Survey on Broadcast Algorithms for Mobile Ad Hoc Networks

PATRICIA RUIZ and PASCAL BOUVRY, University of Luxembourg

Networking at any time and any place paves the way for a large number of possible applications in ad hoc networks, from disaster relief in remote areas to network extension. Thus, for the past decades, many works have been proposed trying to make ad hoc networks a reality. The importance of broadcasting in networking and the broadcast nature of the wireless medium have encouraged researchers to join their efforts on designing efficient dissemination algorithms for Mobile Ad Hoc Networks (MANETs). The many different challenges that MANETs face, such as limited network resources, network partitions, or energy restrictions, gave rise to many different approaches to overcome one or more of those problems. Therefore, literature reveals a huge variety of techniques that have been proposed for efficient message dissemination. In this article, we make an in-depth review of the existing state-of-the-art techniques, as well as propose a new taxonomy that provides a global overview of the most relevant existing algorithms.

Categories and Subject Descriptors: C.2.2 [**Computer-Communication Networks**]: Network Protocols

General Terms: Broadcasting, Communication Protocols

Additional Key Words and Phrases: Broadcast algorithms, ad hoc networks, taxonomy, underlying topology, variable and fixed transmission range

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1. INTRODUCTION

Thanks to technological advances, communicating with a remote person at any time and in any place is now a reality and not just a dream. Wireless technology plays a major role in this process by enabling wireless device connections. Miniaturization and cost reduction also played major roles in the success of this phenomenon. Indeed, wireless communications reaches a mass market.

Nowadays, fixed infrastructures establish and manage the majority of communications between any pair of close or distant nodes. However, researchers envision the possibility of device-to-device communications without the need for any infrastructure. This type of networks is known as an ad hoc network. The term *ad hoc* is widely used in the scientific community. There are two different meanings in the *American Heritage Dictionary of English Language*: (1) *"form for or concerned with one specific purpose"*; (2) *"improvised and often impromptu"* [Heritage 2014]. The combination of both perfectly describes the objective of this new type of wireless network, the *ad hoc* network.

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Authors' addresses: P. Ruiz, Imatrics Image Technologies, Madrid, Spain; email: patriciaruizvillalobos@gmail.com; P. Bouvry, Faculty of Science, Technology and Communication, University of Luxembourg, Luxembourg; email: pascal.bouvry@uni.lu.

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Ad hoc networks are mostly created on the fly; that is, when devices with communication capabilities meet and no infrastructure allowing the communication between devices is needed. The intrinsic characteristics of such networks—self-organization, heterogeneity of devices, and dynamism or unpredictable behavior—make it challenging to create networks with good performance. Broadcasting is a cornerstone in networking and is used by many other protocols and applications (e.g., route discovery, network information update, or neighborhood discovery). Thus, researchers have put much effort into designing efficient broadcast algorithms for Mobile Ad Hoc Networks (MANETs). Not only must the inherent problems of dissemination algorithms be considered, but also the ones inherited from ad hoc networks; this makes efficient communication not only crucial but also a very complex task.

The related literature in broadcasting techniques for MANETs is enormous. Therefore, a survey that compiles all existing techniques and approaches and that familiarizes researchers with the topic is of extreme importance. We can find some surveys on broadcasting protocols in Vollset and Ezhilchelvan [2003], Stojmenović and Wu [2004], Boukerche [2005], Lipman et al. [2009], Zeng et al. [2009], Garbinato et al. [2010], Mkwawa and Kouvatsos [2011], and Koscielnik and Stepien [2011]. However, none of them presents a complete state-of-the-art overview covering all existing approaches in a clear way. There also exist some relevant classifications in the field [Williams and Camp 2002; Wu and Lou 2003; Yi et al. 2003; Stojmenović and Wu 2004], but none thoroughly covers all proposed techniques. The primary focus of this article is to enlighten the reader about what has been done and how in the field of broadcasting, in an organized way. To achieve this, we are not only presenting an extensive literature review but also a new classification that better reflects the existing state of the art. Therefore, in this article, in order to give researchers a global overview of the topic, we first briefly mention the most relevant existing classifications, then introduce our proposed taxonomy. We later review the most noticeable broadcasting protocols, summarize their main characteristics in tabular forms, and finally present some of the most interesting open problems in the field.

The article is organized as follows. The next section introduces the broadcast problem, reviews existing classifications for broadcasting, and proposes a new taxonomy. Sections 3 and 4 provide a thorough literature review in the domain. In Section open issues in the topic are presented, and, finally, Section 6 presents our main conclusions.

2. BROADCAST ALGORITHMS

It is important to properly define the broadcast problem before explaining the mechanisms proposed to approach it.

An ad hoc network can be represented as a graph $G = (V, E)$, where V is the set of nodes composing it, and E is the set of links connecting nodes in range.

Definition 2.1 (*Broadcast*). Given a source node v starting a broadcast process, the *broadcast* operation mode sends the message m to a subset $V' \subseteq V$ such that for all $u \in V'$ there is a $(u, v) \in E$.

According to Basagni et al. [2004], in a wireless network, a *broadcast* is an operation whereby the message is sent to all neighboring nodes.

Definition 2.2 (*Network-wide broadcast problem*). Given a source node v starting a broadcast process, the *network-wide broadcast problem* aims at reaching any $u \in V$ with m.

In Williams and Camp [2002], the *network-wide broadcast problem* was defined as an operation where a single node sends a message to every other node in the network. The different existing techniques for solving this problem are called broadcast algorithms.

In the remainder of the article, we refer to network-wide broadcast as "broadcasting." To disseminate a message in multihop networks, the nodes must forward packets that are not intended for themselves and act as routers. A straightforward approach for solving the network-wide broadcast problem consists of retransmitting every received packet. This is known as *flooding*. Its main drawback is the *broadcast storm problem* [Ni et al. 1999]: The higher the network density, the higher the number of collisions, packet losses, contention of the shared medium, network traffic, and network resource use. Such an approach is not advisable because it not only leads to network congestion but also drains the battery of mobile devices. Boukerche showed in Boukerche and Sheetal [2003] that even a routing failure causes less problems than the inherent overhead introduced by blind flooding. However, with high loss rates and sparse networks, the obtained coverage is low even for the *flooding* approach [Boukerche 2008]. Therefore, efficient broadcasting algorithms that overcome these challenges are still needed.

Broadcast in MANETs needs a completely different perspective with respect to conventional networks. Wireless networks suffer from unique problems like low throughput, dead spots, inadequate support for mobility, high bit error rate, and varying characteristics over short timescales. Additionally, MANETs have a huge variety of specific characteristics that differentiate them from any other instances in the networking paradigm. Literature reveals many different works trying to overcome those problems and presenting different approaches for efficient dissemination in MANETs. Before providing a systematic literature review, we briefly present some of the main characteristics that will be used for algorithm classification, and we also review the existing classifications. We classify the literature in terms of several features, including the existence of a central management node, the network information, the use of random variables in the algorithm, and the location of the forwarding decision.

—*Centralized and decentralized systems*
In a *centralized system,* there must be a central unit that decides on behalf of the whole system. It can make decisions in terms of its own information or by also considering information obtained from different network nodes. Significant coordination, overhead, and delays are associated with this architecture. Moreover, the whole system fails if the central unit fails.

On the contrary, in a *decentralized system*, nodes can make local decisions and modify their behavior using only their own information.

Considering a central unit or global knowledge when emulating an ad hoc network is contrary to its distributed nature.

—*Global or local knowledge*
An algorithm is said to use *global knowledge* if the decision-making requires information on the whole network (e.g., all nodes' positions).

On the contrary, algorithms using *local knowledge* only use locally obtained data. This includes not only information about the node itself, but also information from the node's neighbors (either through eavesdropping or using beacons).

Unless the knowledge is acquired beforehand (some specific cases in sensor networks, for example), if there is no central unit, nodes need to exchange and collect information from all other nodes in order to gain global knowledge. In very small networks, this is achieved using beaconing, but, as density grows, this mechanism is not scalable and becomes unrealistic. Thus, in most cases related to MANETs, nodes are very unlikely to gain global knowledge.

—*Deterministic and stochastic processes*
It is also possible to differentiate algorithms in terms of their predictability: *deterministic* and *stochastic* approaches.

On the one hand, a process is considered *deterministic* when no random decisions are taken. That is, for given a particular input, the corresponding output is always the same. Its behavior is predictable.

On the other hand, when there are random choices, a process is said to be stochastic. Two executions of the same process in the same conditions can give different results.

—*Source-dependent and source-independent techniques*
In the context of the broadcasting process, it is possible to distinguish between *source-dependent* and *source-independent* techniques. In the former, the broadcasting strategy depends on a source node that decides the next forwarding nodes from the 1-hop neighbors. In the latter, the *source-independent* technique, the forwarding decision is taken by the receiving node.

Next, we briefly present the most relevant existing classifications and then propose a new taxonomy.

2.1. Existing Classifications

Williams and Camp classified broadcasting algorithms into four different families: *"simple flooding, probability-based methods, area-based methods and neighbor-knowledge methods"* [Williams and Camp 2002].

(1) *Simple Flooding* is a method for which a source node starts the dissemination process and all nodes rebroadcast the message exactly once.
(2) *Probability-based methods* forward the message with a predefined probability.
(3) *Area-based methods* forward the message considering the additional covered area.
(4) *Neighbor-knowledge methods* use neighbors' information to decide whether to rebroadcast the message or not.

Stojmenovic and Wu proposed another classification using the following characteristics: *"determinism, network information, reliability, hello message content, and broadcast message content"* [Stojmenović and Wu 2004].

(1) *Determinism*: Whether decisions feature some random aspects or not.
(2) *Network information*: Global or local knowledge. A more detailed classification of this specific case was proposed in Wu and Lou [2003], where four different types of information are available: *global*, *quasi-global*, *quasi-local,* and *local information*.
(3) *Reliability*: Full coverage guarantee.
(4) *Hello message content*: Includes additional information in the *hello message* for better performance.
(5) *Broadcast message content*: Includes additional information in the *broadcast message* for better performance.

Additionally, **Yi et al.** proposed yet another classification: *heuristic-based protocols and topology-based protocols* [Yi et al. 2003].

(1) *Heuristic-based protocols* group the first three categories of Williams and Camp: *"probabilistic, counter-based, distance-based and location-based algorithms."*
(2) *Topology-based protocols* exploit topological information:
   —*Neighbor topology-based protocols* that make the forwarding decision in terms of 1- or 2-hop neighborhood information;
   —*Source-tree-based protocols* construct a tree in the network, for which the source node is the root;
   —*Cluster-based protocols* group nodes into clusters and elect a representative (aka clusterhead).

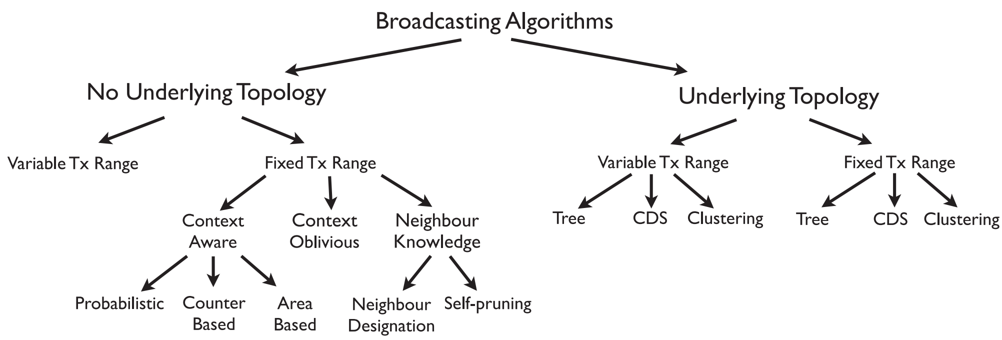

Fig. 1. Taxonomy of the broadcasting algorithms.

Although these classifications reflect many existing techniques and strategies used in broadcasting, none completely covers the literature. Therefore, we propose a new classification that better reflects the current state of the art.

For overcoming the broadcast storm problem, many approaches create or assume the existence of a virtual underlying topology in the network and use this information to smartly forward the message. However, many other works consider that the expenses of creating and maintaining this virtual topology are too high or that, sometimes, creating the structure is simply not feasible. Thus, there are mainly two different approaches: using or not an underlying topology.

Additionally, ad hoc networks are energy-constrained; thus, one of the main goals of all proposed protocols is to reduce their energy consumption. Literature reveals mainly two different approaches for reducing energy expenditure when disseminating a message in the network: (1) trying to reduce the number of rebroadcasts and network resources and (2) reducing the transmission range. Our classification also relies on whether the transmission power is fixed or adjustable. This variable range is found in both cases (i.e., using underlying topology or not using it). Algorithms that do not use any topology but use a fixed transmission range are divided into (1) context oblivious, (2) context aware, and (3) neighbor knowledge. Additionally, for those relying on topologies, three different possible classes are considered: (1) connected dominating sets, (2) tree-based topology, and (3) cluster-based topology. The proposed taxonomy is illustrated in Figure 1.

There also exist some techniques that deal with specific networks, like delay tolerant networks [Fall 2003]. These networks suffer from high latency and continuous network disruption; thus, devices usually communicate using a store-carry-forward mechanism. This is a very particular type of dissemination that is not addressed in this article. However, interested readers can refer to the *Haggle Project* for an intriguing work dealing with content dissemination [American Heritage 2014] (nodes can carry information for other nodes) or to some other seminal works tackling the problem [Hui et al. 2011; Bastani et al. 2012].

Similarly, we can find some approaches that limit the dissemination of a message to a specific area of the network and not to the complete network: *geocast-based routing algorithms*. These mainly use GPS information to locate and limit the targeted area, use routing mechanisms to get to it, and then broadcast the information within predefined boundaries. This can be seen as a multicast approach more than a broadcast approach because the message is not intended for every node in the network. This very specific broadcast technique is not covered in this article. However, interested readers can refer to Maihofer [2004], Al-Kanj and Dawy [2011], and Allal and Boudjit [2012].

In the following, we review the literature according to the previously introduced classification. Unless explicitly mentioned, the presented approaches are deterministic and use local knowledge.

3. ALGORITHMS NOT USING AN UNDERLYING TOPOLOGY

Depending on the application, the benefits of having a virtual structure over the real network topology is not always worth the cost of its creation and maintenance. In those cases, for an efficient broadcast, the nodes' forwarding decision is enhanced by some information about the current situation (context aware) or by some knowledge of their neighbors and their related strategies (neighbor knowledge). Nevertheless, there also exist context-oblivious approaches that rely on probabilistic forwarding decision.

Here, we present the most relevant algorithms that do not assume the existence of any underlying topology in the network, using either a fixed transmission range or a variable one.

