Group Leader Election under Link-State Routing

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Abstract

In this work, we place a long-established distributed computing problem in a new context. Specifically, the group leader election problem is studied "inside the network," meaning that participants in the election process are network switches/routers, rather than hosts. In this context, an election protocol can take advantage of certain internal operations of the network, such as the underlying routing protocol, in order to meet stringent fault-tolerance criteria while minimizing network traffic overhead.

A generic and robust solution to the problem, called the Network Leader Election (NLE) protocol, is proposed for use in networks that are based on link-state routing (LSR). The NLE protocol is "generic," in that it is independent of the leader selection policy, enabling it to support a variety of network services. The protocol is robust, for it achieves leadership consensus in the presence of adverse events, such as leader failures and network partitioning. The correctness of the protocol is proved formally. A simulation study reveals that the NLE protocol incurs low overhead in handling leader failures and in group creation. In addition, it is shown how important network functions, in both the Internet and ATM networks, can benefit from the NLE protocol. These functions include, but are not limited to, routing domain leader election, address resolution, and multicast core management.

Keywords: leader election, ATM networks, link-state routing, multicast communication

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1 Introduction

The problem of leader election concerns the selection of a distinguished member from a set of computing systems that are interconnected by a network. This problem has been extensively studied in the context of distributed computing systems, for example, in coordinating access to shared resources [1] and in implementing fault-tolerant objects [2]. Generally speaking, solutions to the problem are distributed "host-level" algorithms that make use of various services provided by the network, such as reliable delivery of messages, in order to monitor the working status of the established leader or cast ballots for a new leader. Well-known contributions in this area include the Bully algorithm [3] and the Ring algorithm [4]; more recent developments are described in [5].

In this paper, we address the leader election problem as it occurs "inside" the network. The participants in the election process are assumed to be switches (or, interchangeably, routers)[1], rather than hosts or application processes. Solutions to this problem are intended to support underlying network functions, as opposed to being directly invoked by user applications. Whereas a host-level election protocol typically considers the underlying network as a "black box," a *network-level* election protocol can see and take advantage of the internal operation of the network, in particular, the underlying routing protocol.

Network functions that can make use of an efficient leader election protocol are several. In this paper, we focus on three examples. First, in Asynchronous Transfer Mode (ATM) networks and other hierarchical networks, switches in a low-level subnetwork (called a routing domain) select a switch to represent the domain in the next routing level [6]; a solution to this *domain leader election problem* supports routing operations within the network. Second, many address-mapping services, such as the mapping between group addresses and member addresses [7] and the mapping between network addresses and link-layer addresses [8], use a central server approach; a solution to the *server assignment problem* selects a leader to undertake the server responsibilities. Third, some IP multicast protocols, such as CBT [9] and PIM [10], identify a network node, called a core node, as the traffic transit center for each multicast group; a solution to this *multicast core management problem* supports multicast services provided by the network. A common requirement of solutions to the above problems

[1] We will not distinguish the two terms in this work, despite the fact that one of them may be preferred over the other under certain contexts of discussion.

is fault tolerance: since network functions/services are expected to survive not only single-point failures, but also component failures that may partition the network, the solution to these problems must also survive these adverse scenarios.

Our proposed solution, called the Network Leader Election (NLE) protocol, is based on *link-state routing* (LSR) [11, 12], an increasingly popular type of network routing. An LSR protocol makes complete knowledge of the network available to all switches. For this purpose, the local status of each switch, including the bandwidth available at incident links, buffer capacity, delays across links, and so forth, is learned by the network via the broadcasting, or *flooding*, of link-state advertisements (LSAs). Based on received advertisements, each switch locally maintains a complete image of the network, which it uses to make routing decisions. One of the major advantages of LSR is its fault tolerance. Since every link is monitored by its incident switches, and every switch is monitored by neighboring switches, malfunctioning components and congested areas are made known to all functioning switches promptly. Even the earliest LSR protocols were able to survive disastrous situations, such as network partitioning [12]. The Open Shortest Path First (OSPF) protocol [11], introduced by the Internet community, is one of the most well-known LSR unicast protocols. LSR has also been adopted as the routing standard for ATM networks [6].

The proposed NLE protocol extends LSR to include group-leader binding LSAs, which are used by group members to advertise their choice of leader to the rest of the group. Upon receiving such an LSA, other switches in the network either accept this selection, or choose and advertise an alternative leader. The objective of the NLE protocol is to achieve network consensus on leader bindings, even in presence of adverse conditions. The efficiency of the protocol stems from the use of timestamps to identify obsolete advertisements. We argue that previous solutions to the network-level group leader election problem either do not meet the stringent fault tolerance criteria discussed above, or are more costly (in terms of bandwidth consumption and switch workload) when compared to the NLE protocol. As an extension to LSR, the NLE protocol achieves the following properties in fault tolerance.

1. **[Leadership Consensus Property]** Given a group G and a network that has been partitioned into a set of segments $S_1, S_2, \ldots, S_k$, $k \geq 1$, there will be consensus on the leader within each segment S_i, and that leader will be an operational switch within the segment.

2. [**Mutual Consensus Property**] By requiring group members to report to the established leader, the NLE protocol ensures that, within each network segment S_i, the established leader maintains a member list for the group that includes those, and only those, group members in S_i.

It is to be noted that, when the network is not partitioned, the above consensus properties hold throughout the network. Simply put, the NLE protocol can handle leader failures and work properly under catastrophic scenarios such as network partitioning. Results of a simulation study show that these features can be achieved with minimum protocol overhead.

The remainder of this paper is organized as follows. Section 2 reviews the operation of LSR and the current ATM domain leader election protocol. The design of the NLE protocol is presented in Section 3, and the correctness of the protocol, which is modeled as a consensus problem under LSR, is formally proved in Section 4. The performance of the NLE protocol and the ATM domain leader election protocol are compared via simulation in Section 5. In Section 6, we discuss the application of the NLE protocol to the address resolution problem and to the multicast core management problem; included are simulation results regarding the performance of NLE in creating multicast groups. Finally, conclusions are given in Section 7.

2 Background

In this section, we review the operation of LSR, as well as a previous network-level leader election method, the ATM domain leader election protocol, that satisfies the two consensus properties discussed in the previous section.

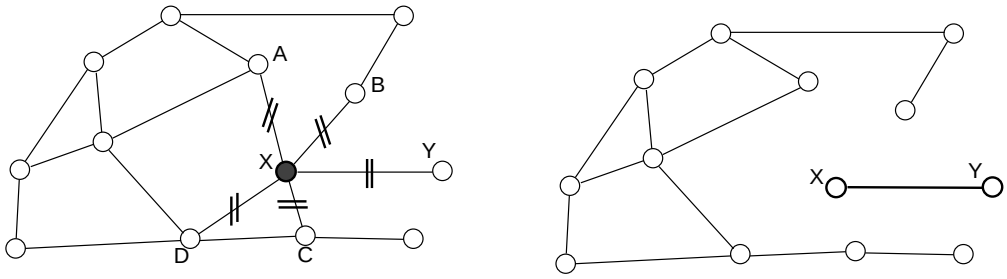
2.1 Link-State Routing

A routing protocol disseminates network information so that switches, when required to relay communication traffic, are able to find paths to reach respective destinations. In the case of LSR, complete knowledge of the network is made available at all switches. For this purpose, every switch broadcasts throughout the network its local state, including the ID of the switch, buffer capacity at the switch, links incident to the switch, bandwidth of individual links, and so forth. For historical reasons, these local status broadcasts are termed *link-state*

advertisements (LSAs) [12]. After constructing an image of the network based on received LSAs, each switch x computes a shortest path from itself to every other node in the network. Since the network images must be updated in response to network dynamics, every switch constantly monitors its local state and immediately advertises any changes. For example, when a link fails, the value of its working state changes from ON to OFF, producing a *link-down* LSA from each of the two switches connected to that link. Similarly, *link-up* LSAs will be flooded when the link later returns to a functional state.

