Energy and Spatial Reuse Efficient Network-Wide Real-Time Data Broadcasting in Mobile Ad Hoc Networks

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Abstract—In this paper, we present NB-TRACE, which is an energy-efficient network-wide voice broadcasting architecture for mobile ad hoc networks. In the NB-TRACE architecture, the network is organized into overlapping clusters through a distributed algorithm, where the clusterheads create a nonconnected dominating set. Channel access is regulated through a distributed TDMA scheme maintained by the clusterheads. The first group of packets of a broadcast session is broadcast through flooding, where each data rebroadcast is preceded by an acknowledgment to the upstream node. Nodes that do not get an acknowledgment for a predetermined time, except the clusterheads, cease to rebroadcast, which prunes the redundant retransmissions. The connected dominating set formed through this basic algorithm is broken in time due to node mobility. The network responds to the broken links through multiple mechanisms to ensure the maintenance of the connected dominating set. We compare NB-TRACE with four network layer broadcast routing algorithms (Flooding, Gossiping, Counter-based broadcasting, and Distance-based broadcasting) and three medium access control protocols (IEEE 802.11, SMAC, and MH-TRACE) through extensive ns-2 simulations. Our results show that NB-TRACE outperforms other network/MAC layer combinations in minimizing energy dissipation and optimizing spatial reuse, while producing competitive QoS performance.

Index Terms—Low-power design, energy-aware systems, data communications, distributed protocols, network communications, network topology, wireless communication, network protocols, protocol architecture, protocol verification, routing protocols, access schemes, mobile computing, algorithm/protocol design and analysis, mobile communication systems.

1 Introduction

Broadcast routing of voice traffic within a mobile ad hoc network has many applications, especially in military communications. For example, the leader of a search and rescue team may need to communicate with all members of the team connected to the network, or the soldiers in a battlefield mission may need to utilize the surveillance information of the region that they are operating within, broadcast by an observer located at a strategic position. Furthermore, it is not possible to restrict the group communication platform to a single-hop network framework, because, in many situations, a platform restricted to single-hop communications will not be enough to fulfill the connectivity requirements of a mobile group. For example, some of the members of a network will not be in direct reach of a source that is beyond their single-hop transmit/receive range due to extended distance, obstacles, or interference. Thus, there is a need for multihop voice broadcasting within a wireless mobile ad hoc network framework.

Energy efficiency, efficient spatial reuse, and application Quality of Service (QoS) are important design constraints in real-time data broadcasting and these parameters are used to evaluate the performance of different network architectures [1]. Energy efficiency is crucial because mobile nodes are equipped with short-range lightweight radios operating with limited energy [2]. Efficient spatial reuse is needed to increase network capacity and achieving efficient spatial reuse necessitates the minimization of the number of rebroadcasts without sacrificing the other criteria, such as QoS [3]. QoS for real-time data, specifically in voice communications, requires that 1) the maximum packet delay is kept within specific bounds, 2) jitter is low, and 3) the packet delivery ratio (PDR) is high [4].

Although all of the major components of energy and spatial reuse efficient QoS-supporting network-wide broadcasting have been investigated in the literature [3], [5], [6], [7], [8], a multiobjective architecture that integrates all of the design goals has not been proposed, to the best of our knowledge. In this paper, we propose such an architecture, called Network-wide Broadcasting through Time Reservation using Adaptive Control for Energy efficiency (NB-TRACE). NB-TRACE is created through the integration of network layer network-wide broadcasting with the MH-TRACE (Multi-Hop Time Reservation using Adaptive Control for Energy efficiency) MAC protocol [9]; thus, NB-TRACE is a cross-layer architecture.

The remainder of this paper is organized as follows: Section 2 presents background information and related work. Section 3 describes the MH-TRACE architecture on which NB-TRACE is built. Section 4 describes the NB-TRACE architecture. The simulation environment and results are presented in Section 5 and conclusions are drawn in Section 6.

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2 Background

2.1 Energy Dissipation

Although there are other possibilities in categorizing the energy dissipation components of a radio, we categorize the energy dissipation modes into the following:

1. transmit mode,
2. receive mode,
3. idle mode,
4. carrier sense mode, and
5. sleep mode.

Transmit energy is dissipated for packet transmissions. Receive energy is dissipated on receiving packets from a node located in the transmit range. Carrier sense energy dissipation is similar to receive energy dissipation, but, in carrier sensing, the source node is located in the carrier sense region rather than the transmit region. Idle energy dissipation is the energy dissipated when none of the nodes in the transmit range and carrier sense range are transmitting packets and the receiving node is not in the sleep mode. In sleep mode, a node is not able to receive or transmit. Sleep mode energy is dissipated on electronic circuitry to keep the radio in a low energy state that can return back to active mode in reasonable time, when required.

In a typical energy model, sleep mode energy dissipation is significantly lower than the other energy dissipation modes [2], [10], [11]. In general, energy-efficient distributed protocol design can be described as creating an appropriate distributed coordination scheme that minimizes a radio's total energy dissipation without sacrificing its functionality by intelligently switching between the radio's different operation modes [12], [13]. In particular, energy efficiency in broadcasting can be achieved by

1. avoiding unnecessary carrier sensing and minimizing the idle energy dissipation,
2. avoiding overhearing irrelevant packets (i.e., promiscuous listening),
3. minimizing the transmit energy dissipation by optimizing the transmit power and minimizing the number of retransmissions in broadcasting scenarios, and
4. reducing the overhead (i.e., bandwidth and energy used for anything other than optimal data transmission and reception) as much as possible without sacrificing the robustness and fault tolerance of the network [5], [14], [15], [16].

Avoiding energy dissipation in the idle mode (idle and carrier sense energy) necessitates coordination through scheduling between the nodes [6], so that nodes avoid idle listening or carrier sensing. Many approaches have been proposed for minimizing the idle energy dissipation in single-hop wireless networks [6], [17], [18].

Several distributed MAC protocols have been developed with the goal of minimizing energy dissipation of the nodes. IEEE 802.11 supports an energy saving mechanism in ad hoc mode called the Ad hoc Traffic Indication Message (ATIM) window, but this is not an attractive energy saving mechanism [13]. This mechanism tries to save energy by reducing the time of idle listening and it does not address the overhearing problem [19]. Furthermore, ATIM is primarily intended for unicast traffic, thus, in broadcasting, its energy saving potential is limited. SMAC [5] is an energy-efficient MAC protocol designed specifically for sensor networks that reduces idle listening by periodically shutting the radios off. It is shown that, in low traffic networks, SMAC is much more energy-efficient than IEEE 802.11. Energy dissipation characteristics of SMAC are mainly determined by the sleep/active ratio, R_{SMAC}, and sleep/active cycle, T_{SMAC}.

Especially in broadcasting, many redundant versions of the same packet are received by each node, which results in receive energy dissipation for no gain. An efficient solution to this problem is information summarization prior to data transmission through a short information summarization (IS) packet that includes metadata summarizing the corresponding data packet transmission (e.g., RTS/CTS packets of IEEE 802.11 in unicasting) [14]. A node that has already received a packet will be prevented from receiving redundant copies of the same packet, which are identified through corresponding IS packets, by entering the sleep mode.

Power aware multiaccess protocol with signaling for ad hoc networks (PAMAS) [15] is an energy-efficient MAC protocol that is built on top of IEEE 802.11. Nodes avoid energy dissipation for overhearing packets destined for other nodes by entering the sleep mode. RTS/CTS packets are used to discriminate the data packets, thus, the metadata is the destination address of the unicast packets in this specific application. Due to the lack of RTS/CTS packets in broadcasting, it is not possible to employ PAMAS for broadcasting.

There is a wealth of studies on optimizing delay, throughput, and transmit energy dissipation in broadcasting [20], [21], [22], [23], [24]. By considering both transmit and receive energy dissipation, it has been shown that, for a given energy and propagation model, there is an optimum transmit radius, D_{OP}, beyond which single-hop transmission is less energy efficient than multihop transmissions [16], [25]. Thus, the optimal broadcast strategy to minimize the transmit energy dissipation in a network consisting of constant transmit range radios is to use a multihop broadcasting scheme, where the transmit radius is chosen lower than D_{OP}. Furthermore, total transmit energy dissipation increases with the number of retransmissions of a broadcast packet.

2.2 Efficient Spatial Reuse

In broadcasting, the efficiency of spatial reuse is measured by the number of retransmissions required for a packet to be received by all the nodes in the network [3]. Many algorithms have been proposed for network-wide broadcasting and they can be classified into three main categories: 1) noncoordinated, 2) fully coordinated, and 3) partially coordinated. Flooding is an example of a noncoordinated broadcast algorithm, where nodes rebroadcast without any coordination [26]. However, in order to avoid excessive collisions, nodes retransmit with a random assessment delay (RAD), which is uniformly distributed in $[0, T_{RAD}]$. Gossiping is another example of a stateless (noncoordinated) broadcast algorithm [14], where nodes rebroadcast with a predetermined probability p_{GSP} in conjunction with

RAD. However, regardless of p_{GSP}, source nodes always transmit.

The goal of a fully coordinated algorithm is to create a Minimum Connected Dominating Set (MCDS), which is the smallest set of rebroadcasting nodes such that the set of nodes are connected and all nonset nodes are within the transmit range of at least one member of the MCDS [27]. However, the creation of an MCDS is not practical, even with the assumption of global knowledge, due to the NP-hardness of the problem. Partially coordinated broadcast algorithms can be considered as approximate limited scope MCDSs based on local information—they do not need global information, unlike fully coordinated algorithms.