3.1. Fixed Transmission Range Protocols

As mentioned, we differentiate algorithms that do not rely on any topological information and use a fixed transmission range. Most relevant works can be classified in terms of the knowledge used for the forwarding decision: context oblivious, context aware, and neighbor knowledge. Here, we review them in detail.

3.1.1. Context Oblivious. Nodes do not periodically exchange information with other nodes or eavesdrop the channel in order to make intelligent forwarding. They simply forward the message with a predefined probability.

In the pure *probabilistic* approach, nodes do not consider the environment or the current network situation. The forwarding decision is made according to a predefined probability. However, this probability may depend on node behavior or the neighboring device's behavior. Thus, we can find both context-oblivious and context-aware probabilistic approaches.

Flooding or *blind flooding* [Ni et al. 1999] consists of retransmitting the message the first time it is received and ignoring any other copy of the message received. No network information or neighbor knowledge is required. However, the shortcomings associated with this algorithm are a high number of collisions, redundancy, and waste of network resources, especially in high-density networks. Additionally, this approach does not handle network partitions or temporary disconnections: The message only reaches nodes within a partition or connected component. This is a deterministic approach.

Probabilistic flooding [Ni et al. 1999] reduces the number of forwarding nodes by assigning a probability of retransmission to every node receiving a message. When the probability is 1, the algorithm behaves as *blind flooding*.

A method to deal with partitions and/or high-mobility *hyper-flooding* was proposed [Viswanath and Obraczka 2002]. Whenever a new neighbor is met, the message is retransmitted so that reliability might increase. However, in dense networks, the reliability could even decrease due to collisions and failures. *Hyper-flooding* is also deterministic.

3.1.2. Context-Aware Approaches. In context-aware approaches, smart forwarding decisions are taken using knowledge about the current network state. We differentiate among (1) *probabilistic-based*, (2) *counter-based* (aware of the network traffic), and (3) *area-based* (aware of the network density).

a. *Probabilistic*
Weighted p-persistence, slotted 1-persistence, and slotted p-persistence probabilistic and timer-based algorithms were introduced in Wisitpongphan et al. [2007] for

Vehicular Ad Hoc Networks (VANETs). The three protocols need location information (either by GPS or signal strength) for calculating the relative distance to the source node. In *weighted p-persistence*, far-away nodes have a higher probability of retransmission. In *slotted 1-persistence*, the time slot assigned for retransmitting depends on the distance to the source node; thus, far-away nodes retransmit sooner. The *slotted p-persistence* is a mix of the first two in that the time slot assigned for retransmission depends on the distance, but a node will retransmit with a probability p that also depends on the distance.

A slightly different approach to the *weighted p-persistence* protocol is proposed in Zhou et al. [2010]: The n^{th} *power p-persistent* broadcasting protocol efficiently disseminates messages in dense VANETs. The main difference resides in the estimation of the probability, which is elevated to the n^{th} power. Both *flooding and weighted p-persistence* are particular cases of n^{th} *power p-persistent*, with $n = 0$ *and* $n = 1$, respectively. Authors claim that the correct value of n can outperform both with less delay, fewer hops, lower load, and higher throughput. However, explaining how to obtain this optimal value of n is a complex task that is not specified in the work.

Another probabilistic approach for vehicular networks is proposed by Slavik in Slavik and Mahgoub [2010]. This method focuses on privacy, scalability, and anonymity because it assumes that drivers are reluctant to share their movements or maneuvers with anyone. Two schemes are proposed. In the first, vehicles retransmit with a uniform and constant probability. The second one depends on an estimation of the distance between the receiver and the furthest node.

The *Speed Adaptive Probabilistic Flooding* (SAPF) algorithm [Mylonas et al. 2008] calculates adaptive forwarding probability in terms the vehicle velocity. SAPF focuses on reducing the delays caused by contention in dense networks. The main target consists of finding the optimal value of the forwarding probability based on the vehicle speed.

In the *gossip-based broadcast* approach, the source node randomly selects k neighbors and sends the broadcast message to them. Any node does the same upon reception of the message for the first time [Kermarrec et al. 2003]. A survey on gossip protocols can be found in Leitao et al. [2010].

Probabilistic schemes are generally suitable for MANETs due to the low overhead (no infrastructure has to be created and maintained), the flexibility to topological changes, the resilience to failures, and the fair energy consumption. However, in using these schemes reliability is not guaranteed nor is the proper functioning of the protocol. Additionally, *SAPF* is suitable for VANETs where cars drive at high speeds, but is not suitable for mobile networks composed of people walking at low speeds [Ruiz et al. 2012]. A review of probabilistic broadcasting protocols and the most common performance metrics used is included in Reina et al. [2015].

b. *Counter-Based Approach*

The stochastic *counter-based* approach [Ni et al. 1999] keeps the node from rebroadcasting in case multiple copies of the message have been received. Upon reception of the broadcast message, the node waits for a random time before rebroadcasting. If during this waiting time several copies of the same message are received, the retransmission is cancelled. In this technique, a node is aware of the network traffic conditions and uses this information in the forwarding decision. All the *counter-based* approaches reviewed next are stochastic.

A low value for the counter threshold (the maximum number of repeated copies allowed) provides high saving in retransmission; however, reachability highly degrades in sparse networks. On the contrary, a high value for this threshold implies high reachability but low savings. This dilemma is tackled in Tseng et al. [2002], where an adaptive and probabilistic counter-based approach is presented. This work introduces the counter threshold as an adaptive function that varies in terms of the number of neighboring nodes.

The *color-based* broadcast algorithm is a variant of the counter-based scheme [Keshavarz-Haddad et al. 2006]. It colors broadcast messages, and all nodes rebroadcast the message after a random timeout unless they already heard η colors at that time.

Chen et al. proposed *DIS RAD* in Chen et al.[2005]. This approach applies the concept of distance-based into the counter-based approach. Nodes closer to the maximal transmission range have higher probability of rebroadcasting and shorter Random Assessment Delay (RAD). How nodes are aware of the distance to the source node is not specified.

An adaptive approach that uses two different threshold values for sparse versus dense networks was proposed in Al-Humoud et al. [2008]. It compares the current number of neighbors to the average and if it is lower, the network is considered sparse, and otherwise dense (how to calculate the average number of neighbors is not specified). The random delay and the counter threshold value are set accordingly.

An adaptive probabilistic counter scheme is presented in Liarokapis and Shahrabi [2009]. In *ProbA*, a node receiving a message sets a random delay. During this waiting time, the node counts the number of repeated copies received, and the forwarding probability is set accordingly. An extension, *Fuzzy Logic Probabilistic* (FLoP) is proposed in Liarokapis and Shahrabi [2011]. The interval of the hello message adapts to the variability of the topology by estimating the difference in the number of neighbors between two consecutive *hello messages*.

c. *Area-Based Approaches*

Two other stochastic techniques, introduced in Ni et al. [1999], are *Distance-Based* (DB) and *location-based*. Both approaches start a random delay when the message is received for the first time, before rebroadcasting. In the former, the forwarding decision is taken in terms of the distance to the source node. In the latter, it is taken in terms of an estimation of the potential additional coverage achieved (using GPS information). Nodes are aware of the network density by estimating the distance to the 1-hop neighbors (or the additional expected coverage area).

In Figure 2, the *distance-based approach* mechanism is shown. Only nodes that are farther than a predefined value (located in the forwarding area; i.e., light gray zone) retransmit the message. In this figure, the candidate nodes for retransmitting the message sent by *Node A* are *Node E* and *Node F*. Next, we mention some of the most relevant work based on these approaches.

Two adaptive versions of the DB approach were presented in Chen et al. [2002], where nodes are sorted according to the received signal strength. The first, *DAD-NUM,* specifies a predefined number of forwarding nodes. The second, *DAD-PER* specifies a percentage of nodes that will rebroadcast the message.

The difficulty of setting up thresholds is highlighted in Sun and Lai [2002]. These authors propose a broadcast algorithm based on a defer time (timeout) before resending. This defer time is inversely proportional to the distance between the sender and receiver nodes. Additionally, an angle-based scheme is proposed to reduce the number of redundant transmissions.

The *Area-Based Beaconless Algorithm* (ABBA) for 2D and 3D needs precise location information [Ovalle-Martínez et al. 2006]. The coordinates of the sender are included in the header of the broadcast packet (e.g., using a GPS). Nodes calculate the portion of the transmission range that is not covered and set a timeout that is inversely proportional to this value. After the waiting time, if more copies

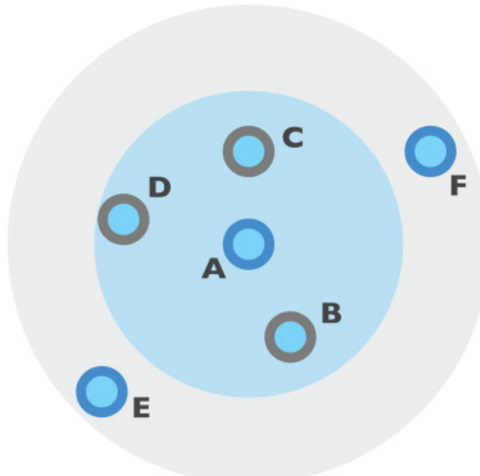

Fig. 2. Distance-based approach.

are received and the transmission range is fully covered, the node cancels the retransmission. Two different approaches for the timeout are proposed: (1) random value between [0 1] seconds (stochastic approach) and (2) proportional to the already covered perimeter (deterministic).

Similar beaconless approaches that include the location of the source node in the header of the message are the *optimized broadcast protocol* [Durresi et al. 2005] and the *geoflood* [Arango et al. 2004]. The former divides the network into a honeycomb. The receiver calculates the distance to the two closest vertices of the honeycomb and starts a delay that is proportional to the shortest distance. The latter divides the transmission area into a cartesian plane. A timeout that is inversely proportional to the distance is set when receiving the message. As soon as a message is received from each of the four quadrants, the retransmission is cancelled. Both approaches are deterministic.

Similar approaches are the *six-shot broadcast* [Garbinato et al. 2008] and the *optimized flooding protocol* [Paruchuri et al. 2003] that considers strategic forwarding positions.

The probabilistic and the distance scheme are combined in Cartigny and Simplot [2003] in their design of a stochastic broadcasting algorithm. The forwarding probability depends on the local density of the network and the distance to the source node. However, no positioning information is used, and only the 1-hop neighbors of the sender are included in the header of the broadcast message. Additionally, the neighbor elimination scheme is used: When no new neighbor is expected to be covered, the node cancels the retransmission.

In CAO et al. [2007], an enhanced distance-based approach is presented including both counter-based and border-aware approaches. The distance to neighboring nodes is calculated using the free space wireless propagation model. This stochastic approach also considers the remaining battery level of the nodes.

An adaptive location-based algorithm that also uses 1-hop information was proposed in Tseng et al. [2002]. The threshold of the covered area is not a fixed value but an adaptive function that adapts to the neighborhood size.

The *efficient directional broadcast* was introduced in Li et al. [2007]. It uses directional antennas and repeaters located at intersections for disseminating the information. Only the furthest node disseminates the message backward (i.e., in the opposite direction to reception). In the same work, a probabilistic scheme is presented. These protocols are intended for VANETs and assume the existence of a network infrastructure.

Transmission failure is mitigated in Huang et al. [2009] who propose a cooperative and opportunistic approach for collision warning in VANETs. Information about the motion is exchanged, and the node's and neighbor's risk of collision are calculated such that, if a danger ahead is detected and the neighbors do not warn, the node can broadcast a message with motion information related to the cars involved in the danger.

In Gang et al. [2012], a directional distance-based broadcasting algorithm that uses percolation theory to select the direction of forwarding is presented. It uses directional antennas for estimating the direction of the source node and the additional coverage area. The value of this additional coverage area influences forwarding probability. Therefore, it is a stochastic model in which no beacons are exchanged.

A distance-based algorithm that takes into account the remaining battery level of devices is proposed in Kasamatsu et al. [2009]. The *Broadcasting Method Considering Battery and Distance* (BMBD) sets a timeout that is inversely proportional to the distance and the battery level; that is, nodes with higher remaining battery and higher distance from the source node set a lower delay. If a copy of the message is heard while waiting, the retransmission is cancelled. This method assumes GPS information is available at nodes.

Three different stochastic approaches are presented in Kokuti and Simon [2012]. The first one, *Distance-Based Handshake Gossiping* (DBHG) is a distance-based protocol where the source node indicates the forwarding probability of neighboring nodes in terms of their distance to itself. The second one, *Valency-Based Handshake Gossiping* (VBHG), adds knowledge of the nodes' degree to the first approach. Finally, *average valency-based handshake gossiping* also considers past decisions for calculating the forwarding probability.

In Slavik et al. [2011], the *distance-to-mean broadcast* method is introduced. The first time a node receives a message, a delay inversely proportional to the distance to the source node is set. When the timeout expires, it calculates the spatial mean of all the neighbors it received the message from and calculates its distance-to-mean. If that distance is higher than a predefined threshold, the message is retransmitted. It requires positional information.

A stateless distance and probability-based approach that does not need to exchange *hello messages* is proposed in Banerjee et al. [2012]. Nodes within 1-hop rebroadcast in terms of the distance to the source. The retransmission probability of nodes located h hops away is calculated and depends on the distance (hops) and network density.

A distance-based beaconless algorithm, *DibA,* is proposed in Liarokapis et al. [2009]. The distance threshold adapts to the number of retransmissions heard of a specific packet. It is a combination of distance-based and counter-based approaches.

Many of the studied works include a RAD before retransmitting the broadcast message. This technique highly reduces the number of collisions and packet losses and allows enough time to receive multiples copies (to decide whether to rebroadcast), but it also increases the delay in the broadcasting process. The maximum value of the RAD highly influences the broadcast time. Indeed, many approaches, including counter-based, area-based, or RAD-based ones, rely on thresholds for decision making, but finding the appropriate value that fits rapidly evolving MANETs is a very complex task that highly influences the performance of the protocols.