Although it may be tempting to represent the states of switches in a similar manner to that of links (for example, "switch-up/switch-down" LSAs), such states are not defined in LSR. The reason is that an LSR protocol cannot distinguish a failed node from one that becomes unreachable due to failed links. To illustrate, let us consider the example shown in Figure 1(a). Assume that node X has crashed. The five switches that are neighbors of X (A, B, C, D, and Y) detect the lack of response on the five links incident to X, and subsequently flood five link-down LSAs. The network as perceived by switch A (and any other switch other than X and Y) after the link-down LSAs have been flooded is depicted in Figure 1(b). Switch A will receive only four of the link-down LSAs because switch Y, which advertises the failure of the (X, Y) link, has been isolated from the rest of the network. As shown, the configuration stored at switch A does not reflect the true state of the network. This example illustrates that an LSR protocol cannot determine whether a switch has failed or not. Instead, the protocol should be concerned with "reachability" of the switch. As we shall see, the NLE protocol relies on the underlying LSR protocol to provide such "leader reachability" information that is needed in handling leader failures and network partitions. Likewise, member reachability information is used by the leader to handle member failures.

We emphasize that LSR-based protocols, including the NLE protocol, are not intended for direct implementation in very large networks or internets. LSR itself is generally intended for use in a set of networks under one routing domain, or one administrative authority (in Internet terminology, an *Autonomous System*) which typically contains a few hundred switches and possibly several thousand hosts. In order to apply such protocols to larger networks, a routing hierarchy can be introduced. The combination of an LSR protocol and a routing hierarchy has been adopted by the ATM PNNI standard [6] to cope with large networks, as discussed next.



(a) Node X crashes.

(b) The perception of the network at nodes other than X and Y.

Figure 1. Indeterministic of node failure.

2.2 Domain Leader Election in ATM Networks

ATM is a connection-oriented communication technology that relays small fixed-size cells in hardware. In ATM networks, a traffic source must set up a connection to the destination before sending data. The connection setup procedure invokes a routing mechanism to determine a path between a given source and destination. Inevitably, the overhead of routing increases when the size of a network grows. As a telecommunications standard, ATM must adopt a hierarchical routing method to cope with networks that are national or even global in scope. In this approach, a large network is divided into segments, called *routing domains*, and the routing decision is divided into two levels, high-level inter-domain routing and low-level intra-domain routing. Given a source/destination pair, inter-domain routing determines a path comprising a series of domains from the source domain to the destination domain. Within each domain on this path, intra-domain routing determines a path that comprises a series of switches that connect the two domains on either side. In the ATM Private Network-Network Interface (PNNI) standard [6], switches in a domain use LSR to perform intra-domain routing, and elect a leader switch to represent the domain in inter-domain routing.

The domain leader election problem is a special case of the network-level group leader election problem. In the domain leader election problem, group membership (that is, identifying a set of switches to constitute a domain) is manually configured by administrators, and all switches in a routing domain participate in election. Further, to continue operation

in the presence of domain leader failures and network partitioning scenarios, any solution to the problem must maintain the leadership and mutual consensus properties as defined earlier.

The domain leader election protocol defined in the current ATM standard [6] is LSR-based. In this protocol, each switch maintains two election-related states: *leader priority* and *preferred leader*. The former is manually configured to determine the rank of the switch. The latter is determined by switches as follows: Every switch independently searches its local database for the switch that has the highest leader priority in the domain; this switch is its preferred leader. Any change in the preferred leader state will be advertised throughout the network immediately. If a switch identifies itself as the preferred leader, after waiting for a period of time, it inspects its local database for the preferred leaders of the other switches. When unanimity is achieved, the candidate will advertise its leader status.

As an example, let us consider a network where the administrator configures a default leader X with leader priority 3 and a backup leader Y with priority 2. The remaining switches are configured with priority 1. We assume that the leadership of X has been established, that is, the current preferred leaders of all switches are X. Now consider what happens when the leader X fails. In this case, neighboring switches of X notice the unresponsiveness of X-incident links and flood link-down LSAs. With these LSAs, every operational network switch finds X unreachable, and searches through its local database for a switch with the next highest priority. In this example, the result would be Y with priority 2. All switches change their preferred leader to Y and advertise this information. These advertisements could be considered as "ballots," which the switch Y must collect before claiming itself the new leader.

As illustrated in the previous example, the current ATM election protocol can handle leader failures. Further, if every switch periodically advertises its preferred leader, then the protocol achieves the leadership and mutual consensus properties under any combination of network component failures, including those that partition the network. However, the protocol is relatively expensive in terms of bandwidth, since every switch must perform flooding. In the NLE protocol, only a small number of members perform flooding; other members in the group use point-to-point messages, rather than LSAs, to cast ballots. Further, the NLE protocol is designed to operate independently of the leader selection criteria used by different

groups. The generality, efficiency, and robustness of the NLE protocol enable its use as a single election protocol to support a variety of network functions.

3 The NLE Protocol

3.1 Overview

The operation of the NLE protocol is summarized below. Since some decision-making processes of the NLE protocol, such as the leader selection policy, are application dependent, we discuss the protocol operation in the context of the domain leader election problem. Adaptation of the protocol to other problems is discussed in Section 6.

1. For every group g, each switch x in the network maintains a *leader binding* to record the leader of the group as perceived by x. A binding entry $Binding_x(g)$ is a triple $(Leader_x(g), Source_x(g), Stamp_x(g))$, where $Leader_x(g)$ is the leader of the group g as perceived by x, $Source_x(g)$ is the switch that suggested this binding, and $Stamp_x(g)$ is the timestamp associated with the binding. The goal of the NLE protocol is to maintain consenting $Binding_x(g)$ values across the network.

2. When a switch x joins a group g, it searches for the $Leader_x(g)$ entry in its local database. If the entry is not found, the group g is said to be *unbound* at x. In this case, the switch x selects a switch c as the leader of the group according to a *leader selection policy*, sets $Leader_x(g)$ to c, and broadcasts this binding. For the domain leader election problem, the leader selection policy selects a reachable switch with the highest leader priority.

3. Once the switch x has a $Leader_x(g)$ entry, it sends a JOIN-REQUEST message to switch $Leader_x(g)$. The join operation will not be considered successful until the return of a JOIN-ACK from the $Leader_x(g)$. Further, the switch x must re-join g (that is, repeat the join process) each time the $Leader_x(g)$ value changes.