Counter-based broadcasting (CBB) and distance-based broadcasting (DBB) are two examples of partially coordinated broadcast algorithms [3], [26]. In CBB, a node that receives a packet randomly chooses its RAD and starts to count the number of receptions of the same packet until its broadcast timer expires. If the number of receptions of the packet is lower than the predetermined maximum counter value, N_{CBB}, then the packet is transmitted; otherwise, it is dropped. DBB is a distance-based scheme, where the nodes calculate the distance to a transmitting node based on received power strength. In DBB, each node picks a RAD upon the reception of a previously unheard packet and starts to record the distance of the nodes that retransmit the same packet. Upon the expiration of RAD, if the closest transmission of the packet to be transmitted is higher than the minimum distance, D_{DBB}, then the packet is transmitted; otherwise, it is dropped.

2.3 QoS

QoS for streaming media throughout the network necessitates timely delivery of packets, low jitter, and high PDR [28], [29]. Packet delay is related to the number of hops traversed by the voice packets and the contention level of the network. To ease congestion, packets that have exceeded the end-to-end delay bound can be dropped rather than transmitting them to the destination, as they are no longer useful to the application [30]. However, excessive packet drops decrease the packet delivery ratio, which is the other important aspect of QoS for streaming media. PDR is also decreased by collisions. Thus, there are two mechanisms that negatively affect the packet delivery ratio: packet drops and collisions. Jitter in packetized voice traffic can be defined as the deviation from the periodicity of packet receptions [31], [32]. For zero jitter, the interarrival time between voice packet receptions should be identical and equal to the packet generation period, T_{PG}. In this study, the QoS objectives are 95 percent packet delivery ratio and 150 ms maximum packet delay. Voice packets exceeding 150 ms delay are dropped at the MAC layer (i.e., $T_{drop} = 150$ ms).

Achieving the goals of QoS and energy efficiency in a multihop network necessitates coordination between the nodes so that they avoid wasting system resources like energy and bandwidth. While these goals can be met using centralized control [33], this is not practical in a mobile ad hoc network, or at least not scalable due to the high overhead to monitor and convey the control information throughout the network. A realizable, yet useful framework for network coordination is to create a network partitioning through clustering [7], [34]. For example, a clusterhead (CH) that manages the channel access through a schedule could inform the nodes about future transmissions so that they can switch to sleep mode to avoid wasting energy.

3 MH-TRACE

Multi-Hop Time Reservation using Adaptive Control for Energy efficiency (MH-TRACE) is a MAC protocol that combines advantageous features of fully centralized and fully distributed networks for energy-efficient real-time data broadcasting [9]. Fig. 1 shows a snapshot of MH-TRACE clustering and medium access for a portion of a distribution of mobile nodes. In MH-TRACE, the network is partitioned into overlapping clusters through a distributed algorithm. Time is organized into cyclic constant duration superframes consisting of several frames. Each CH chooses the least noisy frame to operate within and dynamically changes its frame according to the intercluster interference level. Nodes gain channel access through a dynamically updated and monitored transmission schedule created by the CHs, which eliminates packet collisions within the cluster. Ordinary nodes are not static members of clusters, but they choose the cluster they want to join based on the spatial and temporal characteristics of the traffic, taking into account the proximity of the CHs and the availability of the data slots within the corresponding cluster.

Each frame consists of a control subframe for transmission of control packets and a data subframe for data transmission (see Fig. 2). Beacon packets are used for the announcement of the start of a new frame, CH Announcement (CA) packets are used for reducing coframe cluster interference, contention slots are used for initial channel access requests, the header packets are used for announcing the data transmission schedule for the current frame, and Information Summarization (IS) packets are used for announcing the upcoming data packets. An MH-TRACE Protocol Data Unit (PDU) is similar to an IEEE 802.16 MAC PDU, which consists of a fixed length MAC header, a variable-length payload, and a cyclic redundancy check [35]. IS packets are designed to be versatile, and they are crucial in energy saving.

Each scheduled node transmits its data at the reserved data slot. Once a node receives a reserved slot, that slot is kept in subsequent frames as long as the node has data to send, so nodes only need to contend for channel access at the beginning of a data burst. Nodes that are scheduled to transmit data send a short information summarization (IS) packet prior to data transmission. The IS packet includes information about the data packet, where the content of the IS packets can be modified to fit the requirements of different applications.

Any clock missynchronization beyond the IFS (i.e., the guard band between each time slot) would destroy the superframe structure of MH-TRACE. Network-wide synchronization can be achieved by using commercial Global Positioning System (GPS) receivers, which are capable of operating indoors [36]. Actually, network-wide synchronization within an independent basic service set (IBSS) is also crucial in IEEE 802.11 for the efficient operation of

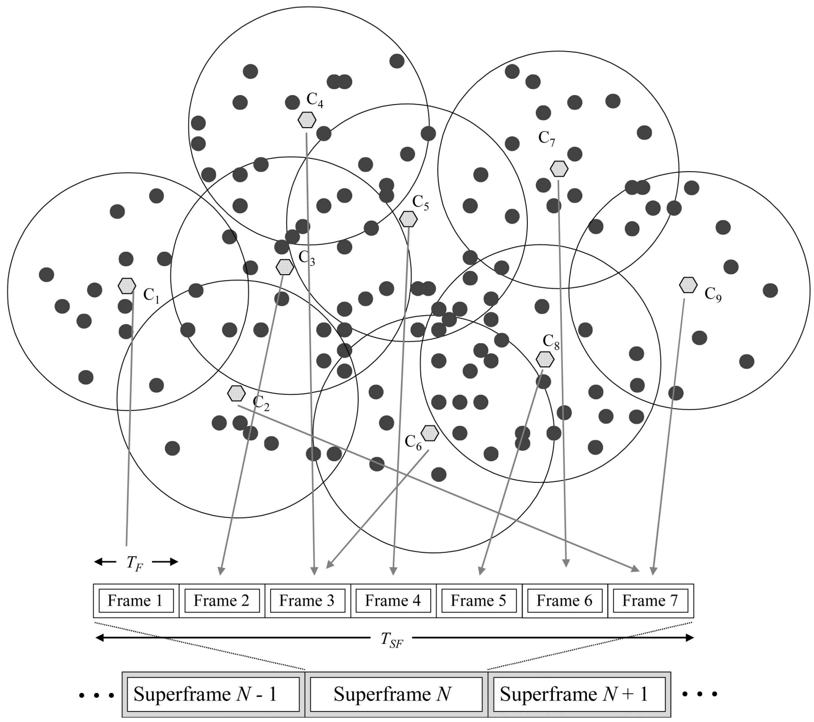


Fig. 1. A snapshot of MH-TRACE clustering and medium access for a portion of an actual distribution of mobile nodes. Nodes C_1 - C_9 are CHs.

frequency-hopped and direct-sequence spread-spectrum (FHSS and DSSS) [37].

4 NB-TRACE

4.1 Design Principles

Since we wanted to keep the MH-TRACE structure intact, we followed a bottom up approach to design the network layer architecture, rather than a top down approach (i.e., the network layer is tailored according to the MAC layer). We considered combining MH-TRACE and an existing network layer broadcast algorithm to achieve energy-efficient network-wide broadcasting of voice data. Due to its simplicity, we first integrated flooding with MH-TRACE. In MH-TRACE-based flooding, each node that can obtain channel access continuously rebroadcasts the voice packets. In network-wide broadcasting, we employ the IS slots of MH-TRACE to transmit the unique ID of the corresponding voice packets (i.e., the source node ID and data packet sequence number constitutes a unique ID). Thus, nodes in the receive range of the transmitting node are informed ahead of time about upcoming data transmissions and avoid receiving multiple copies of the same packet, which saves a considerable amount of energy. However, due to the inherent inefficiencies of flooding, spatial reuse of the combined architecture was not satisfactory (i.e., too many redundant rebroadcasts). On the other hand, the energy dissipation of MH-TRACE-based flooding was far better than flooding with other MAC protocols [38].

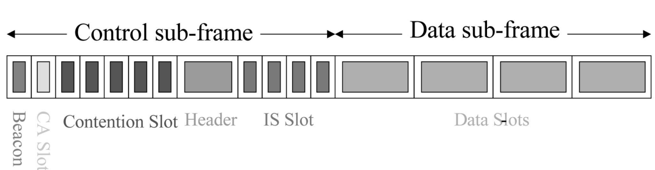


Fig. 2. MH-TRACE frame structure.

The other network layer broadcasting algorithms were not easy to integrate with MH-TRACE without degrading system performance due to the application-specific design of MH-TRACE. For example, when we use gossiping in conjunction with MH-TRACE, due to the per-packet-based probabilistic channel access, the reservation mechanism of MH-TRACE cannot function properly (i.e., continuous utilization of the data slots is necessary). Furthermore, the advantageous features of MH-TRACE (e.g., organization of the network into clusters, automatic renewal of channel access) cannot be fully utilized by any existing network-layer broadcasting algorithm. Thus, there is a need for a new application-specific network layer algorithm integrated with an application-specific MAC layer (i.e., NB-TRACE).

The main function of NB-TRACE is to connect the nonconnected dominating set (NCDS) formed by the CHs, maintained by the underlying MH-TRACE protocol. This mostly eliminates the burden of maintaining a CDS by the network layer because the maintenance of the cluster structure is done by the MAC layer, which is clearly a benefit of cross-layer design.

The basic design philosophy of NB-TRACE is to flood the network and, by using the properties of the underlying MH-TRACE architecture, to prune the network as much as possible while maintaining a connected dominating set with minimal control packet exchange (i.e., minimizing the overhead). We also wanted to keep the data slots exclusively for data packets rather than using them for control packets in order to not interrupt data streams.

