Localized Algorithms and Their Applications in Ad Hoc Wireless Networks

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Abstract. An ad hoc wireless network is a special type of wireless multi-hop network without infrastructure or centralized administration. As a result of the mobility of their nodes, ad hoc wireless networks are characterized by dynamically changing topologies. A localized algorithm is a special distributed algorithm where each node performs an exceedingly simple task based on local information, with no information sequentially propagated globally in the network. The importance of localized algorithms is their scalability in mobile environments. Decisions made based on localized algorithms are adjustable to the change (such as a topological one) due to the mobile node. We discuss a generic framework that can capture many existing localized broadcast algorithms in ad hoc wireless networks. The framework can easily integrate other objectives such as energy-efficient design and reliability that ensures broadcast coverage. In addition, the framework is extensible to cover other collective communication, which includes one-to-many (multicasting), all-to-one (reduction or aggregation), and all-to-all (gossiping).

An ad hoc wireless network [15], or simply ad hoc network, is a special type of wireless multi-hop network without infrastructure or centralized administration. Unlike cellular networks where nodes interact through a centralized base station, nodes in an ad hoc network interact in a peer-to-peer fashion. As a result of the mobility of their nodes, ad hoc networks are characterized by dynamically changing topologies. The applications of ad hoc networks range from civilian (e.g., distributed computing, sensor networks) to disaster recovery (search-and-rescue), and military (battlefield).

Collective communication represents a set of important communication functions that involve multiple senders and receivers. Four basic types of collective communication services include: *one-to-many communication* (also called multicasting), *one-to-all communication* (broadcasting), *all-to-one communication* (reduction or aggregation), and *all-to-all communication*. In ad hoc networks, broadcasting a message to the entire network is a basic operation and has extensive applications. For example, broadcasting is used in the route discovery process in several reactive routing protocols ([8], [12], [14]), when advising an

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error message to erase invalid routes from the routing table [11]. Operations that rely on broadcasting include naming, addressing, and dense-mode multicasting. The aggregation process is frequently used in sensor networks [6], where information captured at each sensor is gathered and sent to the base station. In the reduction process, different messages from different senders are combined to form a single message for the receiver. Although collective communication has been extensively studied in wired networks and multicomputers [5], it is not well studied in ad hoc networks. All solutions in wired networks and multicomputers are based on constructing and maintaining global information/infrastructure. Due to the dynamic nature of ad hoc networks, global information/infrastructures, obtained through global information exchanges, are no longer suitable.

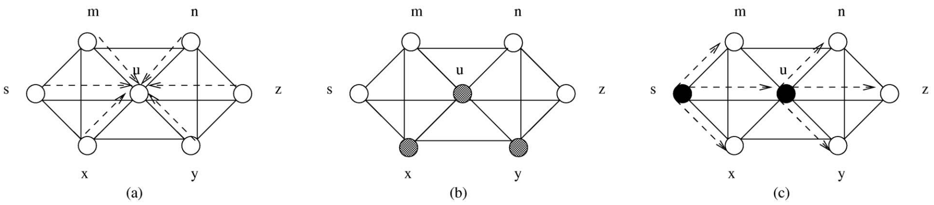

Fig. 1. (a) Broadcast storm problem. (b) Forward node set without routing history (static). (c) Forward node set with routing history (dynamic). Black nodes are visited nodes and gray nodes are forward nodes.

Blind flooding is a simple approach to perform broadcasting without using any global information/infrastructure, where a broadcast message is forwarded by every node in the network exactly once. Due to the broadcast nature of wireless communication (i.e., when a source sends a message, all its neighbors will hear it), blind flooding may generate excessive redundant transmission. Redundant transmission may cause a serious problem, referred to as the *broadcast storm problem* [19], in which redundant messages cause communication contention and collision. Figure 1 (c) shows an example of a broadcasting initiated from source s in an ad hoc network, represented by a unit disk graph model [3] where node connectivity is determined by geographical distance between nodes. Only node u needs to forward the message to ensure the coverage based on the broadcast nature of the communication. When all nodes forward the message once, serious contention and collision may occur at node u (see Figure 1 (a)).