Table I. Classification of Non-Topology-Based Algorithms with Fixed Transmission Range: Context Aware and Oblivious Approaches

	Neigh.	Hops	Determ.	GPS	Forward decision
Simple flooding [Ni et al. 1999] *Hyper-flooding [Viswanath and Obraczka 2002]*	local	–	yes	no	source-independent
Probabilistic flooding [Ni et al. 1999] *SAPF [Mylonas et al. 2008]* *[Banerjee et al. 2012]* *[Gang et al. 2012]* *DibA [Liarokapis et al. 2009]* *[Slavik and Mahgoub 2010]*	local	–	no	no	source-independent
Weighted/slotted 1/p -persistent [Wisitpongphan et al. 2007] *Rewarn [Huang et al. 2009]* *Distance-to-mean [Slavik et al. 2011]* *Defer time [Sun and Lai 2002]*	local	1-hop	no	yes	source-independent
Gossip-based broadcast [Kermarrec et al. 2003] *n^{th} power p-persistent [Zhou et al. 2010]* *Adaptive counter [Tseng et al. 2002]* *Color-based [Keshavarz-Haddad et al. 2006]* *DIS RAD [Chen et al. 2005]* *[Al-Humoud et al. 2008]* *ProbA [Liarokapis and Shahrabi 2009]* *Fuzzy logic probabilistic [Liarokapis and Shahrabi 2011]* *DBHG/VBHG/AVBHG [Kokuti and Simon 2012]*	local	1-hop	no	no	source-independent
DAD-NUM/PER [Chen et al. 2002] *BMBD [Kasamatsu et al. 2009]*	local	1-hop	yes	no	source-independent
Optimized broadcast protocol [Durresi et al. 2005] *Geoflood [Arango et al. 2004]* *Six-shot broadcast [Garbinato et al. 2008]* *Optimized flooding protocol [Paruchuri et al. 2003]*	local	–	yes	yes	source-independent
[Cartigny and Simplot 2003] *[CAO et al. 2007]* *[Tseng et al. 2002]*	local	1-hop	yes	yes	source-independent
[Gang et al. 2012]	local	1-hop	yes/no	yes	source-independent
ABBA [Ovalle-Martínez et al. 2006]	local	–	yes/no	yes	source-independent

In this work, we classified the protocols and present a summary of their main features using tables. In these tables, *Neigh., Hops, Determ. GPS,* and *Forward decision*, stand for *neighbor knowledge, number of hops, determinism, need of GPS, and forward decision*, respectively. Table I presents a summary containing the surveyed works that use a fixed transmission range and that are not topology-based.

3.1.3. Neighbor-Knowledge Approaches. By exchanging *hello messages*, nodes are aware of the neighbors within their transmission range. It is possible to obtain 2-hop neighbors' information by including in the beacon the list of 1-hop neighbors. The 2-hop neighbors knowledge gives more topology information, but, at the same time, in highly mobile networks, it is more difficult to have accurate and up-to-date information. There are many works that use neighbor knowledge for making smart forwarding decisions.

Flooding-Based on 1-Hop Neighbors Information and Adaptive Holding (FONIAH) [Lee and Ko 2006] combines neighbor-knowledge-based and area-based flooding. When receiving a message, a node can hold it for some time before rebroadcasting. This timeout is inversely proportional to the distance to the source node. The source node includes in the broadcast message its position and the distance to the farthest neighbor. If all 1-hop neighbors already received the broadcast message, the retransmission is cancelled.

Tonguz et al. present DV-Cast in Tonguz et al. [2007, 2010], a broadcast protocol that only requires location information obtained using GPS to support a wide range of traffic conditions. Both the broadcast storm problem and network disruptions are handled in a distributed fashion. *DV-Cast* specifies the Region of Interest (ROI) and disseminates the message toward that direction. The forwarding decision is taken in terms of the list of 1-hop neighbors and their relative distance. This approach is intended for alert messages in vehicular networks, such that the broadcast message is disseminated backward.

Within the neighbor-knowledge-based approaches, we can also clearly differentiate between two techniques: *self-pruning* and *neighbor designating approaches*. In the former, the potential forwarding node considers whether it should rebroadcast or not. In the latter, the source node decides the forwarding neighbors.

a. *Self-Pruning*

In *flooding with self-pruning,* the header of the dissemination message includes the list of 1-hop neighbor nodes. If additional neighbors are covered with the retransmission, the node schedules the rebroadcast in RAD seconds. In the meantime, it calculates the number of additional neighbors with redundant copies. After a RAD, the message is either sent or discarded [Lim and Kim 2000].

The stochastic *neighbor-coverage scheme* is proposed in Tseng et al. [2002]. It uses 2-hop neighbors' information to know if the broadcast message was not received by any 1-hop neighbors. A list of 1-hop neighbors is created, and the random delay is set the first time the broadcast message is received. All nodes that are potentially receiving the message are eliminated from this list. If all the 1-hop nodes did receive the packet, the retransmission is interrupted.

The *Scalable Broadcast Algorithm* (SBA) that uses 2-hop neighbors knowledge is presented in Peng and Lu [2000]. It is similar to *flooding with self-pruning,* but the information is included in the beacons, not in the packet header. They also proposed a RAD that dynamically adjusts to network conditions. The lower limit of the RAD interval is 0, and the upper one is proportional to the node maximum degree divided by the number of neighbors it actually has. See Equation (1):

$$RAD : r \in \left[0, \alpha * \frac{max\_degree}{num\_neighbors}\right] \tag{1}$$

Delayed Flooding with Cumulative Neighborhood (DFCN) [Hogie et al. 2004] includes the 1-hop neighbors list in the packet header. The potential coverage obtained in case of forwarding is calculated, and, if the estimation is larger than a predefined value, the message is scheduled to be retransmitted after a RAD. Additionally, it adapts to the local network density: When the number of 1-hop neighbor is lower than a threshold, the predefined value is set to 1 (it rebroadcasts if there is at least one neighbor to cover). Moreover, if the node density is considered to be low and the forwarding probability 1, whenever a new neighbor is met, the RAD is stopped and the message is rebroadcast. Therefore, flooding with self-pruning [Lim and Kim 2000] can be considered a special case of DFCN.

In Khabbazian et al. [2012], a hybrid broadcasting algorithm that uses 2-hop neighbors' information combining the neighbor designating scheme with self-pruning is presented. The source node selects at most one forwarding node from the set of 1-hop neighbors. At reception, if the node is not selected as a relay, it creates a list of neighbors and removes from it the neighbors of the sender and the neighbors of the selected forwarding node. The message is dropped if the list is empty, otherwise retransmitted.

The *Lightweight and Efficient Network-Wide Broadcast* (LENWB) was proposed in Sucec and Marsic [2000]. This approach uses 2-hop neighbors' information and includes the degrees of the 1- and 2-hop neighbors in the beacon. The source node does not select forwarding nodes, but nodes rebroadcast using the knowledge of which of the 1- and 2-hop neighbors are expected to forward the message. Nodes have priority according to their degrees (i.e., nodes with more neighbors have higher priority).

b. *Neighbor-Designating Approaches*

These are source-dependent approaches (i.e., the source node decides which neighbors will retransmit the broadcast message). Different techniques for selecting the forwarding nodes have been proposed. Here, we review the most relevant ones.

Dominant pruning [Lim and Kim 2000] includes in the header of the packet in a list with the forwarding nodes. These nodes calculate the new forwarding list using the *Greedy set cover algorithm* (neighbors of the source node are considered already covered; choose the 1-hop neighbor that covers the most 2-hop neighbors; repeat until all 2-hop neighbors are covered). It is a very promising approach, but it does not prevent redundant retransmissions.

Total Dominant Pruning (TDP) and *Partial Dominant Pruning* (PDP) are both proposed in Lou and Wu [2002] for enhancing *dominant pruning* by further decreasing redundancy. In the former, the sender includes in the broadcast packet the 2-hop neighborhood information such that the receiver can consider all those nodes as already covered, with consequent increase in consumed bandwidth. The latter induces that information from the 2-hop neighbors' knowledge, without piggybacking any information to the broadcast message. In dense networks, this technique is less efficient than in sparse ones.

In *Multipoint Relay* (MPR) [Qayyum et al. 2000], unlike dominant pruning, the list of relaying nodes is included in the exchanged beacons, not in the header of the broadcast message. The selecting mechanism works as follows: first, check the 2-hop neighbors that can only be reached by one 1-hop neighbors and select them as MPRs. Then, from the remaining 1-hop neighbors, select those that cover the most 2-hop neighbors that are not covered yet. Continue until all 2-hop neighbors are covered. For a graphical explanation, please see Figure 3. Only the blue nodes are in charge of retransmitting the broadcast messages.

The well-known Optimized Link State Routing Protocol (OLSR) routing protocol is based on MPR. For a more detailed explanation, please refer to the Internet draft RFC 3626 [Clausen and Jacquet 2003]. A survey on multipoint relays and connected dominating sets approaches for broadcasting is presented in Liang [2007].

In the *Ad Hoc Broadcast Protocol* (AHBP) presented in Lu [2001], the forwarding nodes are called *Broadcast Relay Gateways* (BRGs). The mechanism for selecting the BGRs is identical to MPR. The differences are that (1) nodes are informed about

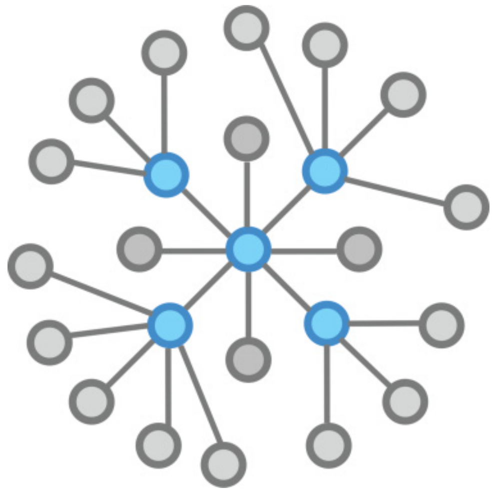

Fig. 3. Multipoint relay mechanism.

becoming a BGR in the header of the packet, not using the beacons; and (2) 2-hop neighbors' knowledge is used to determine which neighbors are already covered. AHBP-EX is an extension of the protocol proposed in Lu [2001] to support mobility aspects. If a message is received but did not previously exchange beacons with the source node (i.e., due to its mobility), it assumes it is a BGR.

There are plenty of MPR-based broadcasting algorithms that modify the MPR selection procedure in order to reduce the number of collisions, the cardinality of the MPR, or to improve the energy management efficiency. We briefly mention some of them. In Mans and Shrestha [2004], the authors propose different models like the *in-degree greedy set cover* that first checks the 2-hop neighbors that can only be reached by one 1-hop neighbor and selects them as MPRs. Then, the algorithm randomly picks up a node from the noncovered 2-hop nodes, among all 1-hop neighbors that can cover this 2-hop node and that have not been selected as MPRs by the source node S; it then selects a node as an MPR that has minimum number of noncovered 2-hop neighbors. It continues until all 2-hop neighbors are covered. The same authors also proposed *MPR Selection with Minimum Overlapping* for reducing traffic and the risk of collisions. As with other approaches, 1-hop neighbors are first listed and then the node with the minimum coverage ratio is chosen as an MPR among the 1-hop neighbors that are not selected as MPRs yet. This is done until all 2-hop neighbors are covered. The coverage ratio is defined as the ratio of covered 2-hop neighbors over noncovered 2-hop neighbors of a node.

Another technique, *weighted set cover*, gives weights to nodes according to a desired property (e.g., bandwidth) and selects the 1-hop neighbor with the largest number of noncovered nodes over the weight ratio. The *MPR Selection with secondary priority* that provides priority to the nodes with a maximal number of neighbors is also proposed. This is applied to OLSR, in case two nodes have the same number of noncovered neighbors.

In Lipman et al. [2002], the authors propose to select MPR nodes in terms of the *forwarding utility* of the 1-hop neighbors. This *forwarding utility* is computed as a function of the power utility of each node (remaining battery) and the neighbor utility (the ratio of noncovered 2-hop neighbors over all the 2-hop nodes that a 1-hop neighbor node covers). As with previous approaches, the algorithm first checks the 2-hop neighbors that can only be reached by one 1-hop neighbor and selects them

Table II. Classification of Non-Topology-Based and Neighbor-Based Algorithms with Fixed Transmission Range

	Neigh.	Hops	Determ.	GPS	Forward decision
FONIAH [Lee and Ko 2006] *DV-CAST [Tonguz et al. 2010]*	local	1-hop	no	yes	source-independent
VMP [Bai et al. 2009]	local	1-hop	yes	yes	source-dependent
Flooding with self pruning [Lim and Kim 2000] *DFCN[Hogie et al. 2004]*	local	1-hop	no	no	source-independent
Neighbor-coverage scheme [Tseng et al. 2002] *SBA [Peng and Lu 2000]*	local	2-hop	no	no	source-independent
TDP/PDP[Lou and Wu 2002] *LENWB[Sucec and Marsic 2000]*	local	2-hop	yes	no	source-independent
[Mans and Shrestha 2004]	local	2-hop	no	no	source-dependent
Dominant pruning[Lim and Kim 2000] *Multipoint relay [Qayyum et al. 2000]* *AHBP [Peng and Lu 2001]* *[Lipman et al. 2002]* *[Lipman et al. 2003]* *[Ahn and Lee 2011]* *[Clausen and Jacquet 2003]* *Double-covered broadcast [Lou and Wu 2004]*	local	2-hop	yes	no	source-independent
[Khabbazian et al. 2012]	local	2-hop	yes	no	source indep./dep.

as MPRs. Then, it selects as MPR the node with highest *forwarding utility* value. The process continues until all 2-hop neighbors are covered. Later in Lipman et al. [2003], the first steps of the MRP approach were eliminated, and MPR nodes are only selected in terms of the *forwarding utility* value.

Additional MPR nodes are chosen in order to provide reliable broadcasts in Ahn and Lee [2011] and Clausen and Jacquet [2003]. The redundancy method proposed in Ahn and Lee [2011] chooses additional MPRs to cover only *selected* 2-hop nodes. In Clausen and Jacquet [2003], the redundant MPRs cover all the subset of 2-hop neighbors, thereby reducing the cardinality of MPRs while at the same time increasing the delivery ratio. The idea is that the 2-hop MPR nodes must be covered at least *m-times*.

The *Double-Covered Broadcast* (DCB) algorithm [Lou and Wu 2004] is a source-dependent protocol in which the source node chooses the set of 1-hop neighbors that covers all 2-hop neighbors and the non-forward 1-hop neighbors are covered by at least two forwarding nodes. The retransmissions of the forwarding nodes are considered acknowledgments; thus, when the source does not hear from the forwarders it will simply rebroadcast the message.

Bai et al. [2009] introduces the *Vehicular Multi-Hop Broadcasting Protocol (VMP)* that disseminates the message in the opposite direction. VMP designates multiple delays and forwarding nodes (i.e., it is source-dependent) for disseminating an alert message in a predefined zone. In order to assure high reachability and avoid unnecessary retransmissions, a cooperation schema between nodes and a procedure for detecting duplicated packets are used.

In Table II, a summary containing the surveyed works that use a fixed transmission range and that are not topology-based is presented.

3.2. Variable Transmission Range

Energy consumption in MANETs is a key problem because the network degrades as the batteries of devices fail. Two different approaches are considered for decreasing energy consumption in MANETs. The first deals with reducing the number of retransmissions. All the above-surveyed papers use this approach. The second approach considers reducing transmission power. The first one can be seen as the *fixed-power approach* that was already surveyed, and the second one is *a variable-power* approach that we review here next.