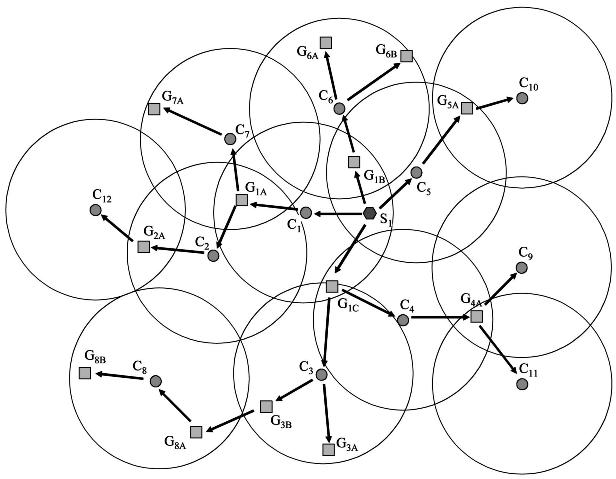


Fig. 3. Illustration of NB-TRACE broadcasting. The hexagon represents the source node, disks are clusterheads, the large circles centered at the disks represents the transmit range of the clusterheads, squares are gateways, and the arrows represent the data transmissions.

4.2 Overview

In NB-TRACE, the network is organized into overlapping clusters, each managed by a CH. Channel access is granted by the CHs through a dynamic, distributed Time Division Multiple Access (TDMA) scheme, which is organized into periodic superframes. Initial channel access is though contention; however, a node that utilizes the granted channel access automatically reserves a data slot in the subsequent superframes. The superframe length, T_{SF}, is matched to the periodic rate of voice generation, T_{PG}.

Data packets are broadcast to the entire network through flooding at the beginning of each data session. Each rebroadcasting (relay) node explicitly acknowledges (ACKs) the upstream node as part of its data transmission. Relay nodes that do not receive any ACK in T_{ACK} time cease to rebroadcast. As an exception, the CHs continue to rebroadcast regardless of any ACK, which prevents the eventual collapse of the broadcast tree. Due to node mobility, the initial tree will be broken in time, so NB-TRACE is equipped with several mechanisms to maintain the broadcast tree over time.

In NB-TRACE, a broadcast tree is formed by the initiation of a source node; however, once a tree is formed (i.e., once nodes determine their roles), then other sources do not need to create another tree; instead, they use the existing organization to broadcast their packets.

NB-TRACE broadcasting and packet flow is illustrated in Fig. 3. NB-TRACE is composed of five basic building blocks:

1. Initial Flooding (IFL),
2. Pruning (PRN),
3. Repair Branch (RPB),
4. Create Branch (CRB), and
5. Activate Branch (ACB).

The NB-TRACE algorithm flowchart is presented in Fig. 4. Actually, all of theses building blocks are functioning simultaneously; however, we describe them as sequential mechanisms to make them easier to understand.

4.3 Initial Flooding (IFL)

A source node initiates a session by broadcasting packets to its one-hop neighbors. Nodes that receive a data packet contend for channel access and the ones that obtain channel access retransmit the data they received. Eventually, the data packets are received by all the nodes in the network, possibly multiple times. Each rebroadcasting node ACKs its upstream node by announcing the ID of its upstream node in its IS packet, which precedes its data packet transmission (see Fig. 2). A source node announces its own ID as its upstream node. Source node ID, Flow ID, Packet ID, CH Status, and IFL ID are also announced in the IS packet (see Fig. 5). At the beginning of a broadcast session, the IFL ID is set to one for T_{IFL} time to force the nodes to switch to active mode. At this point, some of the nodes have multiple upstream nodes. A node with multiple upstream nodes chooses the upstream node that has the least packet delay as

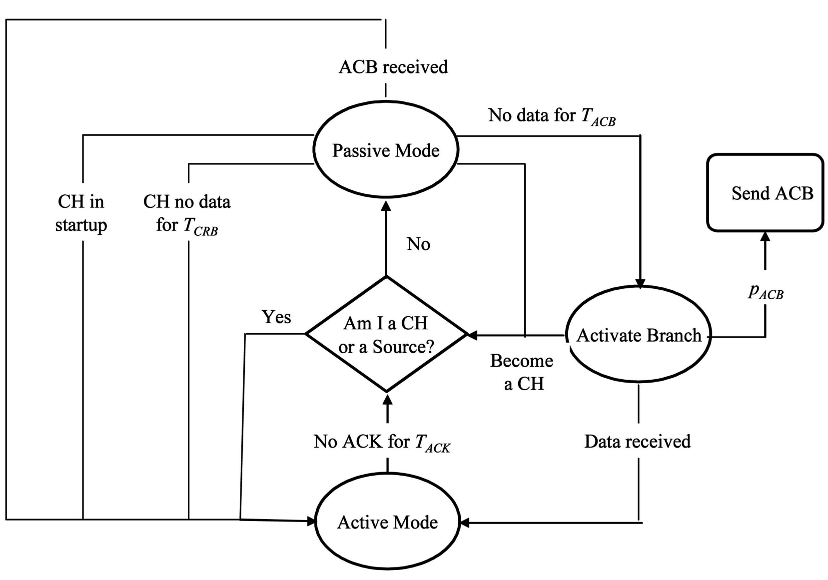
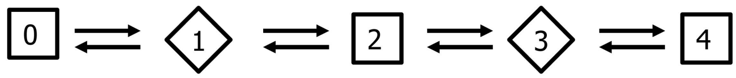


Fig. 4. NB-TRACE flowchart.



t_0	(0, 0, 0, 0, 1, 1)				
t_1		(0, 0, 0, 0, 0, 1)			
t_2			(0, 0, 0, 1, 1, 1)		
t_3				(0, 0, 0, 2, 0, 1)	
t_4					(0, 0, 0, 3, 1, 1)
t_5	(0, 0, 1, 0, 1, 0)				

([Source Node ID], [Flow ID], [Packet ID], [Upst. Node ID] [CH Status] [IFL ID])

Fig. 5. Illustration of IFL and IS contents. Squares and diamonds represent CHs and ordinary nodes, respectively. Node-0 is the source node. The entries below the nodes represent the contents of ([Source Node ID] [Flow ID] [Packet ID] [Upstream Node ID] [(CH Status)] [IFL ID]) fields of their IS packets (t_is represent time instants).

its upstream node to be announced in its IS packet in order to minimize the delay.

Whenever a source node stops its broadcast, it sets the Packet ID field to null-ID. Nodes that receive an IS packet with a null Packet ID mark the corresponding source and flow IDs as inactive for future reference. Furthermore, all the nodes record the time instants that they last received an IS packet with the Upstream Node ID set as their own ID from any other node (i.e., ACK reception).

4.4 Pruning (PRN)

During the initial flooding, the broadcast relays are determined in a distributed fashion. Actually, a node can be in only three states: 1) passive, 2) active, and 3) ACB (activate branch). Nodes in passive mode do not relay packets, they just receive them. Nodes in the active state act as relays, because they are the only nodes that participate in broadcast data forwarding, excluding the transients where some nodes temporarily stay in the active mode. During Initial Flooding, all nodes that obtained channel access switch to the active state (i.e., they rebroadcast data packets). Active nodes that do not receive an ACK for T_{ACK} time cease rebroadcasting and return to passive mode. Nodes need to wait for T_{ACK} time to cease relaying because network dynamics may temporarily prevent a downstream node from ACKing an upstream node (e.g., mobility, cluster maintenance). However, this algorithm has a vital shortcoming, which will eventually lead to the silencing of all relays. The outermost (leaf) nodes will not receive any ACKs, thus they will cease relaying, which also means that they cease ACKing the upstream nodes. As such, sequentially, all nodes will cease relaying and ACKing, which will limit the traffic to the source node only.

To solve this problem, we introduce another feature to the algorithm, which is that the CHs always retransmit, regardless of whether or not they receive an ACK. Thus, the broadcast tree formed by IFL and PRN always ends at CHs. Note that the CHs create a nonconnected dominating set. Thus, if we ensure that all the CHs relay broadcast packets, then the whole network is guaranteed to be completely covered. However, this is not the optimal solution because, in some topologies, some CHs have only one neighbor, which is their upstream node (e.g., node 4 in Fig. 5). Such redundant rebroadcasts deteriorate the spatial reuse efficiency of NB-TRACE. Nevertheless, comparative evaluations of NB-TRACE with other broadcast architectures (see Section 5) show that, overall, the spatial reuse efficiency of NB-TRACE is better than other architectures.

The IFL and PRN mechanisms are illustrated in Fig. 6. After the IFL, all the nodes in the network receive the data packets and they determine whether they are receiving ACKs or not. Eventually, nodes 1, 3, 5, and 7 cease retransmitting and switch to the passive mode and nodes 0, 2, 4, and 6 stay in the active mode (i.e., the broadcast tree consists of nodes 0, 2, 4, and 6 and all the other nodes are in the one-hop neighborhood of at least one tree member). Node 5 ceases rebroadcasting T_{ACK} time after its first data transmission because it does not receive any ACK from any of its neighbors; however, until that time, node 5 is ACKing node 3. Node 3 ceases rebroadcasting $2T_{ACK}$ time after its first data transmission, because, for the first T_{ACK} time, node 3 was being ACKed by node 5. With the same token, node 1 ceases rebroadcasting $3T_{ACK}$ time after its first data transmission. Although the pruning of redundant rebroadcasts takes some time, this does not introduce any additional delay in data traffic (i.e., all of the members of the broadcast tree start to relay packets as soon as they get channel access).

