mapped one-to-one into permanent transmission schedules (right)

In more detail, TSMA uses polynomials over Galois fields to produce the appropriate schedules (codes). For a network with N nodes a prime parameter q and an integer k are chosen such that $q^{k+1} \geq N$ holds. (This ensures that there are enough codes/schedules generated, since one is needed by each node.) Then each node is assigned a unique $k+1$ dimensional q-ary vector $(a_0, a_1, \ldots, a_k)$, where each a_i, $0 \leq i \leq k$, is in the Galois field of order q (denoted by $GF(q)$). Using this vector, a unique polynomial function over $GF(q)$ is constructed for the node: $f(x) = a_0 + a_1 x + a_2 x^2 + \ldots + a_k x^k$, where x and $f(x)$ are in $GF(q)$ and the operations are executed over $GF(q)$. Using this polynomial, a unique TSMA code (schedule) $(c_0, c_1 \ldots c_{q^2-1})$ of length q^2 is constructed for each node according to the following rule: $c_i = 1$ if $(i \bmod q) = f(\lfloor i/q \rfloor)$, otherwise $c_i = 0$. This rule provides the one-to-one mapping of the (finite) graph of the polynomial into the schedule. The meaning of the code is that each node is allowed to transmit in those time slots in which positions its codeword has 1. Figure 1 shows examples of the mapping for a sample network with at most $N = 9$ nodes. In this case, $q = 3$ and $k = 1$.

In (8), it was shown that constructing TSMA schedules in this manner provides each node with guaranteed success in a schedule of length $L = q^2$, where L, the schedule length, is such that

$$L \in O\left(\Delta^2 \frac{\log^2 N}{\log^2 \Delta}\right).$$

Here, Δ is a design parameter that is an upper bound on the maximum node degree in the network. The guaranteed success is to be understood such that conflicts may occur, but for each node at least one of its assigned slots must be conflict free with respect to each of its neighbors. The identity of the conflict free slot is not known in advance since it depends on the actual network topology. Nevertheless, the *existence* of a conflict free slot in a schedule is guaranteed for each node, as long as the maximum node degree does not exceed the design parameter Δ.

In summary, TSMA is a deterministic family of protocols that specifies packet transmissions over the slots of a schedule, and which requires no adjustments to the schedules as topology changes. Further, it provides predictable and reliable delivery of packets, while at the same time providing a high degree of efficiency in very large mobile networks due to a high degree of topology independent spatial re-use. As a result, this family of protocols is appropriate for use in support of real-time multimedia traffic.

III. FLOODING IN AD HOC NETWORKS

As briefly mentioned in the Introduction, a generic scheme for the flooding of a packet p from a source node s to all the other nodes of the network can be described as follows: s sends p to all its one-hop neighbors, and all s's neighbors, in turn, will transmit p to all their neighbors, and so on until all of the nodes in the network receive p. (If nodes are isolated due to partitions in the network, it is possible that the flood will not reach every node. In this case, only those nodes in the connected component containing s will receive p.) A node that has already successfully transmitted p will discard any duplicates of p.

The flooding can be visualized as a series of concentric rings centered at s. The first ring is made up of all the one-hop neighbors of s. The kth ring includes the nodes that have yet to receive p and that are neighbors of the nodes in the $k-1$st ring that have already received p. Thus, the flooding proceeds as a "wave front" starting at s (ring 0) and advancing according to the rules of the specific channel access protocol used to forward p from ring $k-1$ to ring k. If τ is the time needed by a node at ring $k-1$ to correctly forward p to all its ring k neighbors, then the total time for the completion of the flooding is proportional to $D\tau$, where D is the diameter of the network.

As described in the previous section, for probabilistic protocols no deterministic bound can be given on τ, since there is no way to determine the time needed to forward p from a node to its one-hop neighborhood. On the contrary, TSMA simply and efficiently supports the flooding of packets: in order for a node to achieve successful transmission of p to its one-hop neighborhood it merely needs to transmit p in each of its assigned slots in its schedule. This means the bound on τ for TSMA is in $O(f(N)L)$, the length of the TSMA schedule (see Section II), where the constant hidden in the "big-O" (asymptotic) notation and the function $f(N)$ depend only on the stochastic behavior of the packet arrival at the various nodes and on the number N of nodes in the network, and *not* on the possibility of conflicts.