In the *variable-power* approach, each node can transmit using different transmission radii; therefore, the number of reached neighbors when broadcasting a message varies according to the transmission power. Several works try to find a common power level that guarantees a low node degree [Kawadia and Kumar 2005] or ensures that the communication graph is connected with at least k-neighbors over a uniformly distributed network [Blough et al. 2006]. Every node has to communicate with each other for selecting the common transmission power. Such approaches are not scalable because the overhead increases with the size of the network. However, in Gomez and Campbell [2007], it was demonstrated that a variable transmission range provides better energy savings and network capacity than the fixed transmission range. Moreover, the authors assert that there exists a best-choice transmission range that maximizes the nodes' capacity in the presence of mobility. A survey on conserving power by employing transmission power control can be found in Guo and Yang [2007]. When considering the variable transmission power of nodes, adjusting each node with an optimal transmission radius is a key issue that is addressed by the two following instances: the *minimum h range assignment* and the *minimum energy broadcast* problems.

Definition 3.1 (*The minimum h range assignment problem [Clementi et al. 2000]*). "Given a finite set S of points (i.e., the stations of a radio network) on the plane and a positive integer $1 \leq h \leq |S| - 1$, the 2-dimensional minimum h range assignment problem consists of assigning transmission ranges to the stations in order to minimize the total power consumption, provided that the transmission ranges of the stations ensure the communication between any pair of stations in at most h hops."

Definition 3.2 (*The minimum energy broadcast problem [Cagalj et al. 2002]*). Given a graph $G = (V, E)$, where each node $i \in V$ is assigned a variable node power p_i^v, we assign a link cost $c_{ij} : E(G) \rightarrow R_+$ that is equal to the minimum transmission power necessary to maintain link (i, j).

Considering a source node v that wants to broadcast a message, *the minimum energy broadcast problem* consists of finding the power assignment vector $P = [p_1^v, p_2^v \dots p_{|V|}^v]$ such that it induces the directed graph $G = (V, E')$, where $E' = (i, j) \in E : cij \leq p_i^v$, in which there is a path from v to any node of V (all nodes being covered), and such that

$$min \sum_{i \in V} p_i^v$$

As demonstrated in Clementi et al. [2000] and in Cagalj et al. [2002], both *minimum h assignment* and the *minimum energy broadcast* are NP-hard problems. The main difference between them is that, in the former, the source of the broadcasting algorithm is not considered whereas in the latter, it is. Tree topology has been widely used to solve these problems. This approach is addressed in detail in Section 4.

Cartigny et al. presented the *RNG broadcast-oriented protocol* in Cartigny et al. [2003]. It runs locally at each node but requires knowledge of the distance to all neighbors and between neighboring devices. The RNG graph stands for the Relative Neighborhood Graph, and it is an undirected graph in which two points are connected with a new edge if there is no other node closer to both of them (see Figure 4, where there cannot be any neighbor in the striped area in order to have two RNG neighbors). If a packet is received from any RNG neighbor, it is retransmitted using the minimum

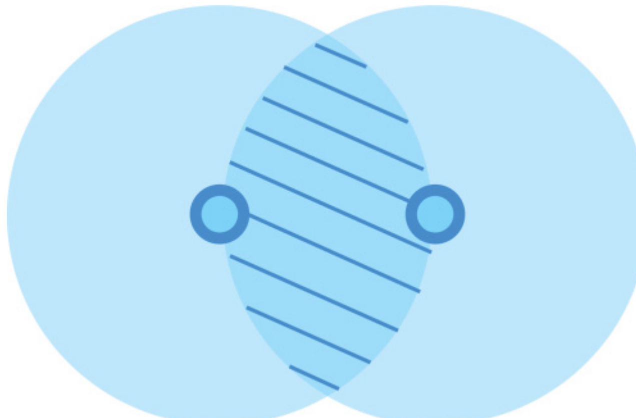

Fig. 4. Relative neighborhood graph.

transmission range that covers the furthest RNG neighbor that did not receive it yet. Otherwise, it starts a timeout and creates a list with all the RNG neighbors that did not receive it. If after the waiting time the list is not empty, it rebroadcasts the message with the minimum transmission range that covers the farthest RNG neighbor in the list. A different version where the timeout is set every time a message is received is proposed in Cartigny et al. [2005].

The notion of a *forbidden set* in the relative neighborhood graph is incorporated in Wang et al. [2010]. This forbidden set prevents nodes with low battery levels to act as forwarders in the dissemination process. Additionally, when redundant retransmissions are received, the node will change its relative neighbor or will ask to be covered by only one.

In Chen et al. [2003], *Power Adaptive Broadcasting with Local Information* (PABLO) is proposed. In PABLO, nodes calculate the transmission power required to reach 2-hop neighbors. After that, the source node estimates the energy needed to reach the farthest node directly or through an intermediary node. In case the latter is cheaper in terms of energy consumption, the source node reduces transmission power and thus discards the farthest node. See Figure 5, where *node A* excludes *node C* from the 1-hop neighborhood if the sum of the power *node A* needs to reach *node B* plus the power *node B* needs to reach *node C* is lower than the power *node A* needs to directly reach *node C*.

In Karenos et al. [2005], an extension to PABLO is proposed that applies neighborhood pruning; that is, after performing the optimization, the algorithm considers the possibility of excluding the farthest node(s).

The transmission range is set in terms of local density in Li et al. [2003]. This local density is estimated using an analytical model.

The *Inside-Out Power Adaptive* (INOP) approach is presented in Chiganmi et al. [2008]. It uses 2-hop neighbors' knowledge to obtain good energy utilization for covering all direct neighbors. The difference from other existing approaches is that each node first sorts the neighbors in terms of the power needed to cover them and then computes the optimal energy strategy starting from the closest neighbor to cover the next neighbor directly or indirectly. Two different versions for selecting the relay nodes are proposed. (1) *INOP with self-pruning* sets a random timeout from an interval whose range inversely depends on the number of noncovered neighbors. If after a delay the list of neighbors that were not covered is empty, the rebroadcast is cancelled. And (2) *INOP with neighbor designation* considers the possibility of increasing the

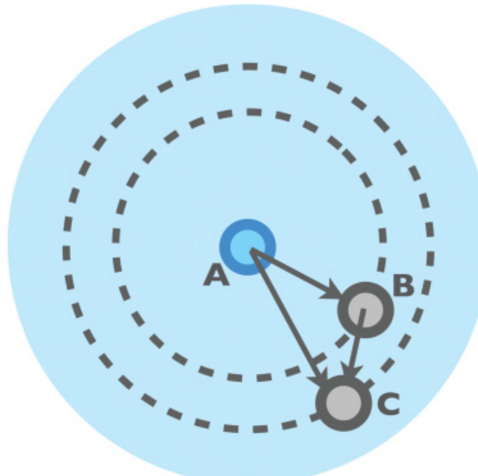

Fig. 5. Mechanism of PABLO.

transmission power of an already selected relay node instead of adding a new relay for covering a noncovered neighbor. Considering that the timeout is randomly set, the INOP approaches are stochastic. The main drawback of the previous approaches is that they do not consider a limit when decreasing the transmission range; thus, it could happen that the number of hops for disseminating a message highly increases. In Woon and Yeung [2011], different versions of *dominant pruning, total dominant pruning, partial dominant pruning, INOP, and PABLO* using different termination conditions and variable transmission power are compared.

A distance-based approach (EDB) aiming at reducing energy consumption and that relies on a cross-layer design and a variable transmission range is introduced in Ruiz and Bouvry [2010b]. An adaptive version that targets energy saving in dense networks by discarding nodes from the 1-hop neighborhood was later presented in Ruiz and Bouvry [2010a], AEDB. In this case, the transmission range is not decreased to any extent but to a predefined value, such that the number of hops does not highly increase.

In Schleich et al. [2011] community knowledge is used for improving the coverage achieved by message dissemination. Nodes that belong to two different communities always rebroadcast the message, although the forwarding policy prevents retransmission. This favors fast dissemination within different communities.

Reumerman and Runi [2005] introduce another technique where the path loss information is included in the beacons so that neighboring nodes can be arranged in a list in terms of average path loss. A predefined number of nodes that must be reached is set. Thus, a node receiving a packet adjusts its transmission range in order to cover the target number of nodes.

The *Efficient Reliable 1-Hop Broadcasting* (EROB) algorithm is introduced in Park and Yoo [2013]. It considers simultaneous transmission over three different channels: two control channels and another for data packets. It proposes the use of a control packet called BIP (Broadcast In Progress) to avoid the *hidden terminal problem* while broadcasting. Additionally, nodes can use different transmission levels for enhancing network throughput and lifetime, as well as reducing power consumption and the number of collisions.

In *RandomCast* [Lim et al. 2009], the algorithm uses the *Power-Saving Mechanism* of 802.11 (PSM) [Anastasi et al. 2008] that allows a device to be in a low-power sleep state if it is not concerned with data transmission. However, nodes in *RandomCast*

Table III. Classification of the Non-Topology-Based Algorithms with Variable Transmission Range

	Neigh.	Hops	Determ.	GPS	Forward decision
RNG [Cartigny et al. 2003] *[Cartigny et al. 2005]* *[Wang et al. 2010]*	local	2-hop	yes	yes	source-independent
PABLO [Chen et al. 2003]	local	2-hop	no	no	source-independent
INOP [Chiganmi et al. 2008]	local	2-hop	no	no	source-indep./dep.
[Reumerman and Runi 2005]	local	1-hop	yes	no	source-independent
EROB [Park and Yoo 2013]	local	1-hop	no	yes	source-independent
RandomCast [Lim et al. 2009] *EDB [Ruiz and Bouvry 2010b]* *AEDB [Ruiz and Bouvry 2010a]* *[Schleich et al. 2011]*	local	1-hop	no	no	source-independent

consistently operate in PS mode. The transmitter can specify the level of overhearing for unicast packets. Additionally, the probability of rebroadcasting is also based on the number of 1- and 2-hop neighbors.

In Table III, a summary containing the surveyed works that use a variable transmission range and that are not topology-based is presented.

4. TOPOLOGY-BASED ALGORITHMS

Topologies in the network provide nodes with extra information that may be used for making smart forwarding decisions. Therefore, many works propose either creating a topology in the network or using it (in case it was already created for other purposes). As already mentioned in Section 2, three topological structures mainly have been used to solve the broadcast problem: *connected dominating sets, tree-based,* and *cluster-based* topologies.

Literature reveals that the construction and maintenance of these three different topologies have been addressed using many different techniques, and many different broadcasting algorithms working on top of those topologies have also been proposed. Mainly, we can classify them into approaches that either use a fixed or a variable transmission range. Here, we briefly review the most relevant works.

4.1. Fixed Transmission Range

4.1.1. Connected Dominating Set. A Connected Dominating Set (CDS) is a source-independent technique that builds a subnetwork, also called *virtual backbone*, for covering every single device in the network. Nodes either belong to the backbone or are adjacent to at least one of the backbone nodes. An extensive review can be found in Yu et al. [2013]. In graph theory, a CDS is defined as follows:

Definition 4.1 (*Connected Dominating Sets [CDS]*). A CDS for $G = (V, E)$ is a subset $V' \subseteq V$ such that for all $u \in V - V'$ there is at least a $v \in V'$ for which $(u, v) \in E$, and the subgraph induced by V', $G[V']$ has only one connected component.

A CDS contains a group of connected nodes that covers all the network, forming a virtual backbone. Efficient broadcasting can be achieved by identifying a CDS, preferably small, and allowing only the nodes in the CDS to forward the message. Peng and Lu propose an efficient CDS-based broadcasting algorithm in Peng and Lu [2001]. The algorithm uses 2-hop knowledge and includes information about the dominant nodes (or nodes belonging to the backbone) in the message. An important difference is that not only are nodes covered by the source node not considered for inclusion in the CDS anymore, but also those nodes covered by other dominant nodes that were selected earlier.

A marking process was proposed in Wu and Li [1999] for efficiently and quickly determining a CDS. Originally, it was proposed only for undirected graphs using the concept of a dominating set, but it was later extended to support directed graphs by introducing the notion of absorbent sets [Wu 2002]. Specifically, a node becomes a gateway if it has two unconnected neighbors.

Wu et al. [2000] proposed a broadcasting and routing algorithm based on CDSs and on dynamic selection of the dominating nodes. The algorithm alternates the nodes belonging to the CDS when possible because they consume more energy. Additionally, nodes with higher remaining battery levels are preferred.

Adjih et al. [2004] proposed a source-independent MPR approach for creating and maintaining a CDS in the network before any broadcasting process starts, using two simple rules. A node belongs to the CDS if it is the smallest in its neighborhood or if it was selected as a forwarder by the neighbor with the lowest node ID. In Wu et al. [2006], Wu and Lou proposed an enhancement of this source-independent MPR [Adjih et al. 2004] for creating a relatively stable CDS. They use 3-hop neighbors' knowledge in order to have complete 2-hop information; that is, the connections between any 2-hop neighbors. The authors extend the concept of coverage by considering that a node is covered by another if it is included in its 1-hop neighborhood (directly covered) or if it is a 2-hop neighbor (indirectly covered). During the construction of the CDS, each node chooses a pair of nodes, a 1-hop and a 2-hop neighbor, to cover all its 2-hop neighbors. The main difference here is that 2-hop nodes can be indirectly selected to cover other 2-hop neighbors.

The *Rule k* was proposed in Dai and Wu [2003] to reduce the overhead for creating CDSs. It is fully decentralized and supports unidirectional links. This protocol was modified in Stojmenović and Wu [2004] to eliminate the exchange of messages needed to create the CDS.

Stojmenović et al. proposed a broadcasting algorithm based on dominating sets and neighbor elimination schemes using 2-hop knowledge [Stojmenović et al. 2002]. Only nodes belonging to the CDS are able to rebroadcast a message. Upon reception, nodes in the CDS set a delay that is inversely proportional to the number of noncovered neighbors. During the waiting period, if copies of the message are heard, all the neighbors receiving the message are also removed from the forwarding list. If there is no neighbor to cover, the neighbor elimination rule cancels the retransmission.

In order to improve reliability and solve disconnection problems, in Stojmenović et al. [2012] the authors proposed a broadcasting algorithm that works like their previous algorithm [Stojmenović et al. 2002], but all nodes can rebroadcast a packet. Nodes that are not included in the CDS set a longer waiting time, and, additionally, every time a new neighbor is met, the broadcast message is sent.

