Reliable Multimedia Broadcasting over Dense Wireless Ad-Hoc Networks (Invited Paper)

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Abstract—**Broadcasting is an essential operation for Wireless Ad Hoc Networks to perform routing path discovery, and it has become the predominant technology for message dissemination in Vehicular Ad Hoc Networks (VANETs). In the reactive routing schemes of wireless ad hoc network, Routing Request (RREQ) packets are broadcast from the source, and once received the destination traces back the broadcasting path to build an on-demand route. In VANETs, different broadcasting schemes have been proposed for safety, comfort, and commercial applications. However, broadcasting usually generates a lot of redundant messages which would cause excessive channel contention and packet collisions, especially when the density of the network becomes higher. In this survey article, we first introduce the most common data dissemination techniques used in wireless ad hoc networks. After that, we discuss techniques that have been proposed to mitigate the broadcast storm problem. Finally, we introduce an effective model for analyzing the broadcasting schemes, and based on the model we propose an adaptively adjusted probabilistic scheme that highly improves the reliability of broadcasting in dense ad hoc networks.**

Index Terms—**The Broadcast Storm; Network Saturation; Wireless Ad Hoc Networks; Mobile Ad Hoc Networks (MANET); Vehicular Ad Hoc Networks (VANET)**

I. Introduction

A wireless ad hoc network consists of a set of nodes where the data delivery among nodes does not depend on any infrastructures; instead, nodes self organize and relay messages among one another. A Mobile Ad Hoc Network (MANET) is a kind of wireless ad hoc network with mobility. Typically, a node in MANETs does not have fixed mobility patterns, and the power of the node would be limited. A Vehicular Ad Hoc Network (VANET) is another kind of wireless Ad Hoc Networks that is intended for a vehicle to communicate with other vehicles, or with road side infrastructures. In VANETs, nodes have high mobility, long battery life and specific mobility patterns. As shown in Figure 1, the major goals of the VANET are to enable vehicle-to-vehicle and/or vehicle to road-side-unit (RSU) communications so as to provide more safety and comfort to the passengers. Broadcasting is an essential operation originally used in wireless ad hoc networks for routing path discovery, and it is now widely used in VANETs as a predominant technology for data delivery.

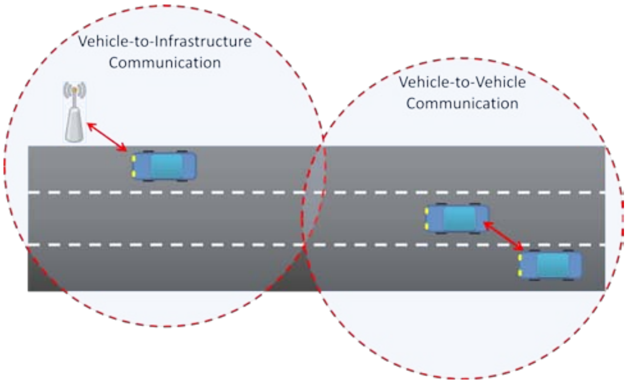

Figure 1. VANETs are to enable Vehicle-to-Infrastructure communication and Vehicle-to-Vehicle communication for better safety and comfort.

There are basically two major kinds of applications in VANETs: safety applications and comfort applications [1]. In the safety applications, safety relevant information is exchanged through inter-vehicle communication. Different warning messages like emergency warning, road condition warning, lane-changing assistant, intersection coordination, and traffic sign/signal violation warning are delivered through single-hop or multi-hop broadcasting technologies. On the other hand, comfort applications include traffic information system, weather information, restaurant location, price information and so on. These comfort applications could be text-based services; however, it is more delightful to provide live multimedia streaming type of services over VANETs. Services such as emergency live video transmission, road-side video advertisement broadcasting and inter-vehicle video conversation will all benefit from reliable video broadcasting services [2].

Take for examples, in battle field and disaster recovery applications, by supporting live multimedia information of the emergency situation, the army or rescue team can easily plan the tactics and equip necessary instruments for the emergency situation. The emergency video could be collected from surveillance camera on different vehicles and transmitted to the rescue team via inter-vehicle communication, in the case of lacking communication infrastructure or the drivers could not respond within critical time duration. In roadside commercial applications, restaurants, hotels, and gas stations can broadcast the video advertisement via roadside infrastructure to nearby vehicles. The video

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advertisement will then be relayed through the inter-vehicle transmission to broaden the effective range of the commercial information. In other comfort applications, passengers can setup a video conversation by using the inter-vehicle streaming technology and connect to the internet via the relay from nearby cars. Drivers or passengers could also enjoy watching live news or sports programs, while the video data streams are relayed from other vehicles.

A recent experimental study, where a many-to-many broadcast scenario in a single-hop 802.11 network with up to 100 nodes, was conducted over the ORBIT test-bed [3]. The experiments first consider a periodic vehicular safety message broadcasting scenario, where each node generates and transmits 10 packets per second, with each packet of size 128 bytes. With the 802.11 nodes rating at 6Mbps, most nodes can successfully receive and decode the 100 streams of messages at 95% of mean packet delivery ratio (PDR), which denotes the ratio of the number of data packets successfully transmitted versus the number of data packets transmitted. When the network scenario is further stretched to a saturation workload, where each node generates and transmits packets at the maximum possible rate, the mean throughput drops approximately to 56%, since almost all frames are involved in collisions. This implies a better broadcast scheme for dense wireless ad hoc networks is critically needed.