The following approach is normally used to address the broadcast storm problem: only a subset of nodes is used to perform message forwarding. Such nodes are called *forward nodes*. Ideally, a small set of forward nodes should be selected to minimize message contention and collision and, at the same time, to ensure broadcast coverage. Both deterministic and probabilistic approaches can be used to find a forward node set. The probabilistic approach ([7], [19]) offers a simple scheme in which each node, upon receiving a broadcast message, forwards the message with probability p. The value p is determined by relevant information gathered at each node. However, the probabilistic approach cannot guarantee broadcast coverage and will not be considered further. In the deterministic approach, the forward node set can be selected statically (independent of any broadcast process) or dynamically (during a particular broadcast process).

In static approaches, the forward node status of each node is determined based on network topology only and it is independant of any particular broadcasting. Figure 1 (b) shows such a forward node set (not a minimum one). The source node may or may not belong to the set, but it will forward the broadcast message. In dynamic approaches, the forward node status of each node is also dependent on the *location of the source and the progress of the broadcast process.* Forward nodes that have relayed the broadcast message are called *visited nodes* (black nodes in Figure 1 (c)), and visited node information can be piggybacked with the broadcast message. The status of each node can be determined right after the first receipt of the broadcast message or after a backoff delay (so more copies of the same message may arrive before the decision). In this way, the status can be better decided with visited node information. Therefore, the resultant forward node set in general is smaller than the one derived statically. In addition, the forward node status of each node can be determined by itself or by its neighbors. The forward node set also forms a *connected dominating set* (CDS). A dominating set is a subset of nodes in the network where every node is either in the subset or a neighbor of a node in the subset. It has been proved that finding the smallest set of forward nodes with global network information/infrastructure is NP-hard.

A localized algorithm [6] is a special distributed algorithm where each node performs an exceedingly simple task based on local information, with no information sequentially propagated globally in the network. The importance of localized algorithms is their scalability in mobile environments. Decisions made based on localized algorithms are adjustable to the change (such as a topological one) due to the mobile node. Many broadcast algorithms ([1], [2], [4], [9], [10], [13], [16], [17], [18], [20], [21], [24]) have been proposed in ad hoc networks to address the broadcast storm problem. Some of them are based on global information/infrastructure. Some others are built on distributed algorithms that are not localized; that is, ones that exhibit sequential information propagation with long delay and costly maintenance, making them less applicable in ad hoc networks. Among existing localized broadcast schemes, some are either ineffective in redundancy reduction or are too specialized to integrate other desirable objectives. Different assumptions and models have been used, but lack a generic framework that provides in-depth understanding of the underlying mechanisms. In addition, there is no systematic approach to integrate other objectives such as energy-efficient design and reliability that ensures broadcast coverage. The challenge in energy-efficient design is to dynamically adjust transmission range to achieve the objectives of reducing contention and minimizing energy consumption in both communication and computation. The traditional reliability approach through redundancy conflicts with reducing contention by avoiding excessive redundancy.

The ACK/NACK approach suffers from possible two problems; either another form of broadcast storm problem when excessive ACK messages are sent back to the sender or, excessive memory used to hold unstable messages in the NACK approach since the broadcast message cannot be ensured of delivery without an ACK message.

We first present our preliminary results of a generic framework [22] that covers many deterministic and localized broadcast schemes, where each node determines its own forwarding/non-forwarding status based on local information. *The framework is built on the theory that global coverage and connectivity can be achieved through local coverage and connectivity based on the notion of local view.* Specifically, this local approach is based on k-hop neighborhood information (for a small k) and h-hop routing history information (for a small h) piggybacked with the broadcast message. The choice of k and h is adjustable without compromising broadcast coverage based on host mobility and cost-effectiveness trade-offs. The forward node set is determined on demand without resorting to any pre-defined infrastructure. Then, a more generic framework [23] is discussed that covers all deterministic and localized broadcasting schemes where the status of each node is either determined by itself or by its neighbors. Our generic framework aims at balancing cost (in collecting network information and in decision making) and effectiveness (in deriving a small forward node set). This generic framework can potentially be used to implement other types of collective communication, such as one-to-all, all-to-one, and all-to-all. We also present ideas to extend the generic framework by including energy-efficiency design, with the objective of reducing both contention and power usage at the same time. Finally, we will discuss thoughts on extending the framework to address the coverage issue by making a sensible trade-off between minimizing forward node set and maintaining a certain degree of redundancy for reliability without solely relying on ACK/NACK.

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