The first two blocks of the algorithm (IFL and PRN) are sufficient to create a broadcast tree for a static network. However, for a dynamic (mobile) network, we need extra blocks in the algorithm, because, due to mobility, the broadcast tree will be broken in time. The simplest

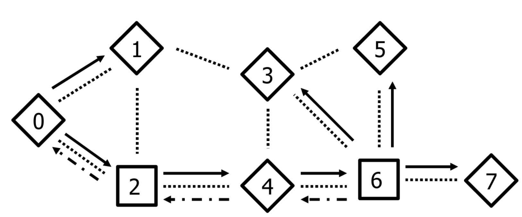


Fig. 6. Illustration of IFL and PRN. Squares and diamonds represent CHs and ordinary nodes, respectively. Node-0 is the source node. Dotted lines represent the links between the nodes. Solid and dash-dotted lines represent the data and IS flows, respectively.

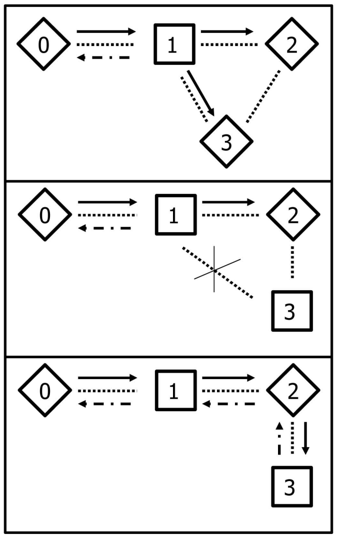


Fig. 7. Illustration of the RPB mechanism.

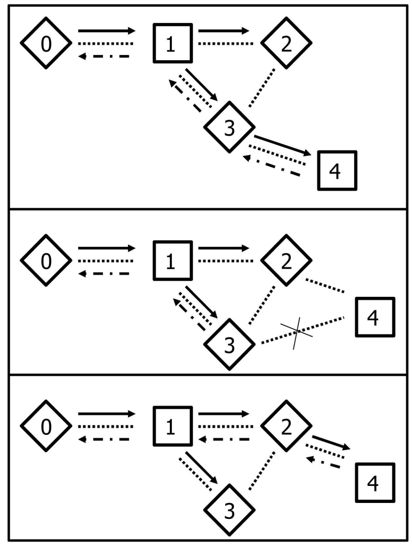


Fig. 8. Illustration of the CRB mechanism.

solution would be to repeat the IF block periodically, so that the broken links will be repaired (actually, recreated) periodically. Although this algorithm is simple, it would deteriorate the overall bandwidth efficiency of the network. The quest for more efficient compensation mechanisms leads us to design three maintenance procedures.

4.5 Repair Branch (RPB)

One of the major effects of node mobility on NB-TRACE is the resignation of existing CHs and the appearance of new CHs (i.e., when two CHs enter each other's receive range, one of them resigns, and, if there are no CHs in the receive range of a node, it contends to become a CH). At the beginning of its operation as a CH, the CH stays in startup mode until it sends its header packet and announces its status with a bit included in the beacon packet. The appearance of a new CH is generally associated with the resignation of an existing CH. Whatever the actual situation, the nodes that receive a beacon packet from a CH in startup mode switch to active mode and rebroadcast the data packets they receive from their upstream neighbors until they cease to relay due to pruning. Fig. 7 illustrates the RPB mechanism in a simple scenario. In the upper panel, only node 1 is a CH and the broadcast tree consists of nodes 0 and 1. Nodes 2 and 3 receive data packets through node 1. However, due to the movement of node 3 (center panel), node 1 is out of the reach of node 3, thus, node 3 becomes a CH. Upon receiving the beacon of node 3, which indicates that it is in the startup mode, node 2, which was in the passive mode, switches to the active mode, thus, node 3 starts to receive data packets from node 2 (lower panel).

Although RPB significantly improves the system performance in combating node mobility, it cannot completely fix the broken tree problem. For example, a CH could just move away from its only upstream neighbor, which creates a broken tree. This problem (and other similar situations) cannot be handled by RPB. Thus, we introduce CRB, which, in conjunction with RPB, almost completely alleviates the tree breakage problem.

4.6 Create Branch (CRB)

One of the basic principles of the NB-TRACE algorithm is that all the CHs should be rebroadcasting. If an ordinary node detects that any of the CHs in its receive range are inactive for T_{CRB} time, then it switches to active mode and starts to rebroadcast data. As in the RPB case, redundant relays will be pruned in T_{ACK} time. The CRB mechanism is illustrated in an example scenario in Fig. 8. Node 4, which is a CH, receives data through node 3 (upper panel). Due to mobility, node 4 moves away from node 3 and the link between node 3 and node 4 is broken. However, node 4 enters into the receive range of node 2 (center panel). Upon detecting an inactive CH (node 4) in its receive range for T_{CRB} time, node 2 switches to the active mode and node 4 starts to receive data from its new upstream node, which is node 2 (lower panel).

The first four building blocks (IFL, PRN, RPB, and CRB) create an almost complete broadcasting algorithm capable of handling mobility. However, in some scenarios, none of the aforementioned blocks can repair broken links. Fig. 9 illustrates such a scenario. The upper panel of Fig. 9 illustrates a network with a complete broadcast tree, where all the nodes can receive the broadcast packets. After some time, due to the mobility of nodes 3 and 5, node 3 gives up being a CH and node 5 becomes a CH (center panel). However, the potential upstream node of node 5, which is node 4, cannot relay data packets to node 5 by using the CRB mechanism because the potential upstream node of node 4, which is node 2, is in the passive mode and does not supply node 4 with data packets. The ACB block comes into play at this point to fix this problem.

4.7 Activate Branch (ACB)

An ordinary node that does not receive any data packets for T_{ACB} time switches to ACB mode and sends an ACB packet with probability p_{ACB}. The underlying MH-TRACE MAC does not have a structure that can be used for this purpose, thus, we modified MH-TRACE to be able to send ACB packets without actually affecting any major building blocks of MH-TRACE. ACB packets are transmitted by

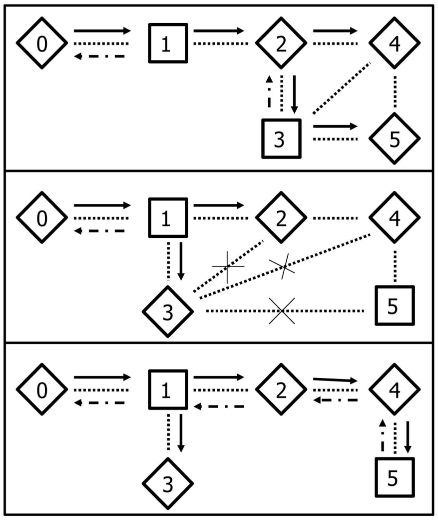


Fig. 9. Illustration of the ACB mechanism.

using the IS slots because all the nodes will be listening to the IS slots regardless of their energy saving mode. Upon reception of an ACB packet, the receiving nodes switch to active mode and start to relay data. If the nodes that receive ACB packets do not have data to send, they are either in ACB mode or they will switch to ACB mode. Upon receiving the first data packet, the nodes in ACB mode will switch to active mode.

The lower panel of Fig. 9 illustrates the ACB mechanism. Upon detecting the inactivity of the CH in its receive range (node 5), node 4 switches to active mode in T_{CRB} time, which does not help to fix the broken link in this situation. After T_{ACB} time, node 4 switches to ACB mode and sends its ACB packet to node 2. Upon receiving an ACB packet from node 4, node 2 switches to active mode and starts to relay the data packets it receives from its upstream node (node 1) to node 4 and, then, node 4 switches to active mode and relays the packets to node 5.

The main functionality of ACB is to activate an inactive distributed gateway formed by two ordinary nodes (i.e., nodes 2 and 4 in Fig. 9). Once the distributed gateway is activated, then the flow of data packets, possibly from multiple flows and/or from multiple sources, can reach the leaf CH (i.e., node 5), hence, the nodes in the CH's one-hop neighborhood. Thus, ACB is not for actually searching for any particular broadcast flow from any particular source node. Rather, it is for connecting the disconnected section of the broadcast tree to the rest of the broadcast tree.

4.8 Multiple Packet Drop Thresholds

Utilizing a single packet drop threshold throughout the network is not a good strategy because of the fact that the source node does not drop packets until the packet delay exceeds the packet drop threshold. Due to the network dynamics, packet delay is accumulated in time. When packets are transmitted by the source node at the verge of being dropped, these packets cannot be relayed and are dropped by the neighbors of the source node. The remedy for this problem is to use a two-level packet drop threshold scheme. Thus, in NB-TRACE, two packet drop thresholds are utilized. A large packet drop threshold, T_{drop}, dictated by the application, is used throughout the whole network. A smaller packet drop threshold, $T_{drop\text{-}source}$, is used only at the source node so that the packets that would not be relayed due to large delays are automatically dropped by the source node. We set $T_{drop\text{-}source}$ to be equal to the packet generation period, T_{PG}, because we want to keep $T_{drop\text{-}source}$ as small as possible to minimize the overall delay and we do not want to drop a packet before there is another packet ready in the queue.