4. When a switch x leaves a group g, it sends a QUIT-REQUEST to switch $Leader_x(g)$. Similar to the join process, the quit process does not not finish until the corresponding QUIT-ACK returns from $Leader_x(g)$.

5. When $Leader_x(g) = x$, switch x acts as the leader of the group g: it processes JOIN-REQUEST/QUIT-REQUEST messages, and returns appropriate acknowledgments. Further, via join and quit requests from members, the leader maintains a member list for g, denoted as $ML_x(g)$. A member of g will be dropped from $ML_x(g)$ if it sends a QUIT-REQUEST message for if it becomes unreachable from the leader x. We point out that, since members are required to re-join the group each time a new leader is elected, a new member list will be compiled at the new leader. Member lists are not required at switches other than the leader.

6. As discussed Section 2, the NLE protocol is not concerned with determining the actual working status of switches, but rather uses reachability information provided by the underlying LSR protocol to handle network component failures. In the NLE protocol, a switch x must select and broadcast a new leader for a group g whenever x is a member of g and the switch $Leader_x(g)$ becomes unreachable from x. To avoid a rush of new leader bindings from all members of g, a delay timer of random length is used to postpone the re-selection task. Typically, one member wakes up before others and advertises a new binding. The remaining members simply accept the binding and re-join the group.

7. Even when switch $Leader_x(g)$ is still reachable from x, the switch x may decide, according to application-specific leader performance criteria, to select and advertise a new leader for the group g. Given a group g, an *objection policy* determines when a switch objects to the current leader binding and selects a new leader. For the domain leader election problem, a switch may object to the current domain leader when it discovers a reachable switch has a higher leader priority than does the current leader. A requirement for a valid objection policy is that, when the network is stable, the policy must be "location independent," that is, different switches will select the same leader given identical images of the network. This requirement ensures that chains of objections will not occur in a stable environment.

8. Each switch periodically advertises a list of groups for which it is the leader. Formally, switch x periodically broadcasts a list of group IDs, G_x, where a group $g \in G_x$ if and only if $Leader_x(g) = x$.

When using the NLE protocol for the domain leader election problem, the consensus property of the NLE protocol assures us that there will be a consenting domain leader binding within each network segment, should the network be partitioned. Moreover, if the JOIN-REQUEST messages are used as ballots for the leader to determine unanimity, the mutual consensus property of the NLE protocol ensures that the leader in each network segment will receive ballots from the switches, and only those switches, within the segment.

3.2 State Machines and Events

At a switch x, the NLE protocol defines two finite state machines (FSMs) for each active group g: a Membership Status Machine, denoted as MSM(x, g), and a Leadership Consensus Machine, denoted as LCM(x, g). Both LCM(x, g) and MSM(x, g) machines access the $Binding_x(g)$ entry; such accesses are assumed to be atomic to avoid race conditions. Figure 2 shows the events processed by the two machines. The LCM(x, g) processes incoming leader bindings for the group g, and reacts to events that indicate problems with the current leader, such as leader-unreachable events and objection events defined by the objection policy. The MSM(x, g) handles join and quit events and is responsible for ensuring that the current leader, $Leader_x(g)$, holds correct information regarding the membership status of the switch x. Whenever the LCM(x, g) accepts a new binding for the group g, it generates a leader change event for processing by the MSM(x, g). When such an event occurs and the switch x is a member of g, the MSM must send a JOIN-REQUEST to the new leader. The MSM(x, g) is also responsible for suggesting and advertising a leader binding when the switch x joins the group g and does not find a leader binding for g in the local database. Such binding advertisements produced by the MSM(x, g) will be received by LCM(v, g), for every switch v in the network, including LCM(x, g).

3.3 The Operation of LCM

The state transition diagram for the LCM is depicted in Figure 3. As shown, an LCM comprises four states: EMPTY, PENDING, REMOTE, and LOCAL. The EMPTY state is the initial state of LCMs. When there is no binding regarding g at x, the LCM(x, g) is in the EMPTY state; the values of $Leader_x(g)$ and $Source_x(g)$ are undefined, and the

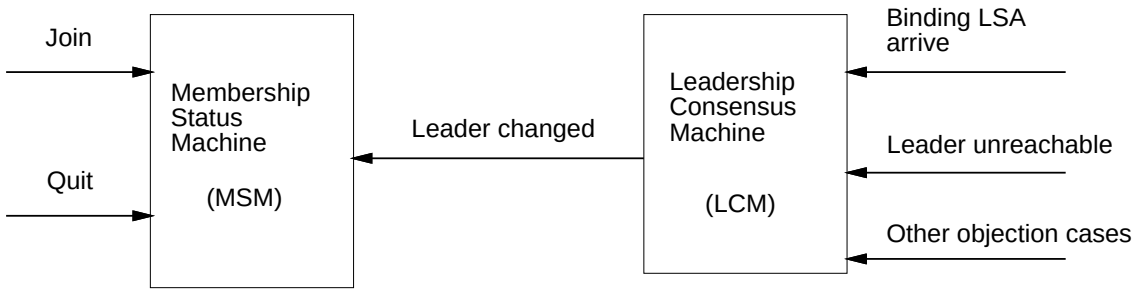


Figure 2. The finite state machines in NLE.

value of the $Stamp_x(g)$ is defined to be zero. An LCM(x, g) is in the LOCAL state when $Leader_x(g) = x$, and in the REMOTE state when $Leader_x(g) \neq x$. The LCM sometimes uses a timer to postpone the task of leader selection. When this happens, the machine enters the PENDING state, waiting for time-out.

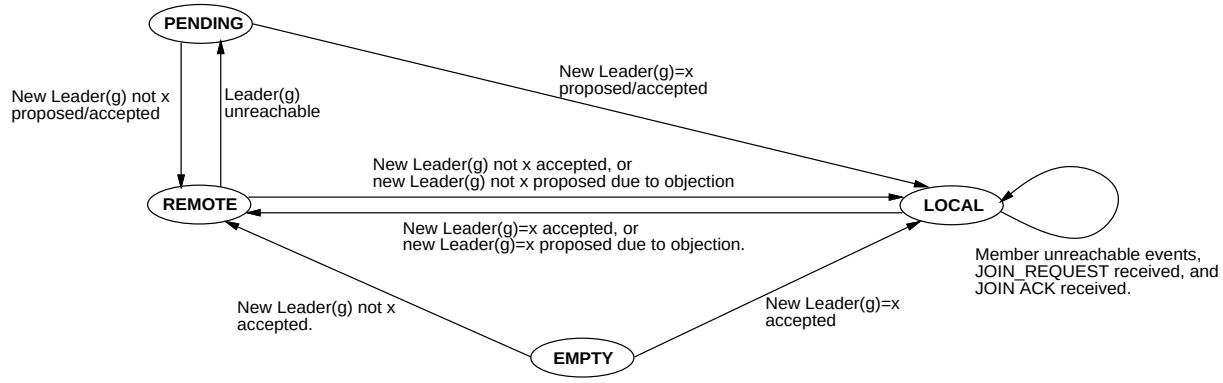


Figure 3. The leadership consensus machine at a switch x for a group g (LCM(x, g)).