Recently, a general framework for broadcasting that seamlessly (without using any parameter) adjusts itself to any mobility scenario was introduced in Stojmenović [2012]. It is built over several recent algorithms using 2-hop topological or 1-hop positional knowledge. When the message is received the first time, nodes set a timeout and also generate 2 lists: R with the nodes believed to have received the packet, and N with the nodes that did not receive the message yet. Nodes belonging to the CDS have shorter timeouts than those not included in the CDS. Once the waiting time is finished, the node retransmits only if N is not empty, and it updates both R and N. After receiving each hello message, nodes reevaluate the CDS status (if it is a dominating or a dominated node) and also update N. If N was empty and a new neighbor not included in R is detected, the timeout is reactivated.

Literature reveals different decentralized CDSs that use local knowledge in dynamic ad hoc networks. Two proposals designed to create k-vertex connected m-vertex dominating set virtual backbones in an asynchronous and computer-effective way are

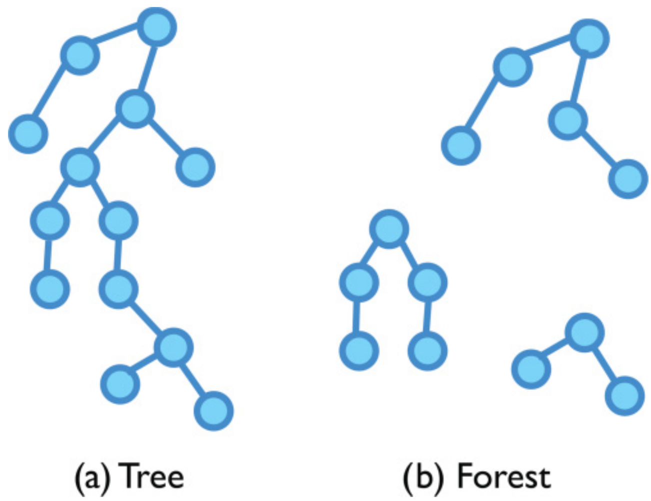

Fig. 6. Tree and forest topologies.

presented in Leu and Chang [2011] and Schleich et al. [2012]. For a more detailed explanation on CDSs, please refer to Schleich [2010].

4.1.2. Tree-Based Topology. All the already-mentioned approaches have to store the ID of the broadcast message in order to simply rebroadcast the first reception of the message. The most straightforward method for avoiding the storage of any ID is to broadcast the packet using an acyclic subgraph (i.e., a tree topology).

A network can be modeled as a graph $G = (V, E)$, where nodes are represented by the set of vertices V and the links are the set of edges E. It is possible to define an underlying structure in the network, as done with the CDS and clustering, that forms a tree. To disseminate a message to all nodes in the network, we can consider the spanning tree structure in which only nodes belonging to the tree that are not leaves retransmit the message. Here, we define both concepts: tree and spanning tree.

Definition 4.2 (*Tree topology*). A tree is an undirected and connected graph that has no cycles.

Definition 4.3 (*Spanning tree*). A spanning tree is an undirected and connected subgraph that has no cycles and contains all nodes. It can be defined as the maximal set of edges of the graph that contains no cycle or as a minimal set of edges that connect all vertices of the graph. The Minimum Spanning Tree (MST) is the minimal set of edges that connect all vertices of the graph, or, in case the graph is weighted, the minimum sum of the weight of all branches.

In case the network is partitioned, we can talk about a *spanning forest*, where a spanning tree is formed in every connected component (see Figure 6).

The maximum leaf spanning tree problem is equivalent to the minimum CDS problem [Fujie 2003]. In a tree-based topology, edges are chosen and play an important role, whereas in CDS the nodes play the central role. However, the construction of the spanning tree from a CDS is quite straightforward. In Figure 7, we can see a graphical representation.

Tree topology has been widely used in telecommunication networks [Information Technology 1998], but most of these algorithms need a stable network, which is not available in MANETs. Therefore, specific algorithms for MANETs must be designed.

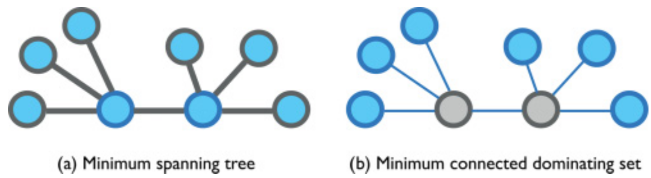

Fig. 7. Minimum spanning tree and and minimum CDS.

Creating and maintaining a tree topology in MANETs is challenging because the nodes have only knowledge about their direct neighbors, and the links are very volatile. Therefore, the data structure and the required maintenance of the tree must be minimal. It is possible to differentiate between source-dependent and shared trees. In a *source-dependent tree,* the root of the tree is located at the source node, and, for each pair of source-multicast group, a different tree is built. In the *shared tree,* only one tree is built over the network, and the source node just needs to be able to send data to the root of the tree or to a member.

In Radhakrishnan et al. [1999], the authors proposed a distributed spanning tree to forward data packets. However, some operations require centralized designs (e.g., when merging two spanning trees, the root node decides which are merging nodes).

Using the overlay of a gossip protocol, the *push-lazy-push multicast tree* (Plumtree) is constructed in Leitao et al. [2007]. The links from which a node receives messages are considered to form the spanning tree, and, when a packet is received twice, the node prunes this link. However, for repairing the tree, every time a node receives a message it sends an *IHAVE message* to the links that do not belong to the spanning tree. Whenever a node requests this message, the link between these two nodes becomes part of the spanning tree.

A fully distributed and decentralized method, *TreeCast,* is proposed in Juttner and Magi [2005]. It is not only capable of dealing with node mobility, but it also forces nodes with high mobility to be leaves; thus, the backbone is composed of the more static nodes.

A parameterless broadcast algorithm working over a tree topology, BODYF, is presented in Ruiz et al. [2008]. It uses topology information for fast dissemination but does not prevent neighboring nodes from receiving the message (i.e., it does not multicast the message to its neighboring tree nodes, but instead broadcasts the message). In a mobile environment, it is very unlikely to have a single tree over the network, but instead a forest. Thus, BODYF is able to disseminate the message over different trees. In Ruiz et al. [2012], a more efficient version of BODYF is proposed and tested over different MANET and VANET scenarios. Additionally, a comparison between different broadcast algorithms is presented.

MaxCST [Flauzac et al. 2010] is a deterministic and self-establishing algorithm that builds a cluster in the network with a diameter of 2 at most and then constructs a spanning tree on the network.

The creation of a tree topology in decentralized systems is a complex task, usually addressed by computing the local tree and then merging adjacent trees (e.g., the LMST [Li et al. 2005]). This approach requires static or low-mobility networks. However, the *dynamicity aware graph relabeling system* [Casteigts and Chaumette 2005] is a high-level abstraction model for creating and maintaining tree topologies efficiently. It is based on local rules that are able to cope with topological changes. Also in Casteigts et al. [2013], a decentralized algorithm able to cope with the creation and maintenance of distributed spanning trees in highly dynamic networks is presented. Both the merging and splitting processes of two trees are purely locally operated.

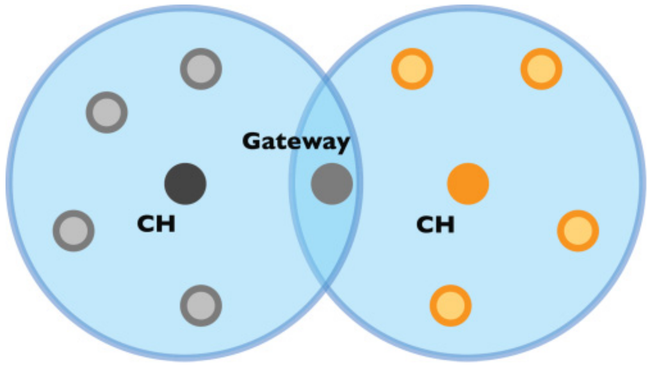

Fig. 8. Two adjacent clusters with a gateway.

Many works also look beyond the topological aspects and attach specific features to nodes; for example, in Piyatumrong et al. [2008], nodes are selected for joining the tree in terms of their level of trust in the network, thus creating more reliable topologies. For a more detailed overview of this type of tree-based topologies, please refer to Piyatumrong [2010].

4.1.3. Clustering-Based Topology. A clustered network is a 2-level hierarchical network that divides nodes into groups and elects only one node as representative of the group, the clusterhead (CH). The CH directly connects to all other members of the cluster. Nodes belonging to one CH, but that can hear at least two CHs, declare themselves *gateway*s (see Figure 8). The set of CHs forms a dominating set, but not a CDS. To build a CDS, CHs must elect the *gateways* as the forwarding nodes for connecting two neighboring CHs.

The main goal of both CDS and trees is to cover the whole network using the minimum number of nodes in the CDS or obtaining the maximum number of leaves. However, in clustering, the main goal is to group nodes in terms of some common features or a joint goal.

This cluster-based network structure has a straightforward application in hybrid networks, where some uplinks are established with a backbone infrastructure. Additionally, designating a special role for one of the nodes, the CH, offers many advantages for optimizing energy consumption, network organization, data aggregation, and the like. However, the failure of a CH has big impact on the performance of the clustered network, as well as on the overhead due to re-election and re-clustering of the network. Also, node mobility plays an important role in clustering because continuous formation and maintenance of the cluster is required, which leads to big overhead and less stable networks.

Mainly, there are two different approaches to clustering: (1) *active clustering*, where nodes cooperate to elect the CH by exchanging information periodically, and (2) *passive clustering,* where the CH election starts with ongoing traffic. Information is propagated in the packets and collected through eavesdropping such that there is no induced overhead or setup costs.

In the *Lowest ID* (LID) clustering algorithm [Ephremides et al. 1987], all nodes are initially colored white. A white node with the lowest ID among its non-CH neighbors chooses itself as CH and turns black, and all white neighbors join this CH and turn themselves gray. The process finishes when there are no more white nodes. The *Highest Degree (HD) algorithm* [Gerla and Tsai 1995], first considers the node degree in the clustering decision. In case of a tie, the lowest ID node is selected. A survey on different clustering techniques can be found in Yu and Chong [2005]. Next, we present some of the most relevant broadcasting algorithms based on clustering approaches.

In Gerla et al. [2000], a broadcasting algorithm based on passive clustering is proposed. Nodes decide to become either a CH, an ordinary node, or a gateway in terms of some predefined thresholds. Both CHs and gateways rebroadcast the message.

For electing the CHs, not only location information but also the battery level is used in Li et al. [2004]. The proposed *vote-based clustering* considers nodes with high degree and battery level better candidates for becoming CHs. However, this results in a frequently changing topology.

A weighted algorithm called WACA was presented in Brust et al. [2007]. It is an application-driven algorithm in that the heuristic weight function depends on the targeted application. The concept of a subhead is considered in this case; that is, nodes elect a neighbor as CH, but this CH also elects another neighbor as CH.

One of the main challenges in clustering is related to mobility: Mobility causes very frequent CH changes and thus leads to an unstable structure. To cope with this problem, link stability is also considered in the *Node and Link Weighted Clustering Algorithm* (NLWCA) [Andronache and Rothkugel 2008]. It uses the node state (device power and signal strength) and link stability for electing CHs. For broadcasting, CHs disseminate the message within their own cluster but also send it directly to all stable neighboring CHs by unicast [Andronache et al. 2008].

Wu and Lou [2003] proposed a clustered network in which each CH selects the forwarding nodes inside the cluster so that all CHs in the vicinity are covered. CHs receiving the message are included in the broadcast message so that CHs can deduce the coverage area by the pruning technique. Instead of the 3-hop covered area, this paper introduces the novel idea of 2.5-hop coverage. Every CH only reaches those CHs that have members not beyond 2 hops.

Node mobility really influences and degrades the quality of the cluster structure. Thus, reducing the number of clusters in the network will improve scalability, and increasing the number of hops inside the cluster reduces the effect of mobility. That motivates the k-hop clustering algorithms that allow us to choose the diameter of the network and add more flexibility. Nocetti et al. generalized the clustering definition in Nocetti et al. [2003], where any node in the cluster is at most k-hops from the CH. In this work, the authors proposed an approach for k-clustering in which CHs are elected in terms of connectivity and lowerID. One main concern in clustering is that a CH may become a bottleneck; thus, Fernandess and Malkhi [2002] give a formal definition of the minimum k-clustering problem in which the network is divided into clusters without using CHs.

Definition 4.4 (*Minimum k-Clustering*). Given a unit disk graph denoted by $G = (V, E)$ and a positive integer k, find the smallest value of l such that there is a partition of V into l disjoint subsets $V_1 \ldots V_l$ and $diam\ (G[V_i]) \leq k$ for $i = 1..l$.

In this work [Fernandess and Malkhi 2002], the authors also proposed an algorithm that first creates a spanning tree and then partitions it. However, it does not deal with mobility or topology changes.

KHOPCA is proposed in Brust et al. [2008], a k-hop clustering algorithm that only uses 1-hop neighborhood information for cluster creation and maintenance based on some rules. Nodes change their status depending on their weight and their direct neighbors. The algorithms works in a distributed fashion and is highly adaptive to mobility. It is based on rules like the max-min heuristic proposed in Amis et al. [2000] k-hop clustering, where CHs are selected according to the ID of the nodes. The number of hops in the cluster determines the number of rounds for exchanging information. Additionally, the system tries to maintain stability in the cluster by re-electing CHs

Table IV. Classification of the Topology-Based Algorithms with Fixed Transmission Range

		Neigh.	Hops	Determ.	GPS	Forward decision
CDS	*[Wu et al. 2006]*	local	3-hop	yes	no	structure
	others	local	2-hop	yes	no	structure
Trees	*PlumTree [Leitao et al. 2007]* *BODYF [Ruiz et al. 2008]* [Ruiz et al. 2012]	local	1-hop	no	no	structure
	[Radhakrishnan et al. 1999]	local/ global	1-hop	yes	no	structure
	TreeCast [Juttner and Magi 2005]	local	2-hop	yes	no	structure
	others	local	1-hop	yes	no	structure
Clustering	*NLWCA [Andronache and Rothkugel 2008]* *WACA [Brust et al. 2007]* *KHOPCA [Brust et al. 2008]*	local	1-hop	yes	no	structure
	[Gerla et al. 2000]	local	–	yes	no	structure
	Vote-based clustering [Li et al. 2004]	local	1-hop	yes	yes	structure
	[Wu and Lou 2003]	local	2.5-hop	yes	no	structure
	Lowest ID [Ephremides et al. 1987] *Highest degree [Gerla and Tsai 1995]*	local	2-hop	yes	no	structure

when possible. A recent survey dedicated to clustering algorithms in MANETs can be found in Bentaleb et al. [2013].

In Table IV, a summary containing the surveyed works with fixed transmission range and that are topology-based is presented.

4.2. Using a Variable Transmission Range

Next, we survey different topology-based algorithms where nodes can vary their transmission range.