5 Simulations

5.1 Simulation Environment

We explored the QoS and energy dissipation characteristics of NB-TRACE, flooding with MH-TRACE, and flooding, gossiping, CBB, and DBB with IEEE 802.11 and SMAC through extensive *ns*-2 simulations within the traffic load and node density parameter space. All the simulations are run for 100 s and averaged over 10 runs. We used a CBR traffic generator with a UDP transport agent to simulate a constant rate voice codec. We used the energy and propagation (two-ray ground) models discussed in [2], [9] as our primary models, which are the default models in *ns*-2 (i.e., $P_T = 0.60$ W, $P_R = 0.30$ W, $P_I = 0.10$ W, and $P_S = 0.01$ W). We also used the energy model presented in [11] (i.e., $P_T = 2.50$ W, $P_R = 0.90$ W, $P_I = 0.11$ W, and $P_S = 0.02$ W) for comparison. Unless otherwise stated, the default energy model in this paper is the former one. Transmit radius, D_{Tr}, and carrier sense radius, D_{CS}, are 250 m and 507 m, respectively. We used the same overhead for IEEE 802.11, SMAC, and MH-TRACE data packets in our simulations (i.e., 10 bytes) to compare all protocols on a fair basis; therefore, all data packets are 110 bytes. MH-TRACE and NB-TRACE control packets are 10 bytes. We evaluated the performance of the broadcast architectures with a single flow at a time. Acronyms, descriptions, and values of the constant parameters used in the simulations are given in Table 1.

We used the random waypoint mobility model where the node speeds are chosen from a uniform random distribution between 0.0 m/s and 5.0 m/s (the average pace of a marathon runner). The pause time is set to zero to avoid nonmoving nodes throughout the simulation time. As reported in [39], [40], we observe a decrease in the average instantaneous node speed with time. Average node speed at the beginning is about 2.5 ± 0.2 m/s; however, at the end (100 s), the average node speed decreases to 2.2 ± 0.4 m/s. Note that, in $x \pm y$ notation, x and y are the mean and standard deviation of an ensemble, respectively.

We simulated several network/MAC combinations to evaluate their performance against NB-TRACE. We have chosen IEEE 802.11, SMAC, and MH-TRACE as the MAC layers because, 1) the IEEE 802.11 standard is well-known by the wireless community and almost all researchers compare their algorithms with IEEE 802.11, 2) SMAC is the most prominent example of a truly distributed energy-aware MAC protocol based on CSMA, and 3) MH-TRACE is an example of a clustering-based approach and a TDMA-based channel access scheme. We have chosen four network layer broadcast algorithms: flooding, gossiping, CBB, and

TABLE 1
Simulation Parameters

Acronym	Description	Value
D_{TR}	Transmit radius	250 m
D_{CS}	Carrier sense radius	507 m
T_{drop}	Packet drop threshold	150 ms
$T_{drop\text{-}source}$	Packet drop threshold at source	25 ms
P_T	Transmit power	0.60 W / 2.50 W
P_R	Receive power	0.30 W / 0.90 W
P_I	Idle power	0.10 W / 0.11 W
P_S	Sleep power	0.01 W / 0.02 W
C	Channel rate	2 Mbps
N/A	Data packet overhead	10 bytes
N/A	Control packet size	10 bytes
N/A	Maximum header packet size	22 bytes
T_{IFS}	Inter-frame space	16 μs
T_{ACK}	Data ACK time	$4T_{SF}$
T_{IFL}	IFL time	T_{SF}
T_{CRB}	CRB time	$5T_{SF}$
T_{ACB}	ACB time	$6T_{SF}$
p_{ACB}	ACB probability	0.5
T_{RAD}	Random assessment delay	12.5 ms
T_{SMAC}	SMAC sleep/active cycle period	25 ms
R_{SMAC}	SMAC sleep/active ratio	0.25
p_{GSP}	Gossiping probability	0.1 - 0.9
N_{CBB}	CBB maximum counter value	2 - 7
D_{DBB}	DBB minimum distance	140 m - 240 m

DBB. Flooding and gossiping are examples of noncoordinated broadcast algorithms, whereas CBB and DBB are examples of partially coordinated broadcast algorithms. Thus, our comparisons span a wide range of algorithms for network-wide broadcasting.

5.2 General Performance Analysis

In this section, we present the simulation results for NB-TRACE and all the other architectures in a 1 km by 1 km network with 80 nodes. Data rate is 32 Kbps, which is realized by 100-byte payload packets with 25 ms packet generation period. We analyze the broadcast architectures independently and, at the end, we compare them.

MH-TRACE-based flooding average and minimum packet delivery ratios (PDRs) are both above 99 percent (see Table 2). Average packet delay and delay jitter of MH-TRACE are 47.8 ms and 2.1 ms, respectively. MH-TRACE average number of retransmitting nodes per data packet (ARN) is 61.2. Note that not all of the nodes are retransmitting even though the network layer algorithm is flooding. One reason for such behavior is that the number of data slots available is less than the number of nodes in the network and, thus, some nodes are denied channel access.

Average and minimum PDRs of NB-TRACE are both above 99 percent (see Table 2). NB-TRACE average packet delay, 35.9 ms, is 31 percent less than MH-TRACE average delay due to the network layer coordination in NB-TRACE. RMS jitter, 2.1 ms, is less than 10 percent of the average delay.

ARN of NB-TRACE is 19.2 ± 1.5 retransmissions per generated packet, which is approximately one third of the ARN of MH-TRACE. Due to the reduction in the number of packet transmissions, NB-TRACE dissipates 20 percent less energy than MH-TRACE. Before analyzing the energy dissipation of NB-TRACE with data traffic, we present an analysis with zero data traffic (i.e., no data packets are generated). NB-TRACE per node energy dissipation with no data traffic is presented in Table 2. Transmit energy is dissipated on the control packet (beacon, CA, header) transmissions by the CHs, receive and carrier sense energy is dissipated for the reception of control packets, and idle energy is dissipated during the IS slots by all nodes and during the contention slots by the CHs. Energy dissipation in the transient periods (i.e., startup, network maintenance) also affects all of the energy dissipation terms. On average, 81.4 percent of the total time is spent in the sleep mode and 16.7 percent of the total time is spent in the idle mode. Only 2.8 percent of the total time is spent in transmit, receive, and carrier sense modes; however, 19.4 percent of the total energy dissipation is due to these modes because of the higher power level of transmit and receive/carrier sense, when compared to idle and sleep modes.

When we compare NB-TRACE energy dissipations with and without data transmissions, we see that sleep mode energy dissipations and time spent in the sleep mode are almost the same for both cases because the only difference when data is present is that the relay nodes switch to transmit mode once in each superframe and all the nodes switch to receive mode once to receive a single copy of a

TABLE 2
MH-TRACE and NB-TRACE Performance

	PDR (Avg/Min)	ARN	Delay (ms)	Jitter (ms)	Total E. (mJ/s)	Transmit E. (mJ/s)	Receive E. (mJ/s)	Carrier Sense E. (mJ/s)	Idle E. (mJ/s)	Sleep E. (mJ/s)
MH-TRACE	99.6±0.2% / 99.4±0.3%	61.2±7.9	47.8±6.6	2.1±0.1	55.8±0.7	8.8±0.3	13.5±0.2	14.2±0.9	11.4±0.3	7.9±0.0
NB-TRACE	99.8±0.1% / 99.7±0.2%	19.2±1.5	35.9±4.0	2.1±0.1	44.5±1.1	3.6±0.4	9.6±0.4	9.1±0.1	14.3±0.4	8.0±0.0
NB-TRACE No Data Traffic	N/A	N/A	N/A	N/A	31.0±0.2	0.3±0.0	1.8±0.1	3.8±0.2	16.9±0.1	8.1±0.0
NB-TRACE 3B	82.0±6.8 % / 24.5±12.4 %	13.7±2.3	40.0±5.3	2.1±0.1	40.5±1.2	2.3±0.3	7.7±0.6	7.3±0.6	15.3±0.2	8.0±0.0
NB-TRACE 4B	99.4±0.2 % / 96.9±2.5 %	18.1±1.2	35.1±4.8	2.1±0.1	43.5±0.6	3.2±0.2	9.3±0.2	8.3±0.4	14.7±0.1	8.0±0.0
NB-TRACE $T_{drop\text{-}source}$ = 150 ms	89.2±13.0 % / 68.4±22.7 %	18.0±3.6	93.6±15.0	2.4±0.3	43.4±1.6	3.1±0.5	9.0±0.9	8.9±0.6	14.4±0.3	8.0±0.0