A binding LSA is a pair $(g, (c, s, t))$, where the first element g specifies the group and the second element (c, s, t) is the value of this binding. The LCM processes binding LSAs according to the rules below:

A1 An incoming binding LSA $\ell = (g, (c, s, t))$ will be *accepted* at a switch x if $(t, s) > (Stamp_x(g), Source_x(g))$, otherwise it is rejected at x. (The comparison is in lexicographical order.) This rule guarantees that more recent bindings override old ones but that the reverse will not happen. When ℓ is accepted, its value (c, s, t) becomes the value of the binding entry $Binding_x(g)$. Subsequently, the LCM(x, g) enters either the LOCAL or REMOTE state, depending whether new $Leader_x(g)$ is x or not.

A2 When a switch x proposes and advertises a leader c for a group g it 1) increases the

$Stamp_x(g)$ by one, 2) sets $Source_x(g)$ to x and $Leader_x(g)$ to c, and 3) floods a binding LSA $(g, Binding_x(g))$. The LCM(x, g) then enters either the LOCAL or REMOTE state, depending on whether new $Leader_x(g)$ is x or not.

There are two situations where the LCM(x, g) may use Rule A2 to propose and advertise new leader bindings for the group g: when the $Leader_x(g)$ becomes unreachable, and when an objection event is raised according to the objection policy. In the latter case, the LCM proposes a new leader only if the machine is in the REMOTE or LOCAL state. When the current leader of g becomes unreachable from a switch x, the switch is triggered to select and advertise a new leader. To avoid a rush of simultaneous leader binding LSAs from group members, the LCM(x, g) sets up a delay timer and enters the PENDING state. There are two ways for the LCM to leave the PENDING state: 1) the timer fires, and the machine selects/advertises a new leader according to Rule A2, or 2) an "acceptable" binding LSA arrives before time-out. In case 2, the delay timer is canceled, and the LCM processes the LSA according to Rule A1. We will discuss the effects of various timer values in Section 5.

When the LCM(x, g) enters the LOCAL state, the switch x must create a member list for the group g and process JOIN-REQUEST/QUIT-REQUEST messages from members of g. The member list of g is created every time LCM(x, g) enters the LOCAL state, and is destroyed every time LCM(x, g) leaves that state. JOIN-REQUEST/QUIT-REQUEST messages will be acknowledged and used to update the member list when LCM(x, g) is in the LOCAL state, but are discarded silently when the machine is in any other state. When an unreachability event concerns a switch y that is not the leader of the group g, the action of LCM(x, g) depends on whether x considers itself to be the leader. If so $(x = Leader_x(g))$, it removes y from the member list of g; otherwise, it discards the event.

3.4 The Operation of MSM

The MSM at a switch x for a group g, denoted as MSM(x, g), reacts to join(g) and quit(g) events. An MSM has four states: MEMBER, JOINING, NON-MEMBER, and LEAVING, among which the NON-MEMBER state is the initial state. With respect to a group g, the MSM at a switch x is in JOINING state if it wishes to join the group but has not completed the "registration" procedure, namely, the exchange of JOIN-REQUEST and JOIN-ACK messages with the leader, $Leader_x(g)$. After the JOIN-ACK message is received, the joining

member enters the MEMBER state. Defined similarly, a member of g is in the LEAVING state during the exchange of QUIT-REQUEST and QUIT-ACK messages with the leader, and will enter the NON-MEMBER state after completion. Retransmissions of REQUEST messages may be necessary to ensure successful delivery.

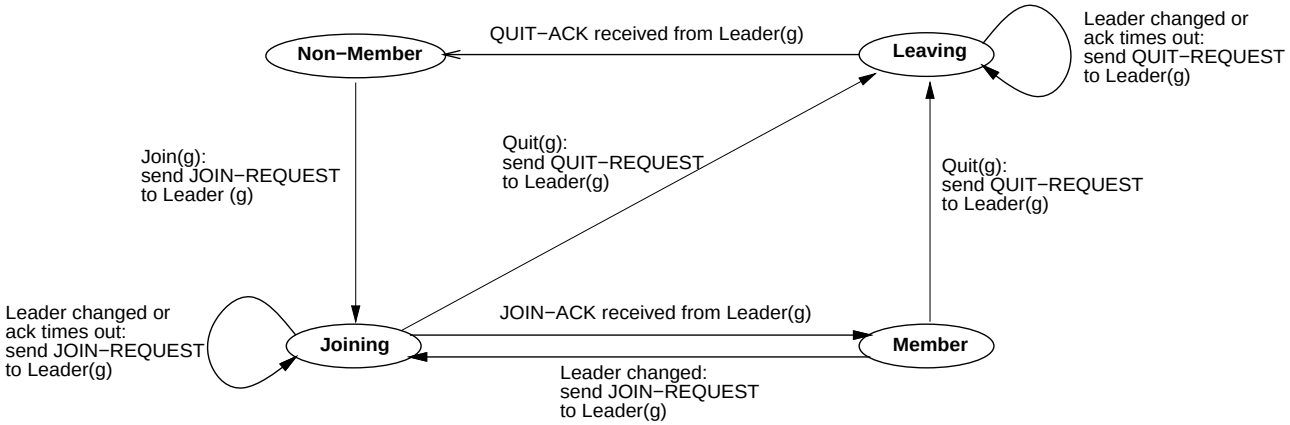


Figure 4. The membership status machine at a switch x for a group g (MSM(x, g)).

The MSM does not deal directly with the leader-unreachable events. However, when the LCM(x, g) changes the leader binding due to leader-unreachable events or other objection events, it generates a leader-change event to be handled by the MSM(x, g). If the switch is a member of the group g, the switch must re-join the group, that is, the MSM(x, g) machine enters the JOINING state so that JOIN-REQUEST and JOIN-ACK messages are exchanged with the new leader.

If a switch x joins a group g when the LCM(x, g) is in the EMPTY state, the switch must select and advertise a leader for the group, following the procedure defined in rule A2, For every switch v in the network, including LCM(x, g), this advertisement will be received by LCM(v, g).

4 Proof of Correctness

We prove in this section that the NLE protocol achieves consensus on group-leader bindings throughout the network. However, we must be careful when defining what can be proved and what cannot be proved. For example, consider a hypothetical scenario where, whenever a switch x is suggested as the leader of a group g, that switch crashes immediately. The other

network switches will detect the unreachability to x and (some of them) will propose new leaders. Meanwhile, switch x resumes execution shortly after new leader binding proposals are made. If the scenario repeats indefinitely and every newly suggested leader immediately crashes, then it is impossible for *any* leader-management algorithm to maintain stable and consistent leader bindings for the group.

We conclude that a more reasonable goal is to study the behavior of the NLE protocol in response to a *finite* set of events. (Similar assumptions have been used in the "classic" LSR consensus problem, where the switches must reach consensus on network images [13].) Precisely, let us be given a group g and a finite set of events, E, which may include network status dynamics, group membership changes, unreachability events and other objection events. In addition, E is assumed to contain at least one join event regarding g (otherwise the group is inactive and does not participate in the protocol). We will show that consensus is eventually reached throughout the network on the Binding(g) entries.