In VANETs, the densities of the networks vary greatly. In rural areas, it is likely that there are only intermittent connections via nearby cars since the network density is very low. In urban areas, the network density is relatively higher. However, the buildings beside the roads would likely to block certain wireless connections. In a congested highway, assuming there are four lanes and there is one vehicle every 20m(meters) with a radio range of 300m, theoretically every node has 120 vehicles within its transmission range [4]. With the penetration rate becomes higher and the VANETs are well deployed, it is foreseeable that the ad hoc network will be easily saturated with excessive contentions and collisions, which result in an unreliable network.

In this paper, we review general broadcast schemes used in ad hoc networks, especially in VANETs and introduce a broadcast scheme that adaptively adjusts the transmission probability to improve the throughput and the reliability of the data delivery. The rest of the paper is organized as follows: Section II reviews general data dissemination schemes in wireless ad hoc networks. Section III presents broadcast storm mitigation techniques. Section IV introduces mathematical modeling of broadcasting and explains our proposed method for improving broadcast reliability. Section V shows our simulation results. Finally, Section VI concludes this paper.

II. Data Dissemination in Wireless Ad Hoc Networks

In general, there are five data dissemination techniques used in wireless ad hoc networks: beaconing, broadcasting, unicasting, multicasting, and gossiping [4]. In some cases, these techniques would be combined to achieve specific goals. Since we are focusing on dense ad hoc networks, the intermittent connectivity problem of ad hoc networks due to spares network is not discussed in this article.

A. Beaconing

Beaconing is one-hop broadcasting. It is used to periodically send out updated information to the interested nodes, e.g. for updating the routing table information in proactive routing traditionally. It is also used for exchanging position information in position-based routing. More recently, it is applied to VANETs for cooperative awareness to increase the driving safety [4].

There are basically two kinds of safety messages in VANETs. One is event-driven messages and the other one is periodic awareness messages. Event-driven messages, such as car accident events, need to be broadcast and relayed to all nearby cars efficiently, while periodic safety messages need to be periodically disseminated via beaconing to the neighbors for cooperative awareness. More specifically, beaconing is used to periodically update neighbors with some safety messages for lane-changing assistance, or to update neighbors your current speed, position, and heading direction information for cooperative awareness (see Figure 2). According to [16], in some applications each vehicle would need to broadcast its status to its neighbors approximately 10 times per second.

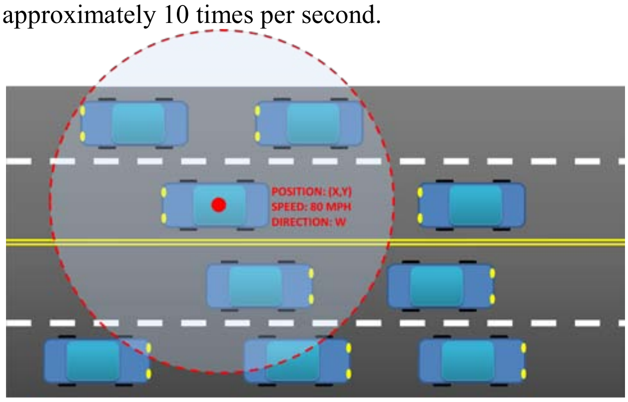


Figure 2. An example of awareness message beaconing in VANETs.

B. Broadcasting

Broadcasting is a technique to deliver data to all nodes in the network. It has been an essential operation used in most ad hoc routing protocols for building the routes by flooding control packets containing routing request information. And, it is becoming a predominant technology for data dissemination in VANETs. The most common broadcasting technique is simple flooding, where a source node broadcasts a packet to all its neighbors and the neighbor who receives the packet further rebroadcasts the packet to the rest part of the network (see Figure 3). The advantage of simple flooding is that there are a lot of redundant messages which increase the robustness to packet loss. The disadvantage is that the redundant message would cause serious resource consumption, channel contention, and collision -- the so-called broadcast storm problem [20].