TABLE 3
General Performance Comparisons

Rank	PDR (Avg / Min)	Delay (ms)	Jitter (ms)	ARN	Energy-1 (mJ/s)	Energy-1 Normalized	Energy-2 (mJ/s)	Energy-2 Normalized
1	NB	CI	NB	NB	NB	NB	NB	NB
	99.8±0.1 % / 99.7±0.2 %	11.5±1.1	2.1±0.1	19.2±1.5	44.5±1.1	1.0	102.5±5.5	1.0
2	CI	CS	MH	CS	MH	MH	MH	MH
	99.7±0.2 % / 99.3±0.3 %	12.3±0.5	2.1±0.1	23.2±0.2	55.8±0.7	1.3	148.0±4.7	1.4
3	MH	GI	CI	CI	CS	CS	CS	CS
	99.6±0.2 % / 99.4±0.3 %	17.0±0.7	6.0±0.7	31.2±2.5	131.2±0.2	2.9	298.3±0.7	2.9
4	DI	DI	CS	GI	CI	CI	CI	CI
	99.2±0.1 % / 99.1±0.1 %	24.8±0.8	6.7±0.5	55.6±0.1	171.5±0.1	3.9	392.7±0.3	3.9
5	GI	FI	GI	DS	DS	DS	DS	DS
	97.6±0.3 % / 94.8±0.3 %	28.8±0.8	6.8±0.8	58.5±0.0	204.0±0.1	4.6	587.1±0.7	5.7
6	CS	NB 6	DI	MH	GS	GS	GS	GS
	98.5±0.1 % / 92.0±0.5 %	35.9±4.0	9.6±0.5	61.2±7.9	205.0±0.1	4.6	590.8±0.4	5.8
7	DS	MH	GS	GS	FS	FS	FS	FS
	92.5±0.1 % / 85.5±0.2 %	47.8±6.6	26.0±0.8	66.3±0.1	205.2±0.1	4.6	592.5±1.3	5.8
8	GS	DS	FI	DI	GI	GI	GI	GI
	92.2±0.2 % / 84.9±0.2 %	90.0±0.8	26.5±0.5	66.9±0.8	222.0±0.3	5.0	594.2±1.4	5.8
9	FS	GS	FS	FS	DI	DI	DI	DI
	91.5±0.2 % / 83.1±0.2 %	95.0±0.8	27.0±0.8	71.6±0.5	229.6±0.1	5.2	625.0±0.6	6.1
10	FI	FS	DS	FI	FI	FI	FI	FI
	91.0±0.7 % / 90.0±0.8 %	96.0±0.2	30.0±0.8	73.7±0.3	243.9±0.4	5.5	682.1±1.9	6.7

new data packet; thus, the average sleep time shows only a small decrease (e.g., from 8.1 ± 0.0 mJ/s to 8.0 ± 0.0 mJ/s). Data packet transmissions constitute 82.4 percent of the transmit energy dissipation; IS packet transmissions and all the other control packet transmissions follow with 7.5 percent and 10.1 percent, respectively. The NB-TRACE transmit energy dissipation is 41 percent of the transmit energy dissipation of MH-TRACE flooding due to the reduction in the ARN. NB-TRACE with data dissipates more energy on receive and carrier sensing and less in the idle mode when compared with the zero traffic case because the IS slots are not inactive anymore. For the same reason, MH-TRACE-based flooding energy dissipation in the receive and carrier sense modes are higher and the idle mode is lower than NB-TRACE.

To observe the effects of the various blocks of NB-TRACE, we ran simulations with several subsets of the five blocks (see Table 2). NB-TRACE 3B and NB-TRACE 4B use the first three (i.e., IFL, PRN, and RPB) and four blocks (i.e., IFL, PRN, RPB, and CRB), respectively. NB-TRACE's 3B average and minimum PDR are 82.0 percent and 24.5 percent, respectively. The main reason for such low PDRs is the lack of block 4 (CRB). NB-TRACE 4B has approximately the same average PDR as the full NB-TRACE (99.4 percent); however, the minimum PDR of NB-TRACE 4B, 96.9 ± 2.5 percent, is slightly lower than full NB-TRACE, which is due to the inactive distributed gateway situation. Total energy dissipation per node per second of NB-TRACE 4B, 43.5 mJ/s, is 2.3 percent less than that of full NB-TRACE, 44.5 mJ/s, due to the ACB block, which quantifies the extra energy dissipation caused by the ACB block.

To illustrate the validity of our concern about the single packet drop threshold, we ran a simulation where we set $T_{drop\text{-}source}$ to T_{drop} (150 ms). The results, listed in Table 2, show that the average and minimum PDRs of NB-TRACE with $T_{drop\text{-}source} = 150$ ms are 89.2 percent and 68.4 percent, respectively, and the average packet delay is 93.6 ms. The reason for such behavior is that a significant portion of the data packets transmitted by the source node have delays close to T_{drop} and, after one or two hops, they are dropped.

Table 3 presents the performance comparisons and rankings of broadcast architectures with the best performance configurations, which are determined through simulations. Random assessment delay, T_{RAD}, is chosen, approximately, as half the packet generation period, T_{PG}, so that a broadcasting node will not contend against another node for the next packet within its two-hop radius. SMAC sleep/active cycle period, T_{SMAC}, is matched to T_{PG}, so that data packets are not accumulated in the queue (i.e., if T_{SMAC} is longer than T_{PG}, then a node needs to send two packets during one active period and packet delay increases). The SMAC sleep/active ratio, R_{SMAC}, is chosen as 0.25, so that SMAC can save energy without decreasing system performance (i.e., higher R_{SMAC} results in lower effective bandwidth and higher energy savings). Gossiping with IEEE 802.11 and SMAC PDRs (average and minimum) reach their maximums at $p_{GSP} = 0.7$ and $p_{GSP} = 0.9$, respectively. Higher and lower p_{GSP}s result in lower PDRs due to the higher collision rates and incomplete coverage, respectively. CBB with IEEE 802.11 and SMAC have the highest PDRs with $N_{CBB} = 3$ and $N_{CBB} = 2$, respectively. We simulated DBB with 20 m D_{DBB} steps to pick the best configurations. DBB with IEEE 802.11 and SMAC PDRs are maximized with $D_{DBB} = 200$ m and $D_{DBB} = 220$ m, respectively.

We use short acronyms (see Table 4) for the architectures to be able to fit them into a single table. In terms of PDR, jitter, ARN, and energy efficiency, NB-TRACE is either the best or as good as all the other architectures. The ARN and energy saving performance of NB-TRACE is especially superior to the other schemes. However, NB-TRACE delay is not among the best. In fact, NB-TRACE packet delay is ranked in the second half of all the architectures. Nevertheless, for the scenario we considered in this section, NB-TRACE delay does not create a vital problem since it is still

TABLE 4
Acronyms and Descriptions for the Broadcast Architectures Presented in Table 3

Acronym	Description
NB	NB-TRACE
MH	MH-TRACE-based flooding
CI	CBB with IEEE 802.11 and $N_{CBB} = 3$
DI	DBB with IEEE 802.11 and $D_{DBB} = 200$ m
GI	Gossiping with IEEE 802.11 and $p_{GSP} = 0.7$
FI	Flooding with IEEE 802.11
CS	CBB with SMAC and $N_{CBB} = 2$
DS	DBB with SMAC and $D_{DBB} = 220$ m
GS	Gossiping with SMAC and $p_{GSP} = 0.9$
FS	Flooding with SMAC

below the packet drop threshold. CBB with IEEE 802.11 is the architecture with the lowest packet delay. Furthermore, it is the second best architecture, overall.

NB-TRACE, MH-TRACE-based flooding, CBB with IEEE 802.11, and DBB with IEEE 802.11 are the broadcast architectures that achieved higher than 99 percent minimum PDR. CBB with SMAC and Gossiping with IEEE 802.11 average PDRs are above 95 percent; however, their minimum PDRs are below 95 percent, which are below acceptable limits. All the other architectures with flooding and SMAC produced average and minimum PDRs below 95 percent. Thus, regardless of the other metrics, only the top four architectures (NB-TRACE, MH-TRACE-based flooding, and CBB and DBB with IEEE 802.11) are within acceptable QoS limits.

The top two minimum delay broadcast architectures are CBB with IEEE 802.11 and SMAC, which have average packet delays of 11.5 ms and 12.3 ms, respectively. The second group is formed by Gossiping with IEEE 802.11 and DBB with IEEE 802.11, which have average packet delays of 17.0 ms and 24.8 ms, respectively. The third tier consists of Flooding with IEEE 802.11, NB-TRACE, and MH-TRACE, which have packet delays of 28.8 ms, 35.9 ms, and 47.8 ms. The largest delay group is all other SMAC architectures: DBB with SMAC, Gossiping with SMAC, and Flooding with SMAC, which have packet delays of 90.0 ms, 95.0 ms, and 96.0 ms, respectively.

NB-TRACE and MH-TRACE are the top two in jitter rankings with 2.1 ms RMS jitter. The second group is formed by CBB with IEEE 802.11 and SMAC, Gossiping with IEEE 802.11, and DBB with IEEE 802.11, ranging from 6.0 ms to 9.4 ms. The highest jitter is observed for Gossiping with SMAC, Flooding with IEEE 802.11, Flooding with SMAC, and DBB with SMAC, ranging from 26.0 ms to 30.0 ms.

NB-TRACE and CBB with SMAC ARNs are the lowest among all the architectures, at 19.2 and 23.2, respectively. CBB with IEEE 802.11 ARN is the third lowest, 31.2, and all the other ARNs are distributed between 55.6 and 73.7. As expected, Flooding with IEEE 802.11 has the highest ARN, 73.7.