We begin with the leadership consensus property. We first prove the property for the case where the network remains connected after the event set E. Following that, we consider the case where the network is partitioned.

Proposition 1 [Weak Leadership Consensus Property] *Let E be a set of network events, including group membership change and network status change events, and let g be a group with at least one join event in E. Assuming that the network is not partitioned after all events in E have taken place, all network switches will eventually agree upon the same leader binding for group g.*

Proof: Considering the set of occurrence times of the events in E, we are interested in the maximum such element, t_{last}, the time of the last event in E. It is to be noted that the assumption of a connected network after time t_{last} does allow for some non-operational switches, as long as the "survivors" remain reachable from one another. If all the network switches are non-operational after t_{last}, the theorem is true vacuously. Let us consider the more interesting cases where at least one switch in the network survives E.

Let A be the non-empty set of switches that are operational after t_{last}, and let B be the set of leader binding LSAs for the group g produced in response to the events in E. Let B_A be the subset of B such that $(g, (c, s, t)) \in B_A$ if and only if $c \in A$. In other words, B_A is the set of leader binding LSAs for which the designated leader c is operational after t_{last}.

We claim two properties regarding the set B_A. First, the set B_A cannot be empty, since members of g will select new reachable leaders if there are no valid bindings for g. (A binding is invalid at a switch x if the designated leader is unreachable from x.) Second, the set B_A is finite. In fact, we will show that the set B is finite. This property comes from the fact that the NLE protocol produces a finite number of bindings in response to a single event of any type. The worst case is M binding LSAs per event, where M is the number of members in the group. The worst case happens when the current leader fails and all the M members select/advertise new leaders. Hence, a very loose upper bound for the cardinality of B (and B_A) is $N \times |E|$, where N is the number of switches in the network and an upper bound of M.

Recall that, for two bindings (c_1, s_1, t_1) and (c_2, s_2, t_2), $(c_1, s_1, t_1) > (c_2, s_2, t_2)$ if and only if $(t_1, s_1) > (t_2, s_2)$. Let $b_{max} = (c, s, t)$ be the maximum binding in B_A. This maximum element is well-defined because the set B_A is finite and non-empty. Since the switch c is connected to switches in A after t_{last}, the periodic advertisements of b_{max} from c will eventually be received by all switches in A, which must accept the binding and ignore any others, due to the maximality of b_{max}. The binding b_{max} becomes the final consensus binding among all operational switches, and the theorem is proved. □

The proof of the theorem also suggests that the final leader binding is "correct" in the sense that b_{max} is in B_A (that is, the final winner is an operational switch after E). Somewhat surprisingly, showing consensus when the assumption of eventual network connectivity is removed is not difficult at all, as shown in the following theorem.

Theorem 1 [Leadership Consensus Property] *Let E be a finite event set that partitions the network into k segments, $S_1, S_2, \ldots, S_k$, where $k \geq 1$. Let g be a group with at least one join event in E. The NLE protocol will achieve consensus on leader bindings for g within each segment S_i, for $1 \leq i \leq k$.*

Proof: To see the correctness of the theorem, we apply the argument regarding the set A in the previous proof to each segment S_i. That is, we simply consider switches in S_i to be operational and all other switches to be non-operational. □

Next, we consider the mutual consensus property of the NLE protocol.

Theorem 2 [Mutual Consensus Property] *Given a group g and a set of events E that partitions the network into k segments, $S_1, S_2, \ldots, S_k$, where $k \geq 1$, the consensus leader of g in S_i produces a member list that includes members, and only those members, in S_i.*

Proof: In the following discussion, the consensus leader of g in S_i is denoted as $Leader_i(g)$, and the member list maintained by the leader is denoted as $ML_i(g)$. It is not difficult to see that members not in S_i after E will be removed eventually from $ML_i(g)$, due to unreachability events about these members. It remains to be shown that all members of g in S_i will be added to the list $ML_i(g)$.

A property of the MSM, shown in Figure 4, is that the MSM insists on having the current leader hear about the current membership status. However, some previous membership changes may not be learned by the leader. For example, if a switch x decides to leave a group g while it is in the JOINING state with respect to g, the MSM simply enters the LEAVING state and issues a QUIT-REQUEST; the previous JOIN-REQUEST and JOIN-ACK exchange process is aborted. As a result of this design, given a sequence of interleaved join/quit events, the MSM does not guarantee the success of all respective REQUEST-ACK exchanges, but will enforce the successful exchange with respect to the last event in the sequence.

Let us assume that there is a switch $y \in S_i$ that is a member of g after events in E, but y is not in $ML_i(g)$. By the previous observation, we are concerned only with the REQUEST-ACK exchange process of the last membership change event, which must be a join event. The assumption that y is not in $ML_i(g)$ implies that the leader in S_i does not receive a JOIN-REQUEST message from y, and hence will not return a JOIN-ACK message. Consequently, the switch y remains in the JOINING state, where the JOIN-REQUEST message will be issued repeatedly until corresponding acknowledgment is heard. Since y and $Leader_i(g)$ are connected, this process will eventually complete, putting y on the $ML_i(g)$. This is a contradiction to the assumption about y, concluding the proof. □

5 Performance Evaluation

In this section, we investigate the performance of the NLE protocol in handling leader failures. Specifically, the NLE protocol is compared against the ATM domain leader election protocol [6]. In our simulations, networks comprising up to 400 switches were used. For each network size, 40 graphs were generated randomly, and two simulation sessions were conducted on each graph. Table 1 shows the characteristics of the graphs generated. In the table, maximum, minimum, and mean values are averages over the 40 graphs of the same size.

Network size	degree			diameter			T_f (in ms)	round (in ms)
	min	mean	max	min	mean	max		
10	1.675	3.6	5.675	2	3.25	5	3.555	3.621
20	1.25	3.573	6.725	4	4.75	7	5.123	5.225
40	1.025	3.733	8.025	5	6.175	9	6.705	6.892
60	1.025	3.875	8.65	5	6.8	11	7.5	7.776
80	1	3.914	8.925	6	7.075	9	7.867	8.235
100	1	4.12	9.675	6	7.15	9	8.1	8.558
120	1	4.103	9.725	6	7.525	8	8.423	8.999
140	1	4.201	10.225	7	7.725	9	8.64	9.308
160	1	4.220	10.375	7	7.575	10	8.798	9.576
180	1	4.307	10.5	7	7.75	10	8.9623	9.851
200	1	4.289	10.825	7	7.95	10	9.075	10.078
250	1	4.503	11.275	7	7.95	10	9.338	10.666
300	1	4.704	11.725	7	7.975	10	9.465	11.123
350	1	4.873	12.325	7	7.85	9	9.533	11.422
400	1	5.065	12.65	7	7.85	9	9.623	11.829

Table 1. Characteristics of randomly generated graphs.