We notice that when packets arrive (or are generated) at a node at least a schedule length apart from each other, then the $O(DL)$ upper bound always holds for TSMA-based flooding (in this case, $f(N)$ is constant). Under this specific traffic pattern, a packet p does not suffer any buffering delay at a node, and within L slots it is successfully forwarded to all its next-hop neighbors. This guarantees that after a maximum of D hops all the nodes have received p. Thus, TSMA-based flooding under this traffic pattern is guaranteed to be completed in time proportional to the current network diameter and the squared logarithm of the number of the nodes.

Finally, we point out that the method used to generate the TSMA transmission schedule guarantees the correct reception of a packet sent by *any* neighbor of a given node A. These neighbors, of course, may be sending packets that were initiated by different nodes. All these packets are received correctly at A by the end of the current schedule. Thus, packets from more than one flood can travel through the network (parallel flooding).

IV. SIMULATION RESULTS

We have simulated our flooding mechanism by using a discrete event simulator implemented in C++. The simulations consisted of 121 nodes in a network whose average degree (i.e., average number of one-hop neighbors) was three. This network is "optimistic" for TSMA in the following sense. If we use large values of the the design parameter Δ to cover all possibilities of node degree, then the latencies for TSMA can become unacceptably high. Instead, we choose a lower value for Δ derived from a lower value for the maximum node degree. With such an optimistic schedule, the performance level of TSMA will suffer depending on the traffic levels and how often (in time and space) the assumed maximum degree is exceeded. We note that this is not completely unrealistic, as some ad hoc networks are beginning to incorporate autonomous topology control mechanisms (9) with the specific aim of controlling certain network parameters (such as node degree) within a certain range. Moreover, probabilistic protocols, such as Aloha and Slotted Aloha, take advantage of the fewer conflicts due to the low network degree.

The arrival rate of packets at each node is Poissonian and traffic is assumed to be homogeneous.

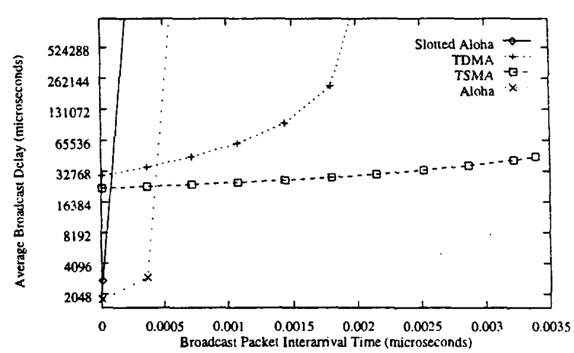

Figure 2. Average one-hop broadcast delay for TSMA, simple TDMA, Aloha and Slotted Aloha.

Figure 2 shows the average one-hop broadcast delay of TSMA-, simple TDMA-, Aloha- and Slotted Aloha-based flooding (the y axis is scaled logarithmically). Here, by interarrival we mean the time interval between two successive packet arrivals into the network.

The average delay of TSMA-based flooding is always less than the average delay of simple TDMA-based flooding. (In general, this is always the case whenever the TSMA parameters yield schedules of length less than N.) Moreover, it outperforms Aloha- and Slotted Aloha-based flooding at higher network loads.

V. CONCLUSIONS AND FURTHER RESEARCH

In this paper the use of TSMA protocols is described for realizing the flooding of packets in ad hoc networks. Due to the unique characteristics of TSMA, the proposed protocol is shown to be independent of the changes in the network topology due to node mobility, and it is deterministic, i.e., it can be used to implement and/or support those networks primitives that are crucial for delay-sensitive applications in ad hoc networks, like multimedia.

Further research is being pursued in order to demonstrate the behavior of TSMA-based flooding, and other operations in support of delay-sensitive applications, in networks in which the degree constraint is not always satisfied. This involves the use of explicit acknowledgments of the packets correctly received and/or also the possibility of adapting the schedule to changing neighborhood (degree) conditions.

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