In Table 3, we present energy dissipation results with two different energy models, described in Section 5.1. In both energy models, NB-TRACE and MH-TRACE are the two lowest energy dissipating architectures. CBB with SMAC and CBB with IEEE 802.11 energy dissipations are in between the first group formed by NB-TRACE and MH-TRACE and the highest energy dissipation group formed by the rest of the architectures. The relative energy efficiency of NB-TRACE is better with the second energy model than the first energy model, which is our default model, yet energy dissipation rankings are not affected by the energy model change. Energy dissipation distributions of the broadcast architectures are presented in Fig. 10. All of the distributions are approximately centered around their average energy dissipation values, thus, average energy dissipation is a sufficient statistical metric to evaluate the energy dissipation characteristics of these architectures. Furthermore, NB-TRACE distribution is well separated from the non-MH-TRACE-based distributions. For example, the highest energy dissipating node of NB-TRACE will live at least twice as long as the lowest energy dissipating

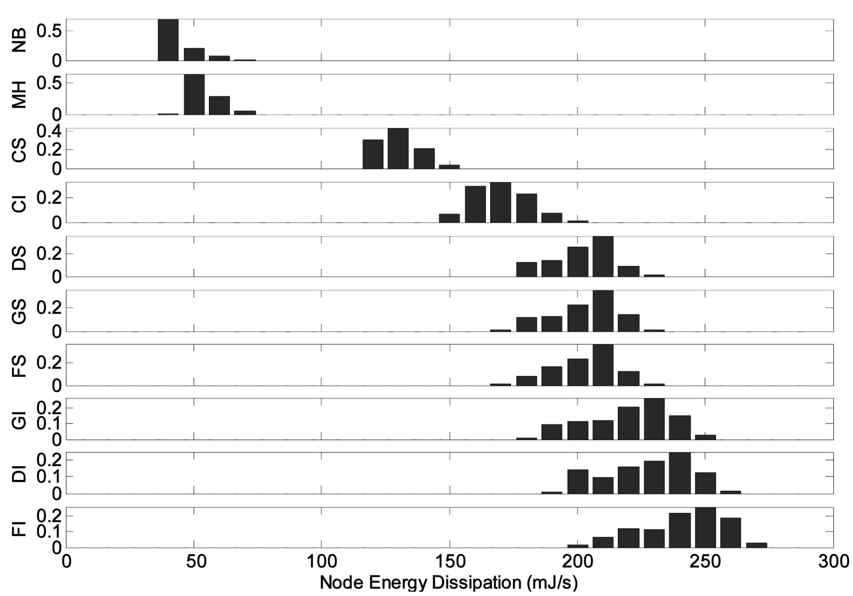


Fig. 10. Normalized histograms of node energy dissipations for different broadcast architectures.

TABLE 5
NB-TRACE Parameters: Number of Frames per Superframe, N_F, Number of Data Slots per Frame, N_D, and Data Packet Payload

Data Rate	N_F	N_D	Payload
16 Kbps	6	9	50 Bytes
32 Kbps	6	6	100 Bytes
48 Kbps	6	4	150 Bytes
64 Kbps	6	3	200 Bytes
80 Kbps	6	3	250 Bytes
96 Kbps	6	2	300 Bytes

node of CBB with SMAC, which is the lowest energy dissipating non-MH-TRACE-based architecture.

Having completed our analysis for this particular set of parameters (i.e., data rate and node density), we now investigate the effects of varying the data rate on NB-TRACE. For the rest of the simulations, we compare the performance of NB-TRACE with CBB with IEEE 802.11 and DBB with IEEE 802.11 only, since these architectures are the only other architectures that produced acceptable QoS, except MH-TRACE-based flooding. Since network conditions get harsher with increasing node density and/or data rate, the already unacceptably low performance of the other architectures will deteriorate further.

5.3 Varying the Data Rate

In this section, we explore the effects of varying the data rate on the protocol performance. The data rate is varied by changing the size of the data packets by keeping the packet generation period constant. NB-TRACE parameters (e.g., number of frames within a superframe, N_F, and number of data slots per frame, N_D) are reconfigured with the changing data packet sizes (see Table 5). The number of frames and the number of data slots per frame along with other parameters (e.g., the number of contention slots) are adjusted to keep the superframe time approximately 25.0 ms.

NB-TRACE, CBB, and DBB performances as a function of data rate are presented in Table 6 for an 80 node 1 km by 1 km network. NB-TRACE average and minimum PDR stays above 95 percent for all data rates. The drop in PDR with increasing data rate is due to the small number of data slots per CH, which limits the operation characteristics of NB-TRACE. For example, the number of data slots that can be utilized in response to an ACB request decreases with increasing data rate. NB-TRACE ARN stays almost constant around 19.0 for all data rates. Both delay and jitter slightly increase with increasing data rate.

There are two factors affecting the energy dissipation of NB-TRACE: a decrease in the number of data slots, which also means a decrease in the number of IS slots and total IS time, and an increase in the amount of data transmitted and received with increasing data rate. Higher data traffic means a reduction in the total amount of time spent in the IS period, where nodes spend less energy when compared to a longer IS period. Remember that all of the nodes stay in active mode during the IS slots. Thus, the energy dissipated in the IS slots, which is a significant component of the energy dissipation in NB-TRACE, decreases with increasing data rate. On the other hand, energy dissipated on the transmission and reception of data packets increases with the increasing data rates because the packet length (amount of data) increases. Note that the number of data packets generated per packet generation time stays constant for all data rates, and each node receives at most one copy of each

TABLE 6
Performance of NB-TRACE and CBB as a Function of Data Rate

	Data Rate (Kbps)	16	32	48	64	80	96
NB-TRACE	PDR (Avg/Min)	99.9±0.1 % / 99.9±0.1 %	99.8±0.1 % / 99.7±0.2 %	99.7±0.3 % / 99.4±0.3 %	99.5±0.4 % / 98.4±0.5 %	99.4±0.5 % / 96.7±0.5	98.4±1.1 % / 95.6±0.5
	ARN	19.1±0.9	19.2±1.5	19.1±1.2	19.0±1.3	19.6±0.7	18.7±0.2
	Delay / Jitter (ms)	35.6±3.5 / 2.1±0.1	35.9±4.0 / 2.1±0.1	36.5±4.3 / 2.1±0.1	37.1±3.7 / 2.1±0.1	37.0±3.8 / 2.2±0.2	39.4±4.2 / 2.5±0.5
	Energy (mJ/s)	45.9±0.7	44.5±1.1	44.1±0.7	46.1±0.6	47.7±0.5	50.8±0.8
CBB	PDR (Avg/Min)	99.9±0.1 % / 99.9±0.1	99.7±0.2 % / 99.3±0.3	99.6±0.3 % / 98.3±0.3	92.6±0.3 % / 88.8±0.4	90.2±0.4 % / 87.5±0.5	90.0±0.4 % / 81.5±0.5
	ARN	28.9±0.1	31.2±0.3	36.2±0.1	52.7±0.2	58.8±0.4	59.2±0.2
	Delay / Jitter (ms)	9.93±0.2 / 6.0±0.3	11.5±0.3 / 6.0±0.3	12.6±0.6 / 6.0±0.5	64.3±1.0 / 19.2±0.9	95.7±0.5 / 23±1.2	106.0±0.8 / 25.2±1.3
	Energy (mJ/s)	136.9±0.1	171.5±0.2	212.8±0.2	267.4±0.1	274.5±0.2	276.9±0.1
DBB	PDR (Avg/Min)	99.9±0.1 % / 99.9±0.1 %	99.2±0.1 %/ 99.1±0.1 %	98.2±02 % / 98.0±0.2 %	95.3±0.2 % / 92.2±0.7 %	91.3±0.4 % / 84.0±0.9	88.0±0.5 / 75.7±0.9
	ARN	67.3±0.1	66.9±0.8	66.1±0.2	64.0±0.2	60.8±0.3	58.0±0.1
	Delay / Jitter (ms)	12.1±0.1 / 5.0±0.1	24.8±0.8 / 9.6±0.5	61.0±0.8 / 22.7±0.5	92.0±0.9 / 27.3±0.5	102.3±1.1 / 28.0±0.7	106.1±1.0 / 29.3±0.9
	Energy (mJ/s)	178.6±0.1	22.9.6±0.1	262.8±0.2	272.0±0.1	274.4±0.1	278.3±0.1

TABLE 7
Performance of NB-TRACE, CBB, and DBB as a Function of Node Density

	Node Density (nodes / km^2)	80	120	160	200
NB-TRC	PDR (Avg/Min)	99.7±0.3 % / 99.4±0.3 %	99.6±0.2 % / 98.7±0.5	99.4±0.5 % / 97.5±1.3	99.5±0.4 % / 97.8±1.5
	ARN	19.1±1.2	23.2±0.6	23.4±0.9	23.7±1.4
	Delay / Jitter (ms)	36.5±4.3 / 2.1±0.1	36.0±1.0 / 2.0±0.1	36.5±1.2 / 2.0±0.1	36.3±0.9 / 2.0±0.1
	Energy (mJ/s)	44.1±0.7	43.3±0.5	42.7±0.4	41.9±0.3
CBB	PDR (Avg/Min)	99.6±0.3 % / 98.3±0.3	90.3±0.3 % / 85.0±1.0	82.2±1.2 % / 73.2±1.2	85.3±0.1 % / 82.8±0.3 %
	ARN	36.2±0.1	60.8±1.4	81.6±1.5	99.9±0.2
	Delay / Jitter (ms)	12.6±0.6 / 6.0±0.5	44.2±3.3 / 12.7±0.9	83.0±0.7 / 21.9±0.7	95.7±0.5 / 22.0±0.8
	Energy (mJ/s)	212.8±0.2	249.2±1.3	260.6±0.2	262.0±0.1
DBB	PDR (Avg/Min)	98.2±02 % / 98.0±0.2 %	93.9±0.1 % / 90.5±0.1	91.7±0.2 % / 82.3±0.4 %	88.7±0.1 % / 77.9±0.4 %
	ARN	66.1±0.2	89.9±0.1	115.1±0.2	141.4±0.1
	Delay / Jitter (ms)	61.0±0.8 / 22.7±0.5	93.3±1.2 / 26.3±0.7	103.3±0.5 / 29.1±1.0	106.7±2.1 / 30.3±0.5
	Energy (mJ/s)	262.8±0.2	266.9±0.1	269.2±0.3	270.7±0.1

generated packet. Furthermore, the number of packet transmissions also stays almost constant (i.e., ARN) for all data rates. Thus, when these two mechanisms are combined, the total per node energy dissipation decreases in the first half of the data rate space, reaching 44.1 mJ/s at 48 Kbps and increases in the second half, reaching 50.8 mJ/s at 96 Kbps. Nevertheless, the variation of the energy dissipation lies in a narrow band.