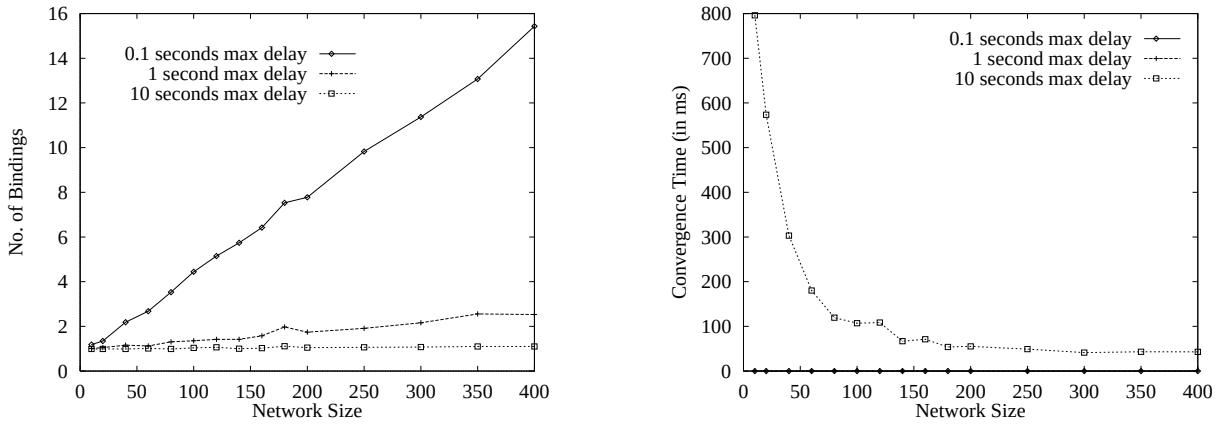
The following flooding protocol is assumed: LSAs arriving at a switch for the first time are forwarded along all incident links, except the incoming one. LSAs arriving at a switch for the second time are dropped silently. LSAs are forwarded to neighboring switches one by one. For each LSA forwarding, we used software overheads as measured on the ATM testbed in our laboratory. The testbed comprises Sun SPARC-10 workstations equipped with Fore SBA-200 adapters and connected by three Fore ASX-100 switches. From these measurements, we obtained the figure 600 μsec, which includes the overhead at both the sending and receiving switches.

We consider two metrics for the performance of leader election: the leader-binding convergence time and the number of leader binding LSAs produced for an election. The former refers to the length of the period from the moment the election begins to the moment that all network switches agree on the same leader node. (When an election is held due to the failure of the current leader, the election begins at the moment the leader fails.) The latter measures the number of leader-binding LSAs that are sent before consensus on the leader node is reached. For the sake of evaluating the handling of leader failures, in these tests we assume that the network is connected and that no adverse network component failures take place during election period.

When a leader fails under the NLE protocol, group members select a new leader and send join requests to that switch. Since all members are informed (by corresponding LSAs) almost simultaneously, they all could potentially rush to suggest new leaders, resulting in a large number of conflicting leader binding LSAs. The NLE protocol avoids this problem by deferring member rejoins with a random timer. We assume that the current leader crashes at time 0, and that delay timers are uniformly distributed between 0 and a simulation parameter *max_delay*. We used max_delay values of 0.1 seconds, 1 seconds, and 10 seconds. In addition, we measured the bandwidth consumption of the two approaches. This is motivated by the fact that switches use point-to-point messages to cast ballots in the NLE protocol, but must use flooding operations in the ATM election protocol.

The results regarding the metric of the number of bindings are plotted in Figure 5(a). Even the very short maximum delay value (0.1 seconds) introduces fewer than 16 bindings in 400-switch networks. When the maximum delay is set to 1 second, fewer than 3 bindings are generated in large networks. When the maximum delay value of 10 seconds is used, only one binding is created in almost all simulation sessions. Although not shown in the figure, the current ATM election protocol produces N preferred-leader LSAs, the equivalent of binding LSAs, in an N-switch network for every leader failure event.

The results for convergence time are plotted in Figure 5(b). For this performance metric, the shorter the maximum delay value, the faster the convergence, since a short maximum delay value produces early time-out of the delay timers, and hence switches take less time to flood new leader bindings. Also, the larger the network size, the faster the binding converge; not surprisingly, a large number of switches that set up random delay timers tends to produce



(a) number of bindings.

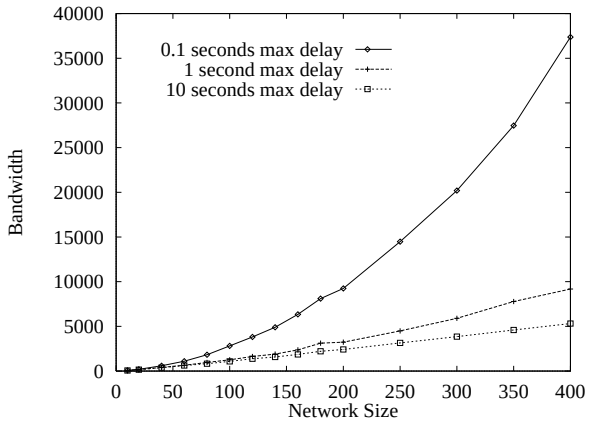
(b) convergence time.

Figure 5. Performance of the NLE protocol.

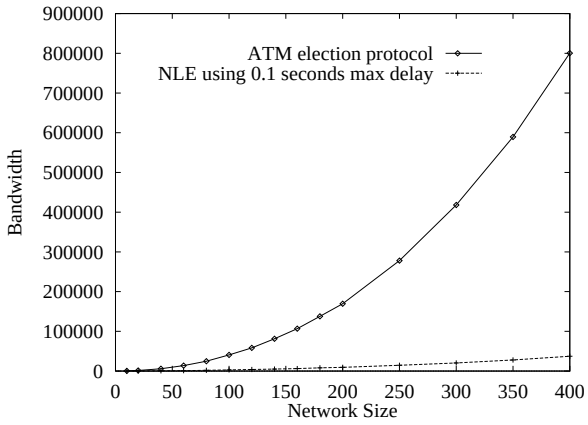
one that times out quickly.

The results for bandwidth consumption are plotted in Figures 6(a) and (b). Bandwidth consumption is measured by counting the total number of links traversed by every LSA associated with the election. Figure 6(a) shows the results of the NLE protocol, which uses flooding operations to broadcast leader bindings and point-to-point messages to cast ballots (that is, to send JOIN-REQUEST messages). The curves in Figure 6(a) conform with those in Figure 5(a), that is, the more concurrent bindings produced, the more bandwidth consumed. The bandwidth consumption of the ATM election protocol is significantly larger than that of the NLE protocol, as shown in Figure 6(b).

In summary, compared to the ATM leader election protocol, the NLE protocol incurs far fewer flooding operations and consumes a small fraction of the bandwidth. We further emphasize that the ATM leader election protocol requires every switch to periodically advertise its preferred leader, while the NLE protocol requires only the leader to periodically broadcast its leader status. We conclude that the NLE protocol is more efficient than the ATM leader election protocol, while being equally robust.



(a) NLE bandwidth.



(b) ATM bandwidth.

Figure 6. Bandwidth usage of alternative election protocols.

6 Other Potential Uses of The NLE Protocol

We have discussed the use of the NLE protocol for the domain leader election problem. In this section, we briefly discuss the application of the protocol to two other important network services, namely, multicast address resolution and multicast core management. In addition, we evaluate the performance of the NLE protocol in group creation.