4.2.1. Connected Dominating Sets. A broadcasting algorithm that uses a variable transmission range based on CDSs is presented in Wu and Wu [2003]. As nodes belonging to the CDS consume more energy, they alternate when possible. Additionally, the transmission power of every node is reduced during dissemination, with no detriment to the reachability.

Some distance rules where node's transmission power might be adjusted based on distance are proposed in Stojmenović and Wu [2004]. Moreover, nodes with less distance to their neighbors have higher preference for joining the CDS.

In Li et al. [2012], two decentralized approaches are proposed for constructing the CDS that minimizes the total communication power. The goal is to find the CDS that minimizes the sum of the transmission power of CDS nodes.

4.2.2. Tree-Based Topology. To solve the *minimum energy broadcast problem*, the well-known *Broadcast Incremental Power* (BIP) was presented in Wieselthier et al. [2000]. In BIP, the construction mechanism is as follows. The tree is constructed at the source node, and the next node to be included in the tree is the one that is reached using minimum power. The *sweep* procedure is also proposed in the same work for further reducing the total energy consumption. BIP requires global information.

BAIP, the *Broadcast Average Incremental Power* algorithm [Wan et al. 2001] is a variant of BIP that considers the average incremental cost for selecting a new node that will be included in the tree. This value is the ratio between the minimum power required by a node in the current tree to reach new nodes and the number of new nodes that will be reached.

The *Hop-Constrained Minimum Broadcast Incremental Power* (HC-BIP) algorithm is proposed in Bulbul et al. [2009]. It ensures that all nodes in the network receive the broadcast message in less than k hops. It requires global knowledge.

The *Iterative Maximum-Branch Minimization* (IMBM) algorithm was presented in Li and Nikolaidis [2001]. It focuses on the construction of a tree that minimizes the energy required for broadcast. In an initial step, the source builds a *basic broadcast tree* to all destinations. Then it tries to reduce the required power by replacing the most energy-expensive branch with an alternative that uses less power. Liang [2002] proposes an approximation algorithm that uses global knowledge and is based on Steiner trees.

In Cagalj et al. [2002], the *Embedded Wireless Multicast Advantage* (EWMA) algorithm starts with an initial solution obtained using the MST; this solution is improved by replacing branches of the initial tree with new ones, so that the overall energy used for maintaining the tree is lower. Two EWMA approaches are proposed: one centralized, the other distributed. The distributed approach, however, requires information from multiple hops away, such that it might not work properly in frequently changing topologies.

Wieselthier et al. [2002] proposed two distributed versions of the well-known BIP: *distributed-BIP-all Dist-BIP-A* and *distributed-BIP-gateways Dist-BIP-G*. Both use 2-hop neighbors' information for constructing trees. In the former, only nodes that can be reached directly are included in the tree. Each node builds a local tree that is then assembled in a global tree. In the latter, nodes that can be reached using a relay are considered gateways. Only those gateways are in charge of building local trees. Once the global tree is formed, a centralized *sweep* operation is applied.

The *Local Minimum Spanning Tree* (LMST) [Li et al. 2003, 2005] needs the local exchange of positions in the beacons to build the neighborhood graph. Each node applies Prim's algorithm to find the local MST. Once, the tree is constructed, it reduces the transmission power to reach the farthest neighbor. The *directed LMST Broadcast Oriented Protocol* (LBOT) [Cartigny et al. 2004] is based on LMST but uses directional antennas and lies on the LMST topology. The source node sends the message, and the message is propagated using neighbor elimination (or self-pruning rule) on the LMST.

In Miyao et al. [2009], the *Local Tree-Based Reliable Topology* (LTRT) motivated from LMST ensures k-edge connectivity of the network to ensure reliable communications.

The *Broadcast on Local Minimum Spanning Tree* (BLMST) is proposed in Li and Hou [2004]. It first constructs an underlying topology using LMST, then the source node broadcasts the message, and any node receiving the message from all its neighbors cancels the retransmission. This work also includes an analytical study indicating that it is more efficient to use lower transmission power in a multihop fashion than to use longer transmission ranges, under some circumstances.

The redundant radius scheme is introduced in Xu and Garcia-Luna-Aceves [2010], in which two different transmission radii are used. First, a smaller range is considered for building the broadcast tree in terms of the neighborhood, then a longer one is used for the actual transmission.

In Ingelrest et al. [2006], the optimal transmission range that considers both the number of relays and energy consumption is calculated. Moreover, two broadcasting algorithms are proposed: the *Target Radius LMST Broadcast-Oriented Protocol* (TR-LBOP) and the *Target Radius and Dominating Set-Based Protocol*. The former considers neighbor elimination to reduce the subset of direct neighbors, and it reduces the radius to preserve connectivity, increasing it when possible. The latter computes a CDS in trying to choose relays nodes as close as possible to the target radius.

Table V. Classification of the Topology-Based Algorithms with Variable Transmission Range

	Neigh.	Hops	Determ.	GPS	Forward decision
BIP [Wieselthier et al. 2000] *BAIP [Wan et al. 2001]* *HC-BIP [Bulbul et al. 2009]* *IMBM [Li and Nikolaidis 2001]* *[Liang 2002]* *EWMA [Cagalj et al. 2002]*	local	global	yes	no	structure
Dist-BIP-A / Dist-BIP-G [Wieselthier et al. 2002]	local	2-hop/global	yes	no	structure
LMST [Li et al. 2003] *LBOT [Cartigny et al. 2004]* *LTRT [Miyao et al. 2009]* *BLMST [Li and Hou 2004]*	local	1-hop	yes	yes	structure
[Xu and Garcia-Luna-Aceves 2010]	local	1-hop	yes	no	structure
TR-LBOP [Ingelrest et al. 2006]	local	1-hop	no	yes	structure
[Wu and Wu 2003] *[Stojmenović and Wu 2004]* *[Li et al. 2012]*	local	1-hop	yes	no	structure
[Oda et al. 2010] *[Ni et al. 2010]* *[Ahluwalia and Modiano 2005]*	local	2-hop	yes	no	structure

4.2.3. Clustering Topology. An autonomous cluster scheme is proposed in Oda et al. [2010]. It adapts the transmission power of every node in terms of the distance between the node and neighboring nodes to have a specific number of neighbors.

In Ni et al. [2010], the node residual energy, the nearby topology, the relative location, and the relative mobility are used to elect the CH. Additionally, cluster members are able to estimate the distance to the CH and reduce transmission power accordingly. When the residual energy of the CH is lower than a predefined threshold, the reclustering operation is triggered.

In Ahluwalia and Modiano [2005], 2-hop neighborhood information is used in a distributed clustering algorithm to divide the network, where clusters may overlap. Then, a distributed *sweep* operation is used to find nodes whose transmission power can be decreased while still guaranteeing that every node belongs to at least one cluster. Finally, it runs the DMST [Humblet 1983] algorithm to construct the directed MST to join the clusters.

In Table V, a summary containing the surveyed works that use a variable transmission range and that are topology-based is presented.

5. OPEN ISSUES AND CHALLENGES

In the previous sections, we surveyed the most relevant existing protocols and classified them. As we have seen, broadcasting in MANETs has been extensively studied, but there are still many open issues and challenges to be addressed. Here, we outline some of the most interesting ones.

—Due to the changing and unpredictable topology in MANETs, most of the algorithms rely on different thresholds so that they can adapt to topological changes. Those thresholds are usually experimentally chosen or set for a specific network configuration. Distributed and online algorithms able to tune the value of the parameters in real time would highly increase the performance of these broadcasting protocols.

—Broadcasting is a MAC-level operation; transmission errors and interference make it unreliable. In Boukerche [2008], the authors state that the network-wide broadcast problem must be viewed as having two components: redundancy control and robustness control. The former aims at reducing redundancy while maintaining coverage, whereas the latter tries to recover from lost messages while maintaining coverage. Efficient broadcasting protocols that deal with redundancy, robustness, and the overhead produced by the control mechanisms are still challenging the research community.
—It is important to enhance the underlying topology intelligence in order to automate the forwarding mechanism by reacting to topological changes. For example, the topology must be aware if network stability is highly volatile or if the network is very sparse, and it must act consequently by forwarding the broadcast message as soon as a node enters the tree/cluster/CDS or cancels the RAD. Additionally, some proactivity might be added by retransmitting the message before some topological split happens.
—The higher the number of nodes resending the message, the higher the probability of reaching the whole network, but the higher the network use. Therefore, the development of intelligent distributed methods able to estimate the optimal number of nodes forwarding the message will significantly help the dissemination process and optimize the utilization of network resources.
—MANETs suffer from network partitioning and disruption that make broadcast message dissemination difficult and very often unreliable. Thus, methods aware of node mobility and network partition and that can predict node movements to promote message dissemination can significantly improve the broadcast process.

6. CONCLUSION AND PERSPECTIVES

Broadcasting is a cornerstone in networking, which means that much work has already been done. But there is still room for improvement. There are yet many problems that have to be solved efficiently. Classifying and compiling existing works is key for newcomers to the topic, so that they can easily familiarize themselves with the work to date and have a global picture of the literature.

In this article, we surveyed the most relevant works that have been proposed during the past decades for solving the broadcast problem. In order to do that, we first analyzed the existing classifications and proposed a new taxonomy that better covers all existing techniques.

According to our proposed taxonomy, we then analyzed in detail the state of the art in this field and categorized the approaches in terms of the type of system centralization, the knowledge used, the predictability of the system, and the role of the source node.

With this global view of the broadcast problem, open issues were identified and new research lines proposed.

REFERENCES

2014. The Haggle Project. Retrieved from http://www.haggleproject.org.

C. Adjih, P. Jacquet, and L. Viennot. 2004. *Computing Connected Dominated Sets with Multipoint Relays*. Technical Report. Retrieved from http://gyroweb.inria.fr/∼viennot/publis/articles/mpr-cds.pdf.

A. S. Ahluwalia and E. H. Modiano. 2005. On the complexity and distributed construction of energy-efficient broadcast trees in wireless ad hoc networks. *IEEE Transactions on Wireless Communications* 4, 5 (2005), 2136–2147.

J.-H. Ahn and T.-J. Lee. 2011. A multipoint relay selection method for reliable broadcast in ad hoc networks. In *ICT Convergence (ICTC), 2011 International Conference on*. 616–617.

S. O. Al-Humoud, L. M. Mackenzie, and J. Abdulai. 2008. Neighbourhood-aware counter-based broadcast scheme for wireless ad hoc networks. In *Proceedings of the IEEE 2008 GLOBECOM Workshops*. 1–6.

L. Al-Kanj and Z. Dawy. 2011. Offloading wireless cellular networks via energy-constrained local ad hoc networks. In *IEEE Global Telecommunications Conference, GLOBECOM*. 1–6.

S. Allal and S. Boudjit. 2012. Geocast routing protocols for VANETs: Survey and guidelines. In *Proceedings of the 6th International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing*. 323–328. DOI:http://dx.doi.org/10.1109/IMIS.2012.133

A. D. Amis, R. Prakash, T. H. P. Vuong, and D. T. Huynh. 2000. Max-min d-cluster formation in wireless ad hoc networks. In *Proceedings of the 19th Annual Joint Conference of the IEEE Computer and Communications Societies. INFOCOM*, Vol. 1. 32–41.

G. Anastasi, M. Conti, E. Gregori, and A. Passarella. 2008. 802.11 power-saving mode for mobile computing in Wi-Fi hotspots: Limitations, enhancements and open issues. *Wireless Networks* 14, 6 (Dec. 2008), 745–768.

A. Andronache and S. Rothkugel. 2008. NLWCA node and link weighted clustering algorithm for backbone-assisted mobile ad hoc networks. In *Proceedings of the 7th International Conference on Networking*. 460–467.

A. Andronache, P. Ruiz, and S. Rothkugel. 2008. Improving inter-cluster broadcasting in ad hoc networks by delayed flooding. In *MCO*. 478–487.

J. Arango, M. Degermark, A. Efrat, and S. Pink. 2004. An efficient flooding algorithm for ad-hoc networks. In *Proceedings of the 2nd Workshop on Modeling and Optimizations in Mobile Ad Hoc and Wireless Networks (WiOpt)*.

S. Bai, Z. Huang, D. Kwak, Sa. Lee, H. Oh, and J. Jung. 2009. Vehicular multi-hop broadcasting protocol for safety message dissemination in VANETs. In *Proceedings of the 70th Vehicular Technology Conference Fall (VTC 2009-Fall), IEEE 70th*. Anchorage, AK, 1–5.

A. Banerjee, C. H. Foh, C. K. Yeo, and B. S. Lee. 2012. Performance improvements for network-wide broadcast with instantaneous network information. *Journal of Network and Computer Applications* 35, 3 (2012), 1162–1174.

S. Basagni, M. Conti, S. Giordano, and I. Stojmenović. 2004. *Mobile Ad Hoc Networking*. Wiley-IEEE Press.

S. Bastani, B. Landfeldt, C. Rohner, and P. Gunningberg. 2012. A social node model for realising information dissemination strategies in delay tolerant networks. In *Proceedings of the 15th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM'12)*. ACM, New York, NY, 79–88.

A. Bentaleb, A. Boubetra, and S. Harous. 2013. Survey of clustering schemes in mobile ad hoc networks. *Communications and Network* 5 (2013), 8–14.

D. M. Blough, M. Leoncini, G. Resta, and P. Santi. 2006. The k-neighbors approach to interference bounded and symmetric topology control in ad hoc networks. *IEEE Transactions on Mobile Computing* 5, 9 (2006), 1267–1282.

A. Boukerche (Ed.). 2005. *Handbook of Algorithms for Wireless Networking and Mobile Computing*. Chapman & Hall/CRC Computer and Information Science Series.

A. Boukerche (Ed.). 2008. *Algorithms and Protocols for Wireless, Mobile Ad Hoc Networks*. Wiley-IEEE Press.

A. Boukerche and V. Sheetal. 2003. A performance evaluation of a dynamic source routing discovery optimization protocol using GPS system. *Telecommunication Systems* 22, 1–4 (2003), 337–354.

M. R. Brust, A. Andronache, and S. Rothkugel. 2007. WACA: A hierarchical weighted clustering algorithm optimized for mobile hybrid networks. In *Proceedings of the 3rd International IEEE Conference on Wireless and Mobile Communications*. 23–23.

M. R. Brust, H. Frey, and S. Rothkugel. 2008. Dynamic multi-hop clustering for mobile hybrid wireless networks. In *Proceedings of the 2nd International Conference on Ubiquitous Information Management and Communication*. ACM, 130–135.

K. Bulbul, O. Ercetin, and T. Unluyurt. 2009. Hop constrained energy-efficient broadcasting: Insights from massively dense ad hoc networks. *IEEE Transactions on Mobile Computing* 8, 2 (2009), 188–202.