For all data rates, the rebroadcast counter of CBB, N_{CBB}, is three. Higher values of N_{CBB} resulted in unacceptable PDRs due to the increase in congestion with a higher number of retransmissions, whereas lower values of N_{CBB} failed to create a complete set cover.

Average and minimum PDRs of CBB are lower than 95 percent starting with 64 Kbps, reaching 90.0 percent and 81.5 percent, respectively, at 96 Kbps data rate due to the increase in the congestion level of the network, which causes an increase in the average number of data collisions per transmission and the average number of dropped data packets per second.

The increase in ARN of CBB is also due to collisions. Nodes that cannot receive a packet due to collisions cannot increment their counter, which gives rise to the number of rebroadcasts and an increase in ARN. Actually, packet drops do not decrease the PDR of CBB; instead, if there were no packet drops, then the average PDR of CBB would be lower than its current value for higher data rates due to the reduction in the congestion by dropping packets.

CBB average delay exhibits two regimes: 1) low data rate regime, where CBB packet delay is a small fraction of the NB-TRACE packet delay due to the low level of congestion and 2) high data rate regime, where the balance is reversed (i.e., NB-TRACE delay is a small fraction of CBB delay) due to the high level of congestion. CBB RMS jitter also shows a similar trend with CBB packet delay for the same reasons mentioned; however, at all data rates, NB-TRACE jitter is a small fraction of CBB jitter. The increase in the CBB energy dissipation is due to the higher number of larger packet transmissions, receptions, and carrier sensing with the increasing traffic. CBB energy dissipation at 16 Kbps and 96 Kbps data rates are 3.0 and 5.5 times the energy dissipation of NB-TRACE, respectively.

For all data rates, the minimum rebroadcast distance of DBB, D_{DBB}, is 200 m. DBB minimum PDR drops below 95 percent starting with 64 Kbps data rate, reaching 75.7 percent at 96 Kbps data rate. Unlike CBB, DBB ARN drops with increasing data rate, reaching 58.0 at 96 Kbps data rate. DBB delay, jitter, and energy dissipation trends are similar to CBB.

With the current implementation, NB-TRACE parameters need to be tuned for the data rate chosen. One way to alleviate this restriction is to keep the data slot length small and assign multiple data slots for higher data rate applications, which is similar to IEEE 802.15.3 [18] channel access. However, in a real deployment, most probably all nodes are equipped with the same rate voice codecs, thus, all nodes can be tuned for the same parameters.

5.4 Varying the Node Density

Next, we investigate the effects of node density on NB-TRACE and CBB. Table 7 presents the performance of NB-TRACE and CBB as a function of node density for a constant data rate source (48 Kbps) within a 1 km by 1 km area network. NB-TRACE average and minimum PDR stays above 95 percent for all node densities. The increase in ARN is due to the fact that the average number of CHs increases slightly with increasing node density. NB-TRACE average packet delay and delay jitter stay in a narrow band around 36.0 ms and 2.1 ms, respectively. The energy dissipation of NB-TRACE shows a slight decrease with node density, starting at 44.1 mJ/s for an $80\ \mathrm{nodes/km^2}$ network and reaching 41.9 mJ/s for a $200\ \mathrm{nodes/km^2}$ network.

CBB gives the highest PDRs with $N_{CBB} = 3$ for the results presented in this section, for the same reason described in the previous section. Similarly, D_{DBB} is set to 200 m. CBB and DBB average and minimum PDRs drop below 95 percent starting with the $120\ \mathrm{nodes/km^2}$ network because of the high congestion. Average delay and jitter values of CBB and DBB show a steep increase with increasing node density. NB-TRACE delay is less than 38 percent of CBB delay and jitter is less than 10 percent of CBB jitter at the $200\ \mathrm{nodes/km^2}$ network.

5.5 Summary

We have presented a simulation-based comparative evaluation of NB-TRACE and other broadcast architectures. Detailed investigation of NB-TRACE revealed the relative impact of the different building blocks and design trade-offs of the NB-TRACE architecture. Furthermore, the performance gains of NB-TRACE over MH-TRACE-based flooding in terms of spatial reuse and energy efficiency were quantified. Comparisons with other broadcast architectures showed that NB-TRACE performance in terms of energy efficiency, jitter, PDR, and ARN is better than the other architectures and delay performance is worse than several other architectures at low node density and low data rate networks. However, with increasing node density and/or data rate networks, the relative delay performance of NB-TRACE becomes better than the other architectures due to the deterioration of the performance of these architectures and the relative stability of NB-TRACE with harsher network conditions.

6 Conclusions

In this paper, we presented NB-TRACE, an energy and spatial reuse efficient network-wide broadcasting architecture. We investigated the performance of NB-TRACE and compared it with nine other broadcast architectures through extensive simulations. The contributions and results of this study are itemized as follows:

1. Although there has been much research that aims to reduce the energy consumption in network-wide broadcasting, most of this work is targeted at reducing transmit energy dissipation only. On the other hand, NB-TRACE is a completely distributed algorithm, and it is targeted at reducing the total energy dissipation, which consists not only of transmit energy dissipation, but receive, carrier sense, idle, and sleep energy dissipation terms as well. Although transmit energy dissipation is the dominant energy dissipation term in some energy models where transmit power is several orders higher than receive power, for the energy models we utilized, which are experimentally obtained from two actual radios, it is shown that transmit energy dissipation is not the dominant component of the total energy dissipation.
2. NB-TRACE is capable of satisfying the requirements of voice QoS (e.g., PDR, delay, and jitter) under a wide range of parameters, such as data rate and node density, because of

    a. the robustness of its distributed broadcast tree creation and maintenance algorithm,
    b. the explicit local coordination provided by the underlying MAC protocol, which does not create hard boundaries within the network and guarantees the availability of an underlying nonconnected dominating set,
    c. the cross-layer design, which enables the full integration of the network and MAC layers, and
    d. the distributed realization of the automatic renewal of channel access in a mobile ad hoc network and incorporating this into the tree creation and maintenance procedures.
3. NB-TRACE energy dissipation is much lower than the other schemes because of

    a. the coordinated channel access, which enables the nodes to switch to sleep mode whenever they are not involved with control or data packet traffic,
    b. packet discrimination, which enables nodes to avoid receiving redundant data packets, and
    c. a comparatively lower number of rebroadcasts per generated data packet (ARN), which eliminates redundant data transmissions.
4. NB-TRACE packet delay is larger than some of the other broadcast architectures (CBB with IEEE 802.11 and SMAC, Gossiping with IEEE 802.11, DBB with IEEE 802.11, and Flooding with IEEE 802.11) in low node density and low data rate networks because of the restricted channel access in NB-TRACE (i.e., nodes can only access the channel during their reserved data slots). However, this mechanism enables NB-TRACE to keep the average packet delay approximately constant for a wide range of parameters (e.g., data rate and node density). In dense and/or high data rate networks, NB-TRACE packet delay is lower than both CBB and DBB with IEEE 802.11, because packet delay in these architectures exhibits a steep increase with the increasing congestion level of the network, which is related with node density and data rate.
5. NB-TRACE jitter is significantly lower than the other schemes, except MH-TRACE-based flooding. The main reason for such a low level of delay jitter is the automatic renewal of channel access (i.e., once a node successfully contends for channel access, it is granted channel access automatically by the CH as long as it continues to utilize its granted data slot).
6. NB-TRACE spatial reuse efficiency is better than the other architectures, especially in highly congested networks, because of the robustness of the channel access and the full integration of the network and MAC layers. On the other hand, other network layer broadcast algorithms, which have high spatial reuse efficiency in low traffic load networks, lose their efficiencies in high traffic load networks because of the congestion created by the medium access control layer. For example, at high node density or high data rate networks, CBB ARN exhibits a steep increase because of the fact that the collisions due to the underlying IEEE 802.11 MAC layer prevent CBB from getting correct channel information, which gives rise to the number of retransmissions. Actually, the network layer tries to compensate for the packet collisions by increasing the retransmissions; however, the increase in the network layer rebroadcast attempts worsens the situation. Thus, the primary reason for the higher ARN of CBB in high data rate and high node density networks is the IEEE

802.11 MAC, which fails to prevent excessive collisions and causes congestion. The secondary reason is the lack of sufficient integration between the network layer (CBB) and the MAC layer (IEEE 802.11).

7. NB-TRACE energy savings are directly related to the energy model utilized (i.e., characteristics of the radio). For example, NB-TRACE energy dissipation will be approximately the same as the other schemes for a radio that does not support a low energy sleep mode. Nevertheless, NB-TRACE continues to be an energy efficient architecture with a radio that supports a comparatively low power sleep mode.

Our future work will concentrate on extending the TRACE framework to multicasting and unicasting. Most of the building blocks of NB-TRACE can easily be used for both multicasting and unicasting by minor modifications. For example, IFL and PRN blocks can be used as they are with slight modifications to the contents of the IS packets for the initial route discovery in unicasting and for initial multicast-tree construction in multicasting. Furthermore, by transferring the role of CHs in NB-TRACE to multicast group members, it is possible to obtain a multicasting scheme. In fact, our initial design and simulation of such a multicasting architecture produced satisfactory system performance. NB-TRACE is the third member of the TRACE family of protocol architectures and each new addition is designed to support the functionalities of the former.

In this study, we assumed a perfect channel with no error models. However, in a realistic environment, channel errors are unavoidable. An evaluation of MH-TRACE performance under a realistic channel error model has shown that the performance of MH-TRACE stays better than IEEE 802.11, even under very high error rates [41]. Characterization and improving the fault tolerance of NB-TRACE are also among our ongoing research efforts.

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