6.1 Multicast Address Resolution

In the last several years, a great deal of research has addressed the issue of implementing IP over new link layer protocols, such as ATM/AAL5. One of the difficult tasks in implementing IP over ATM networks is how to handle multicast addressing. Whereas IP allows a source node to send a datagram to an abstract multicast group address, the current ATM standard does not support such an abstraction. Rather, ATM supports multicasting through point-to-multipoint unidirectional virtual channels, which require the sender to explicitly establish a connection to each destination.

One approach to this problem is to use a Multicast Address Resolution Server (MARS) [7], a central server that acts as a registry, associating IP multicast group identifiers with the ATM interfaces representing the members of the groups. The MARS is queried when an IP multicast address needs to be resolved, and hosts and routers must update the MARS

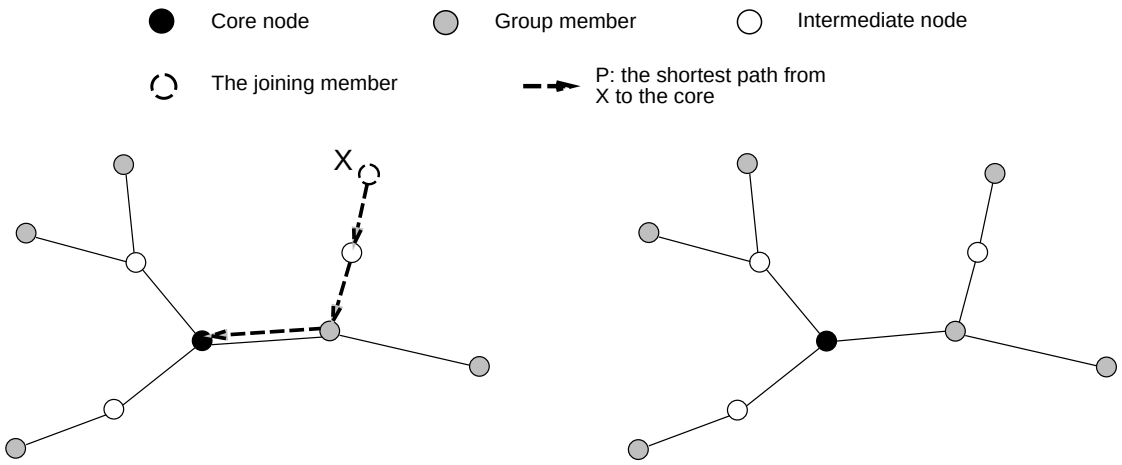
when they join and leave groups. As a centralized solution, however, the potential for MARS failure is an important issue. The approach described in [7] is to configure nodes with the addresses of one or more backup MARS nodes that they can contact in descending order of preference.

An alternative method is to use an election protocol, such as NLE, to "automatically" handle MARS failures and, just as important, accommodate network partitions. Such an implementation might work as follows. A specific group identifier (call it MARS-GID) could be reserved for the election of the MARS; every switch is assumed to be a member of this group. The selection and objection policies of the MARS could follow a ranking scheme similar to that described earlier for domain leader election. If the current MARS crashes, the NLE protocol can be used to establish consensus on a new $Leader_x(MARS - GID)$ binding. For the new MARS to operate properly, member lists must be re-collected. As mentioned, during normal operation of an established MARS, switches must report multicast group membership changes to the MARS. Typically, every switch in the network maintains an *interested multicast addresses* (IMA) list, $M_x = \{m_1, m_2, \ldots, m_k\}$, where each element m_i is a multicast address that one or more of the attached hosts is interested in. This list is usually maintained by a local membership management protocol, such as the IGMP [14]. Since every switch must send a JOIN-REQUEST to a newly elected MARS, reconstruction of member lists at the MARS can be implemented by simply augmenting each JOIN-REQUEST message from switch x to include a copy of M_x. Moreover, the consensus properties of the NLE protocol guarantee that, should the network be partitioned, there will be a MARS within each segment that maintains multicast group member lists for those, and only those, switches in the segment. Since a leader periodically floods its status, re-unification of two segments will produce an election of a single MARS.

6.2 Multicast Core Management

In the Internet, IP multicast groups are receiver groups (that is, the source of a datagram is not required to be a member of the group) and are identified by unique multicast addresses. Further, IP multicast groups are dynamic: a group is created when the first member joins and is destroyed when the last member leaves. Some prominent IP multicast protocols, such as CBT [9] and PIM [10], associate a multicast traffic transit center, or *core node*, with

each multicast group. In such approaches, datagrams destined to a multicast group are first forwarded to the core node, from which they are distributed along a multicast tree to reach group members. A new member joins the group by sending a JOIN-REQUEST message toward the core node. The path traversed by the message defines a tree branch to reach the new member. An example of this join process is shown in Figure 7. Figure 7(a) shows the shortest path P from a joining member X to the core node. The result of this join operation is shown in Figure 7(b).



(a) a shortest path from the joining member to the core.

(b) the resultant tree.

Figure 7. Member join operation in the CBT/PIM protocols.

We point out that CBT/PIM JOIN-REQUEST messages are not issued by host members. Rather, when a host joins a group, it is its *ingress switch*, the point at which the host is attached to the network, that sends the request on behalf of the host. That switch consequently becomes a *switch member* of the multicast group, and need not send further JOIN-REQUEST messages when other attached hosts subsequently join the group. In the following discussion, and in Section 6.3 the term member refers to switch member.

Since all members of a multicast group must send JOIN-REQUESTs to the core, these members must somehow agree on the same core. Hence, the association of the core node with a multicast group can be modeled as a leader election problem, and the NLE protocol can be applied. One approach is as follows. We assume that a core election is held whenever a multicast group is created (that is, when the first member joins), and that a new core is elected if the current core fails. Regarding the core/leader selection policy, we can assume

that the default is the *random member* policy [15]: whenever a member is required to select and advertise a core node (including group creation time), the member simply recommends itself. A number of other core selection policies are discussed in [15] and could be incorporated into the NLE protocol. The accompanying objection policy is equally straightforward: we must object to a leader that is no longer a member of the group. Specifically, when the leader x of a group g leaves the group, a "non-member leader" objection event will be detected by x itself, forcing the exiting leader to suggest a new leader for g. Since it maintains a list of members, it can easily do so. Alternatively, sophisticated objection policies could be defined in which the current core selects a new core based on performance criteria. Finally, as with the applications discussed earlier, the mutual consensus property of the NLE protocol enables arbitrary multicast groups to handle network partitions and re-unifications.

6.3 Performance of Multicast Group Creation

When the NLE protocol is used in domain leader election and MARS election, all switches in the network are members of the (single) group, and the group is assumed to be created at network initialization, a relatively rare event. In the case of multicast core management, on the other hand, there are many multicast groups directly tied to applications. More importantly, group creation time may be important to the performance of those applications.

Therefore, we conducted a study to evaluate the performance of the NLE protocol when a multicast group is created. As in the previous performance study, we assume that there are no network component failures during an election process, and we are interested in two performance metrics: convergence time and the number of binding LSAs. It turns out that the convergence time in this case is quite predictable, as shown in the following theorem. Therefore, in our simulations we measured only the number of binding LSAs.