M. Cagalj, J.-P. Hubaux, and C. Enz. 2002. Minimum-energy broadcast in all-wireless networks: NP-completeness and distribution issues. In *MobiCom'02: Proceedings of the 8th Annual International Conference on Mobile Computing and Networking*. ACM, 172–182.

Z.-Y. Cao, Z.-Z. Ji, and M.-Z. Hu. 2007. An energy-aware broadcast scheme for directed diffusion in wireless sensor network. *Journal of Communication and Computer* 4, 5 (2007), 28–35.

J. Cartigny, F. Ingelrest, D. Simplot-Ryl, and I. Stojmenovic. 2005. Localized LMST and RNG based minimum-energy broadcast protocols in ad hoc networks. *Ad Hoc Networks* 3, 1 (2005), 1–16.

J. Cartigny and D. Simplot. 2003. Border node retransmission based probabilistic broadcast protocols in ad-hoc networks. In *Proceedings of the 36th Hawaii International Conference on System Sciences*. 189–204.

J. Cartigny, D. Simplot, and I. Stojmenovic. 2003. Localized minimum-energy broadcasting in ad-hoc networks. In *Proceedings of the Twenty-Second Annual Joint Conference of the IEEE Computer and Communications (INFOCOM'03)*. IEEE Societies, Vol. 3. 2210–2217. DOI:10.1109/INFCOM.2003.1209241

J. Cartigny, D. Simplot-Ryl, and I. Stojmenović. 2004. An adaptive localized scheme for energy-efficient broadcasting in ad hoc networks with directional antennas. In *Personal Wireless Communications*, Ignas Niemegeers and SoniaHeemstra Groot (Eds.). Lecture Notes in Computer Science, Vol. 3260. Springer, Berlin, 399–413.

A. Casteigts and S. Chaumette. 2005. Dynamicity aware graph relabeling system - a local computation model to describe MANET algorithms. In *Proceedings of the 17th IASTED International Conference on Parallel and Distributed Computing and System*. 198–204.

A. Casteigts, S. Chaumette, F. Guinand, and Y. Pigné. 2013. Distributed maintenance of anytime available spanning trees in dynamic networks. In *Proceedings of the 12th International Conference on Ad Hoc Networks and Wireless, ADHOC-NOW*.

C. Chen, C.-K. Hsu, and H.-K. Wang. 2005. A distance-aware counter-based broadcast scheme for wireless ad hoc networks. In *Proceedings of the IEEE Military Communications Conference (MILCOM)*. 1052–1058.

X. Chen, M. Faloutsos, and S. Krishnamurthy. 2002. Distance ADaptive (DAD) broadcasting for ad hoc networks. In *Proceedings of MILCOM*, Vol. 2. 879–883.

X. Chen, M. Faloutsos, and S. V. Krishnamurthy. 2003. Power adaptive broadcasting with local information in ad hoc networks. In *Conference on Network Protocols*. IEEE Computer Society, 168.

A. Chiganmi, M. Baysan, K. Sarac, and R. Prakash. 2008. Variable power broadcast using local information in ad hoc networks. *Ad Hoc Networks* 6, 5 (July 2008), 675–695.

T. H. Clausen and P. Jacquet. 2003. *Optimized Link State Routing Protocol (OLSR)*. Technical Report. IETF. 75 pages.

A. E. F. Clementi, P. Penna, and R. Silvestri. 2000. The power range assignment problem in radio networks on the plane. In *Proceedings of the 17th Annual Symposium on Theoretical Aspects of Computer Science (STACS'00)*. Springer-Verlag, London, UK, UK, 651–660.

F. Dai and J. Wu. 2003. Distributed dominant pruning in ad hoc networks. In *Proceedings of the IEEE International Conference on Communications*, Vol. 1. 353–357.

A. Durresi, V. K. Paruchuri, S. S. Iyengar, and R. Kannan. 2005. Optimized broadcast protocol for sensor networks. *IEEE Transactions on Computing* 54, 8 (2005), 1013–1024.

A. Ephremides, J. E. Wieselthier, and J. Baker. 1987. A design concept for reliable mobile radio networks with frequency hopping signaling. *Proceedings of the IEEE* 75, 1 (1987), 56–73.

K. Fall. 2003. A delay-tolerant network architecture for challenged internets. In *Proceedings of the 2003 Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications (SIGCOMM'03)*. ACM, New York, NY, 27–34. DOI:http://dx.doi.org/10.1145/863955.863960

Y. Fernandess and D. Malkhi. 2002. K-clustering in Wireless Ad Hoc Networks. In *Proceedings of the 2nd ACM International Workshop on Principles of Mobile Computing (POMC'02)*. ACM, New York, NY, 31–37.

O. Flauzac, B. S. Haggar, and F. Nolot. 2010. Tree and cluster management for MANET. In *Proceedings of the 2010 10th International Conference on New Technologies of Distributed Systems (NOTERE'10)*. 73–80.

IEEE Standard for Information Technology. 1998. Telecommunications and information exchange between systems - Local and metropolitan area networks - Common specifications Part 3: Media Access Control (MAC) bridges. *ANSI/IEEE Std 802.1D, 1998 Edition* (1998), i–355. DOI:http://dx.doi.org/10.1109/IEEESTD.1998.95619

T. Fujie. 2003. An exact algorithm for the maximum leaf spanning tree problem. *Computers and Operations Research* 30, 13 (Nov. 2003), 1931–1944.

W. Gang, W. Shigang, L. Cai, and Z. Xiaorong. 2012. Research and realization on improved MANET distance broadcast algorithm based on percolation theory. In *International Conference on Industrial Control and Electronics Engineering (ICICEE)*. 96–99.

B. Garbinato, A. Holzer, and F. Vessaz. 2008. Six-shot broadcast: A context-aware algorithm for efficient message diffusion in MANETs. In *Proceedings of the OTM 2008 Confederated International Conferences, CoopIS, DOA, GADA, IS, and ODBASE 2008. Part I: On the Move to Meaningful Internet Systems: (OTM'08)*. 625–638.

B. Garbinato, A. Holzer, and F. Vessaz. 2010. Context-aware broadcasting approaches in mobile ad hoc networks. *Computer Networks* 54, 7 (May 2010), 1210–1228.

M. Gerla, T. Kwon, and G. Pei. 2000. On-demand routing in large ad hoc wireless networks with passive clustering. In *Wireless Communications and Networking Confernce, 2000. WCNC. 2000 IEEE*, Vol. 1. 100–105.

M. Gerla and J. T. Tsai. 1995. Multicluster, mobile, multimedia radio network. *Journal of Wireless Networks* 1 (1995), 255–265.

J. Gomez and A. T. Campbell. 2007. Variable-range transmission power control in wireless ad hoc networks. *IEEE Transactions on Mobile Computing* 6, 1 (2007), 87–99.

S. Guo and O. W. W. Yang. 2007. Energy-aware multicasting in wireless ad hoc networks: A survey and discussion. *Computer Communications* 30, 9 (June 2007), 2129–2148.

American Heritage. 2014. The American Heritage Dictionary. Definition of the Term Ad Hoc. Retrieved from http://www.ahdictionary.com/word/search.html?q=ad+hoc&submit.x=0&submit.y=0.

L. Hogie, F. Guinand, and P. Bouvry. 2004. A heuristic for efficient broadcasting in the metropolitan ad hoc networks. In *KES*. 529–536.

C.-M. Huang, L. Tu, and C.-H. Chou. 2009. ReWarn: An opportunistic relay scheme for cooperative collision warning in VANET. In *Proceedings of the IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*. Tokyo, 3030–3034.

P. Hui, J. Crowcroft, and E. Yoneki. 2011. BUBBLE Rap: Social-based forwarding in delay-tolerant networks. *IEEE Transactions on Mobile Computing* 10, 11 (Nov 2011), 1576–1589. DOI:http://dx.doi.org/10.1109/TMC.2010.246

P. A. Humblet. 1983. A distributed algorithm for minimum weight directed spanning trees. *IEEE Transactions on Communications* 31, 6 (1983), 756–762.

F. Ingelrest, D. Simplot-Ryl, and I. Stojmenovic. 2006. Optimal transmission radius for energy efficient broadcasting protocols in ad hoc and sensor networks. *IEEE Transactions on Parallel and Distributed Systems* 17, 6 (2006), 536–547.

A. Juttner and A. Magi. 2005. Tree based broadcast in ad hoc networks. *Mobile Networks and Applications* 10, 5, 753–762. Issue 5.

K. Karenos, A. Khan, S. Krishnamurthy, M. Faloutsos, and C. Xiaohu. 2005. Local versus global power adaptive broadcasting in ad hoc networks. In *Proceedings of the IEEE Wireless Communications and Networking Conference*, Vol. 4. 2069–2075.

D. Kasamatsu, N. Shinomiya, and T. Ohta. 2009. A broadcasting method considering battery lifetime and distance between nodes in MANET. In *29th IEEE International Conference on Distributed Computing Systems Workshops (ICDCS)*. 406–411.

V. Kawadia and P. R. Kumar. 2005. Principles and protocols for power control in wireless ad hoc networks. *IEEE Journal on Selected Areas in Communications* 23, 1 (2005), 76–88.

A. M. Kermarrec, L. Massoulié, and A. J. Ganesh. 2003. Probabilistic reliable dissemination in large-scale systems. *IEEE Transactions on Parallel Distributed Systems* 14, 3 (March 2003), 248–258.

A. Keshavarz-Haddad, V. Ribeiro, and R. Riedi. 2006. Color-based broadcasting for ad hoc networks. In *Proceedings of the 4th International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks*. 1–10.

M. Khabbazian, I. F. Blake, and V. K. Bhargava. 2012. Local broadcast algorithms in wireless ad hoc networks: Reducing the number of transmissions. *IEEE Transactions on Mobile Computing* 11, 3 (2012), 402–413.

A. Kokuti and V. Simon. 2012. Adaptive multihop broadcast protocols for ad hoc networks. In *Proceedings of the 8th International Symposium on Communication Systems, Networks Digital Signal Processing (CSNDSP)*. 1–6.

D. Koscielnik and J. Stepien. 2011. The methods of broadcasting of information in ad-hoc wireless networks with mobile stations. In *Proceedings of the IEEE International Symposium on Industrial Electronics (ISIE'11)*. 2043–2048.

S.-H. Lee and Y.-B. Ko. 2006. An efficient neighbor knowledge based broadcasting for mobile ad hoc networks. In *Proceedings of the 6th International Conference on Computational Science - Volume Part II (ICCS'06)*. Springer-Verlag, Berlin, 1097–1100.

J. Leitao, J. Pereira, and L. Rodrigues. 2007. Epidemic broadcast trees. In *Proceedings of the 26th IEEE International Symposium on Reliable Distributed Systems*. 301–310.

J. Leitao, J. Pereira, and L. Rodrigues. 2010. Gossip-based broadcast. In *Handbook of Peer-to-Peer Networking*, Xuemin Shen, Heather Yu, John Buford, and Mursalin Akon (Eds.). Springer, 831–860.

S. Leu and R.-S. Chang. 2011. Simple algorithm for solving broadcast storm in mobile ad hoc network. *Communications of the IET* 5, 16 (2011), 2356–2363.

D. Li, H. Huang, X. Li, M. Li, and F. Tang. 2007. A distance-based directional broadcast protocol for urban vehicular ad hoc network. In *Proceedings of the International Conference on Wireless Communications, Networking and Mobile Computing (WiCom'07)*. 1520–1523.

D. Li, D. Kim, Q. Zhu, L. Liu, and W. Wu. 2012. Minimum total communication power connected dominating set in wireless networks. In *Wireless Algorithms, Systems, and Applications*, Xinbing Wang, Rong Zheng, Tao Jing, and Kai Xing (Eds.). Lecture Notes in Computer Science, Vol. 7405. Springer, Berlin, 132–141.

F. Li and I. Nikolaidis. 2001. On minimum-energy broadcasting in all-wireless networks. In *Proceedings of the 26th Annual IEEE Conference on Local Computer Networks*. 193–202.

F. Li, S. Z., X. Wang, X. Xue, and H. Shen. 2004. Vote-based clustering algorithm in mobile ad-hoc networks. In *Proceedings of the International Conference on Networking Technologies for Broadband and Mobile Networks (Lecture Note in Computer Science)*. 13–23.

N. Li and J. C. Hou. 2004. BLMST: A scalable, power-efficient broadcast algorithm for wireless networks. In *Proceedings of the1st International Conference on Quality of Service in Heterogeneous Wired/Wireless Networks, QSHINE*. 44–51.

N. Li, J. C. Hou, and S. Lui. 2003. Design and analysis of an MST-based topology control algorithm. In *Proceedings of the 22nd Annual Joint Conference of the IEEE Computer and Communications (INFOCOM)*, Vol. 3. 1702–1712.

N. Li, J. C. Hou, and S. Lui. 2005. Design and analysis of an MST-based topology control algorithm. *IEEE Transactions on Wireless Communications* 4, 3 (2005), 1195–1206.

X. Li, T. D. Nguyen, and R. P. Martin. 2003. Using adaptive range control to optimize 1-hop broadcast coverage in dense wireless networks. In *SenSys*. 314–315.

O. Liang. 2007. *Multipoint Relay and Connected Dominating Set Based Broadcast Algorithms for Wireless Ad Hoc Networks*. Ph.D. Dissertation. Melbourne, Australia.

W. Liang. 2002. Constructing minimum-energy broadcast trees in wireless ad hoc networks. In *Proceedings of the 3rd ACM International Symposium on Mobile Ad Hoc Networking & Computing (MobiHoc'02)*. 112–122.

D. Liarokapis and A. Shahrabi. 2009. A probability-based adaptive scheme for broadcasting in MANETs. In *Proceedings of the 6th International Conference on Mobile Technology, Application & Systems (Mobility'09)*. Article 46, 8 pages.

D. Liarokapis and A. Shahrabi. 2011. Fuzzy-based probabilistic broadcasting in mobile ad hoc networks. *Wireless Days (WD), 2011 IFIP*. 1–6.

D. Liarokapis, A. Shahrabi, and A. Komninos. 2009. DibA: An adaptive broadcasting scheme in mobile ad hoc networks. In *Communication Networks and Services Research*. IEEE Computer Society, 224–231.

H. Lim and C. Kim. 2000. Multicast tree construction and flooding in wireless ad hoc networks. In *Proceedings of the 3rd ACM International Workshop on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWIM'00)*. ACM, New York, NY, 61–68.

S. Lim, C. Yu, and C. R. Das. 2009. RandomCast: An energy-efficient communication scheme for mobile ad hoc networks. *IEEE Transactions on Mobile Computing* 8, 8 (2009), 1039–1051.

J. Lipman, P. Boustead, J. Chicharo, and J. Judge. 2003. Resource aware information dissemination in ad hoc networks. In *Proceedings of the 11th IEEE International Conference on Networks*. 591–596.

J. Lipman, P. Boustead, and J. Judge. 2002. Utility-based multipoint relay flooding in heterogeneous mobile ad hoc networks. In *Proceedings of the Workshop on the Internet, Telecommunications and Signal Processing*. 27–33.

J. Lipman, H. Liu, and I. Stojmenović. 2009. *Guide to Wireless Ad Hoc Networks*. Springer, Chapter Broadcast in Ad hoc Networks. Chapter 6, 121–150.

W. Lou and J. Wu. 2002. On reducing broadcast redundancy in ad hoc wireless networks. *IEEE Transactions on Mobile Computing* 1, 2 (2002), 111–122.

W. Lou and J. Wu. 2004. Double-covered broadcast (DCB): A simple reliable broadcast algorithm in MANETs. In *Proceedings of the 23rd AnnualJoint Conference of the IEEE Computer and Communications Societies (INFOCOM)*, Vol. 3. 2084–2095.

C. Maihofer. 2004. A survey of geocast routing protocols. *IEEE Communications Surveys Tutorials* 6, 2 (Second 2004), 32–42. DOI:http://dx.doi.org/10.1109/COMST.2004.5342238

B. Mans and N. Shrestha. 2004. Performance evaluation of approximation algorithms for multipoint relay selection. In *Med-Hoc-Net 2004, Proceedings of the 3rd Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net'04)*. 480–491.

K. Miyao, H. Nakayama, N. Ansari, and N. Kato. 2009. LTRT: An efficient and reliable topology control algorithm for ad-hoc networks. *IEEE Transactions on Wireless Communications* 8, 12 (2009), 6050–6058.

I.-H. M. Mkwawa and D. D. Kouvatsos. 2011. Broadcasting methods in MANETS: An overview. In *Network Performance Engineering*, DemetresD. Kouvatsos (Ed.). Lecture Notes in Computer Science, Vol. 5233. Springer, Berlin, 767–783.

Y. Mylonas, M. Lestas, and A. Pitsillides. 2008. Speed adaptive probabilistic flooding in cooperative emergency warning. In *Proceedings of the 4th Annual International Conference on Wireless Internet*. 1–7.

M. Ni, Z. Zhong, K. Wu, and D. Zhao. 2010. An energy efficient clustering scheme for mobile ad hoc networks. In *Proceedings of the IEEE 71st Vehicular Technology Conference (VTC 2010-Spring)*. 1–5.

S.-Y. Ni, Y.-C. Tseng, Y.-S. Chen, and J.-P. Sheu. 1999. The broadcast storm problem in a mobile ad hoc network. In *Proceedings of the 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking*. 151–162.

F. G. Nocetti, J. S. Gonzalez, and I. Stojmenovic. 2003. Connectivity based k-hop clustering in wireless networks. *Telecommunication Systems* 22, 1–4 (2003), 205–220.

R. Oda, T. Ohta, and Y. Kakuda. 2010. A transmission power control adaptive to variation of node density in mobile ad hoc network clustering. In *Proceedings of the 2nd International Conference on Communication Software and Networks*. 141–146.

F. J. Ovalle-Martínez, A. Nayak, I. Stojmenović, J. Carle, and D. Simplot-Ryl. 2006. Area based beaconless reliable broadcasting in sensor networks. In *Proceedings of the 2nd International Conference on Algorithmic Aspects of Wireless Sensor Networks*. Springer-Verlag, 140–151.

S. Park and S.-M. Yoo. 2013. An efficient reliable one-hop broadcast in mobile ad hoc networks. *Ad Hoc Networks* 11, 1 (2013), 19–28.

V. Paruchuri, A. Durresi, and R. Jain. 2003. Optimized flooding protocol for ad hoc networks. *CoRR* cs.NI/0311013 (2003).

W. Peng and X. Lu. 2000. On the reduction of broadcast redundancy in mobile ad hoc networks. In *Proceedings of the 1st Annual Workshop on Mobile and Ad Hoc Networking and Computing, 2000. MobiHOC 2000*. 129–130.

W. Peng and X. Lu. 2001. Efficient broadcast in mobile ad hoc networks using connected dominating sets. 12, 4 (2001), 1265–1275.

W. Peng and X.-C. Lu. 2001. AHBP: An efficient broadcast protocol for mobile Ad hoc networks. *Journal of Computer Science and Technology* 16 (2001), 114–125. Issue 2.

A. Piyatumrong. 2010. *Efficient and Robust Spanning Forest for Topology Management in DT-MANETs: A Tree-Based Decentralized and Multi-Objective Approach*. Ph.D. Dissertation. University of Luxembourg, Luxembourg.

A. Piyatumrong, P. Bouvry, F. Guinand, and K. Lavangnananda. 2008. Trusted spanning tree for delay tolerant MANETs. *EUC (2)*. 293–299.

A. Qayyum, L. Viennot, and A. Laouiti. 2000. *Multipoint Relaying: An Efficient Technique for Flooding in Mobile Wireless Networks*. Technical Report 3898. INRIA.

S. Radhakrishnan, G. Racherla, C. N. Sekharan, N. S. V. Rao, and S. G. Batsell. 1999. DST-A routing protocol for ad hoc networks using distributed spanning trees. In *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC'99)*. Vol. 3, 1543–1547.

D. G. Reina, S. L. Toral, P. Johnson, and F. Barrero. 2015. A survey on probabilistic broadcast schemes for wireless ad hoc networks. *Ad Hoc Networks* 25, Part A, 0 (2015), 263–292.

H. Reumerman and M. Runi. 2005. Distributed power control for reliable broadcast in inter-vehicle communication systems. In *2nd International Workshop on Intelligent Transportation*.

P. Ruiz and P. Bouvry. 2010a. Distributed energy self-adaptation in ad hoc networks. In *Proceedings of the IEEE International Workshop on Management of Emerging Networks and Services (MENS), in Conjunction with IEEE Globecom*. Miami, FL, 539–543.

P. Ruiz and P. Bouvry. 2010b. Enhanced distance based broadcasting protocol with reduced energy consumption. In *Proceedings of the Workshop on Optimization Issues in Energy Efficient Distributed Systems (OPTIM), Part of the 2010 International Conference on High Performance Computing and Simulation (HPCS)*. 249–258.

P. Ruiz, B. Dorronsoro, P. Bouvry, and L. J. Tardón. 2012. Information dissemination in VANETs based upon a tree topology. *Journal of Ad Hoc Networks* 10 (2012), 111–127. Issue 1.

P. Ruiz, B. Dorronsoro, D. Khadraoui, P. Bouvry, and L. Tardón. 2008. BODYF–A parameterless broadcasting protocol over dynamic forest. In *Proceedings of the High Performance Computing & Simulation Conference (HPCS 08)*. Nicosia, Cyprus, 297–303.

J. Schleich. 2010. *Robust Dominating Set-based Virtual Backbones for Wireless Ad hoc Networks*. Ph.D. Dissertation. University of Luxembourg, Luxembourg.

J. Schleich, G. Herbiet, P. Ruiz, P. Bouvry, J. Wagener, P. Bicheler, F. Guinand, and S. Chaumette. 2011. Enhancing the broadcast process in mobile ad hoc networks using community knowledge. In *Proceedings of the 1st ACM International Symposium on Design and Analysis of Intelligent Vehicular Networks and*

Applications in Conjunction with the 14th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems. Miami, FL, 23–30.

J. Schleich, A. Le Thi Hoai, and P. Bouvry. 2012. Solving the minimum M-dominating set problem by a continuous optimization approach based on DC programming and DCA. *Journal Combinatorial Optimization* 24, 4 (2012), 397–412.

M. Slavik and I. Mahgoub. 2010. Stochastic broadcast for VANET. In *Proceedings of the 7th IEEE Consumer Communications and Networking Conference (CCNC)*. Las Vegas, NV, 1–5.

M. Slavik, I. Mahgoub, and F. N. Sibai. 2011. The distance-to-mean broadcast method for vehicular wireless communication systems. In *Proceedings of the International Conference on Innovations in Information Technology (IIT)*. 371–374.

I. Stojmenović. 2012. A general framework for broadcasting in static to highly mobile wireless ad hoc, sensor, robot and vehicular networks. In *Proceedings of the IEEE 18th International Conference on Parallel and Distributed Systems (ICPADS)*. 8–13.

I. Stojmenović, A. Khan, and N. Zaguia. 2012. Broadcasting with seamless transition from static to highly mobile wireless ad hoc, sensor and vehicular networks. *International Journal of Parallel Emergent and Distributed Systems* 27, 3 (June 2012), 225–234.

I. Stojmenović, M. Seddigh, and J. Zunic. 2002. Dominating sets and neighbor elimination-based broadcasting algorithms in wireless networks. *IEEE Transactions on Parallel and Distributed Systems* 13, 1 (2002), 14–25.

I. Stojmenović and J. Wu. 2004. *Broadcasting and Activity Scheduling in Ad Hoc Networks.* S. Basagni and M. Conti and S. Giordano and I. Stojmenović (Eds.). 105–139 pages.

J. Sucec and I. Marsic. 2000. *An Efficient Distributed Network-Wide Broadcast Algorithm for Mobile Ad Hoc Networks*. Technical Report 248. Rutgers University, CAIP.

M.-T. Sun and T.-H. Lai. 2002. Location aided broadcast in wireless ad hoc network systems. In *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC)*, Vol. 2. 597–602.

O. K. Tonguz, N. Wisitpongphan, and B. Fan. 2010. DV-CAST: A distributed vehicular broadcast protocol for vehicular ad hoc networks. *IEEE Wireless Communications* 17, 2 (April 2010), 47–57.

O. Tonguz, N. Wisitpongphan, F. Bai, P. Mudalige, and V. Sadekar. 2007. Broadcasting in VANET. *Mobile Networking for Vehicular Environments*. 7–12.

Y.-C. Tseng, S.-Y. Ni, and E.-Y. Shih. 2002. Adaptive approaches to relieving broadcast storms in a wireless multihop mobile ad hoc network. *IEEE Transactions on Computing* 52 (2002), 545–557.

K. Viswanath and K. Obraczka. 2002. An adaptive approach to group communications in multi hop ad hoc networks. In *7th International Symposium on Computers and Communications*. 559–566.

E. Vollset and P. Ezhilchelvan. 2003. *A Survey of Reliable Broadcast Protocols for Mobile Ad-Hoc Networks*. Technical Report CS-TR-792. University of Newcastle.

P.-J. Wan, G. Calinescu, X.-Y. Li, and O. Frieder. 2001. Minimum-energy broadcast routing in static ad hoc wireless networks. In *Proceedings of 20th Annual Joint Conference of the IEEE Computer and Communications Societies, INFOCOM 2001*. Vol. 2. 1162–1171.

H.-C. Wang, J.-B. Lin, F.-C. Kuo, and K.-C. Ting. 2010. Combination of relative neighborhood graph and forbidden set in the design of distributed broadcast algorithms for wireless ad hoc networks. In *Proceedings of the International Conference on Cyber-Enabled Distributed Computing and Knowledge Discovery (CyberC)*. 94–100.

J. E. Wieselthier, G. D. Nguyen, and A. Ephremides. 2000. On the construction of energy-efficient broadcast and multicast trees in wireless networks. In *Proceedings of the 19th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM)*, Vol. 2. 585–594.

J. E. Wieselthier, G. D. Nguyen, and A. Ephremides. 2002. The energy efficiency of distributed algorithms for broadcasting in ad hoc networks. In *Proceedings of the 5th International Symposium on Wireless Personal Multimedia Communications, 2002.* Vol. 2. 499–503.

B. Williams and T. Camp. 2002. Comparison of broadcasting techniques for mobile ad hoc networks. In *Proceedings of the ACM International Symposium on Mobile Ad Hoc Networking and Computing (MOBIHOC)*. 194–205.

N. Wisitpongphan, O. K. Tonguz, J. S. Parikh, P. Mudalige, F. Bai, and V. Sadekar. 2007. Broadcast storm mitigation techniques in vehicular ad hoc networks. *IEEE Wireless Communications* 14, 6 (December 2007), 84–94.

W. Woon and K. L. Yeung. 2011. Variable power broadcasting based on local information for source-dependent broadcasting protocols. In *IEEE Wireless Communications and Networking Conference (WCNC)*. 796–801.

J. Wu. 2002. Extended dominating-set-based routing in ad hoc wireless networks with unidirectional links. *IEEE Transactions on Parallel and Distributed Systems* 13, 9 (2002), 86–881.

J. Wu, M. Gao, and I. Stojmenovic. 2000. On calculating power-aware connected dominating sets for efficient routing in ad hoc wireless networks. *IEEE/KICS Journal of Communications and Networks* 4 (2000), 59–70.

J. Wu and H. Li. 1999. On calculating connected dominating set for efficient routing in ad hoc wireless networks. In *Proceedings of the 3rd International Workshop on Discrete Algorithms and Methods for Mobile Computing and Communications (DIALM'99)*. 7–14.

J. Wu and W. Lou. 2003. Forward-node-set-based broadcast in clustered mobile ad hoc networks. *Wireless Communications and Mobile Computing* 3, 2 (2003), 155–173.

J. Wu, W. Lou, and F. Dai. 2006. Extended multipoint relays to determine connected dominating sets in MANETs. *IEEE Transactions on Computing* 55, 3 (March 2006), 334–347.

J. Wu and B. Wu. 2003. A transmission range reduction scheme for power-aware broadcasting in ad hoc networks using connected dominating sets. In *IEEE Vehicular Technology Conference (VCT2003)*.

H. Xu and J. J. Garcia-Luna-Aceves. 2010. Efficient broadcast for wireless ad hoc networks with a realistic physical layer. *Ad Hoc Networks* 8 (2010), 165–180.

Y. Yi, M. Gerla, and T.-J. Kwon. 2003. Efficient flooding in ad hoc networks: A comparative performance study. In *Proceedings of the IEEE International Conference on Communications (ICC'03)*. 1059–1063.

J. Y. Yu and P. H. J. Chong. 2005. A survey of clustering schemes for mobile ad hoc networks. *IEEE Communications Surveys Tutorials* 7, 1 (2005), 32–48.

J. Yu, N. Wang, G. Wang, and D. Yu. 2013. Connected dominating sets in wireless ad hoc and sensor networks – A comprehensive survey. *Computer Communications* 36, 2 (2013), 121–134.

H. Zeng, M. Li, H. Liu, and X. Jia. 2009. Efficient flooding in mobile ad hoc networks. In *Ad Hoc Networks: New Research*, J. N. Turner and C. S. Boyer (Eds.). Nova Science Publishers.

L. Zhou, G. Cui, H. Liu, Z. Wu, and D. Luo. 2010. NPPB: A broadcast scheme in dense VANETs. *Information Technology Journal* 9, 2 (2010), 247–256.

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