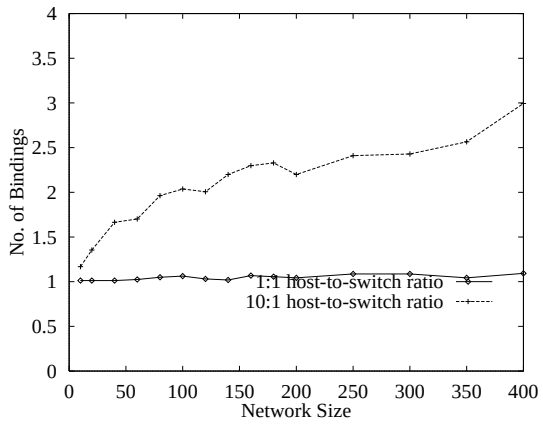
Theorem 3 *Given the flooding diameter T_f of a network (the worst-case time to finish a flooding operation), the convergence time for group creation under NLE is less then $2T_f$, assuming that no network component failures occur during group creation.*

Proof: Assume that the first member joins a group at time 0. This member finds the group unbound and advertises a leader-binding, which will reach all network switches by T_f. Assuming no component failures, any other switch must join the group by time T_f if it

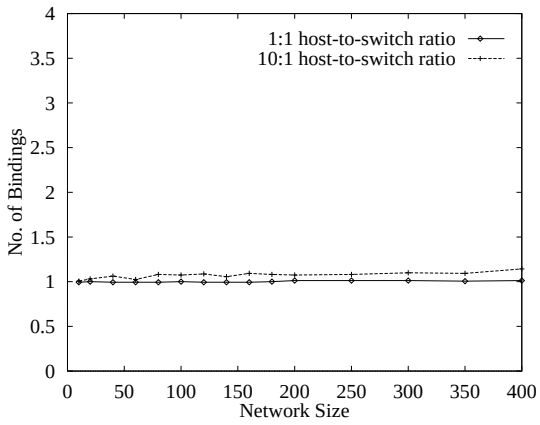
is to find the group unbound and propose its own binding. Flooding of any such additional bindings will require another T_f time to finish in the worst case. Therefore, after time $2T_f$, all network switches will have received all the bindings that have been flooded, and will agree upon the one with the largest value. Hence, the worst case convergence time for leader binding is $2T_f$. □

We simulated the creation periods of multicast sessions with M participants. The arrival time of each participant is normally distributed with mean zero; this value is chosen because we are interested only in the relative arrive times of participants. The standard deviation value is set in such a way that 99% of the participants arrive within a predetermined time interval; this interval will simply be called an arrival interval. We used arrival intervals of lengths 1 second and 0.1 seconds. A switch joins the multicast group when its first attached participant arrives. In a simulation session, the size of the participant population, M, is controlled by the participant-to-switch ratio; we used the values 1 and 10 in this investigation. As such, our simulation study covers a wide range of participant population sizes, from 10 (obtained by 10-switch networks and 1 participant per switch) to 4000 (obtained by 400-switch networks and 10 participants per switch). Simulation sessions involving a small number of participants could represent teleconferencing applications, whereas those involving very large population sizes may represent Distributed Interactive Simulation (DIS) applications. The combination of very short arrival intervals with very large population sizes is intended to produce extremely busy group creation periods, in order to stress the NLE protocol.

Figure 8 shows the results of this simulation study. Figure 8(a) plots the results when using the 0.1 seconds arrival interval. The worst case in the figure is just approximately 3.0, meaning that even when 4000 participants join a multicast group within 0.1 seconds, the NLE protocol produces only three leader binding LSAs. Figure 8(b) plots the results for the 1 second arrival interval. As shown, this relatively longer (but still very short) arrival interval produces virtually no redundant bindings, that is, there is one leader binding produced per group creation event. We believe that the results in Figure 8(b) demonstrate that the NLE protocol is a viable method for supporting real-world circumstances.



(a) 0.1 seconds arrival intervals.



(b) 1 second arrival intervals.

Figure 8. Number of bindings generated for group creation.

7 Conclusion

We have considered a long-established distributed computing problem in a novel context. Specifically, the leader election problem has been studied in a context where participants of the election process are network switches, rather than hosts, and applications of the problem are network functions, rather than conventional distributed computing applications. The proposed solution, called the Network Leader Election protocol, models the group-leader binding problem as a consensus problem under link state routing. In this model, the local databases at network switches are extended with leader binding entries, whose network-wide consistency is guaranteed by the protocol. We have formally proved the correctness of the NLE protocol, including its leadership consensus property and the mutual consensus property, under any combination of group member and network status changes. Our simulation studies revealed that the NLE protocol incurs minimal overheads for multicast group creation, and moderate overheads to handle leader failures. The performance of the NLE protocol compares favorably with a previous network group leader election protocol for ATM networks. We believe that the efficiency and robustness of the NLE protocol make it suitable for use in supporting several important network functions, including, among others, hierarchical routing, address resolution, and multicast communication.

References

[1] D. Menasce, R. Muntz, and J. Popek, "A locking protocol for resource coordination in distributed databases," *ACM TODS*, pp. 103–138, 1980.

[2] K. Birman, "Implementing fault tolerant distributed objects," *IEEE Transaction on Software Engineering*, pp. 502–508, 1985.

[3] H. Garcia-Molina, "Elections in a distributed computing system," *IEEE Trans. on Computers*, vol. 31, pp. 48–59, January 1982.

[4] N. Fredrickson and N. Lynch, "Electing a leader in a synchronous ring," *Journal of the ACM*, vol. 34, pp. 98–115, January 1987.

[5] S. Singh and J. Kurose, "Electing 'good' leaders," *Journal of Parallel and Distributed Computing*, vol. 21, pp. 184–201, May 1994.

[6] ATM Forum, "Private network-network interface specification version 1.0." ATM Forum technical specification af-pnni-0055.0000, March 1996.

[7] G. Armitage, "Support for multicast over UNI 3.0/3.1 based ATM networks." Internet RFC 2022, November 1996.

[8] M. Laubach, "Classical IP and ARP over ATM." Internet RFC 1577, January 1994.

[9] A. Ballardie, "Core based trees (CBT) multicast routing architecture." Internet draft, March 1997.

[10] S. Deering, D. L. Estrin, D. Farinacci, V. Jacobson, C.-G. Liu, and L. Wei, "The PIM architecture for wide-area multicast routing," *IEEE/ACM Trans. on Networking*, vol. 4, pp. 153–162, April 1996.

[11] J. Moy, "OSPF version 2." Internet RFC 1583, March 1994.

[12] J. M. McQuillan, I. Richer, and E. C. Rosen, "The new routing algorithm for the ARPANET," *IEEE Transactions on Communications*, pp. 711–719, MAY 1980.

[13] D. Bertsekas and R. Gallager, *Data Networks*. Prentice-Hall, 1987.

[14] S. Deering, "Host extensions for IP multicasting." Internet RFC 1112, August 1989.

[15] K. L. Calvert, E. W. Zegura, and M. J. Donahoo, "Core selection methods for multicast routing," in *Proceedings of IEEE ICCCN '95*, (Las Vegas, Nevada), 1995.