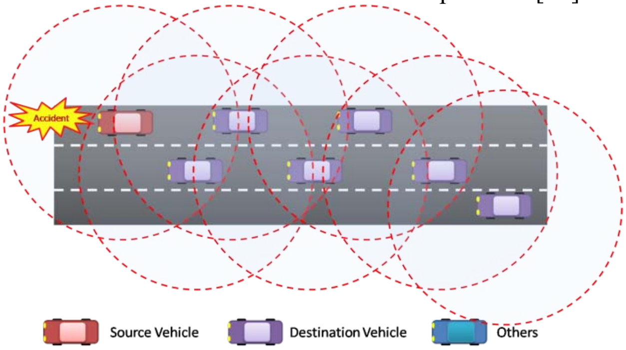
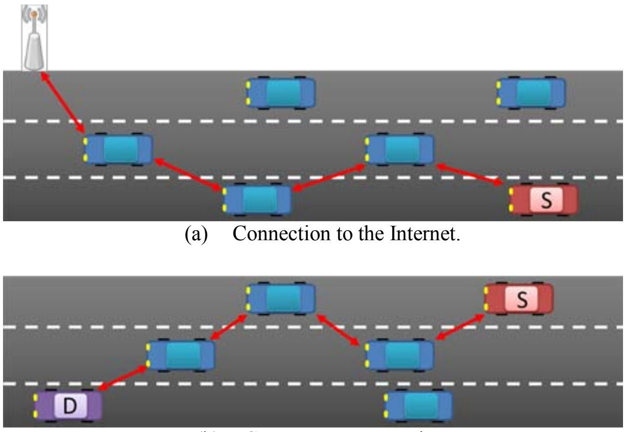


Figure 3. Simple flooding for broadcasting.

C. Unicasting

Unicasting is an end-to-end communication technique. To send a data packet from a source to a specific destination, a route should be built first (See Figure 4). The routing protocols can be categorized into *topology-based* routing and *position-based* routing [5, 6]. In a topology-based routing, a source node can find a route to the destination based on proactive, reactive, or hybrid routing schemes. In position-based routing, each node is required to know its position information by positioning devices, such as Global Positioning Systems (GPS). The position information of the destination node could be retrieved from location services.



(a) Connection to the Internet.

(b) Car-to-car conversation.

Figure 4. Two unicast applications in a VANET.

In the proactive routing, such as Destination Sequenced Distance Vector (DSDV) [7], each node in the network needs to maintain a regularly updated table with routing information of available paths. The scheme is quite efficient since each node knows how to route the packets to the destination. However, the regular update of unused routing information would affect the available bandwidth of the routes currently in use.

In the reactive routing, such as Ad-hoc On-Demand Distance Vector (AODV) [8], the nodes in a network only need to maintain the routing information that is currently in use. The way to collect the reactive routing information is mostly based on flooding a routing request packet to the network, i.e. the source node broadcasts a control packet to the network, and once the destination node receives the control packet, it traces back to build the route. Once the route is built, the data packets are then delivered along the route to the destination. Since the route is built on demand, there is always a route discovery process before actual communication. If the network topology changes frequently, the source would need to continuously flood the network with control packets to discover a new route. When a route to the destination changes, the data packets are likely to be lost.

Hybrid routing protocols, such as Zone Routing Protocol (ZRP) [9], try to take advantage of both proactive and reactive routing protocols. ZRP proactively maintains routing information within local neighborhood (routing zone) and reactively connects routing zones. However, when the topology changes frequently, ZRP still suffers from route discovery flooding and data packet losses.

With the growing advance of the technology, more and more mobile nodes and vehicles are equipped with positioning devices, e.g., global positioning system (GPS), to locate their geographical positions. The position information can then be used for more effective routing. The destination position could be queried from the location services. More specifically, in the position-based routing, the node would only need to keep its neighbors' position information. This makes the protocol scale better than traditional topology-based routing protocols. One popular way of using position information is greedy routing, where one node forwards the packets to a node that is geographically closest to the destination. However, greedy routing does not guarantee to always reach the destination; instead, it could be trapped in local minima. One well-known solution for this dead-end problem in greedy routing is using Greedy Perimeter Stateless Routing (GPSR) [10], which employs planar graph traversal to recover from dead-ends.

It is intriguing to have stable unicast connections for different applications in an ad hoc network. However, unicast in general suffers from losing routing information because of the dynamic behavior of the ad hoc networks, especially in the VANETs with high mobility nature.

D. Multicasting

Multicasting is a technique for delivering data to a group of nodes. Figure 5 shows a typical multicast data delivery over a VANET. To efficiently deliver data to the member nodes of a group, the members would be organized into a tree, mesh, or hybrid structure. The tree-based structure is a well established concept used in wired multicast. Basically there are two kinds of tree structures, one is the source-specific tree and the other is the shared multicast tree. In a source specific tree, each source could build a multicast tree rooted at itself. The data are efficiently delivered through the source-specific tree from each source. In a shared multicast tree, a single spanning tree is constructed for a group that accommodates all sources. The shared multicast tree requests all source nodes to send data through a designated node (the so-called Rendezvous point) before delivery to the intended receiving nodes. All these concepts have been extended to provide multicast in MANETs. Ad-hoc Multicast Routing protocol utilizing Increasing Id numberS (AMRIS) [11] is a well-known protocol for building a shared multicast tree on demand.

In contrast to tree-based protocol, mesh-based approach aims to provide robustness to mobile environment. On-demand Multicasting Routing Protocol (ODMRP) [12] is a well-known protocol to establish a mesh-based structure. In ODMRP, the group is established by the source on demand. To build the group, the source broadcasts a Join-Query message to the entire network. The receivers that are interested in the multicast content reply a Join-Reply message to join the group. In ODMRP, a node does not need to send out any explicit message for joining or leaving a group. The node simply stops sending Join-Reply to leave the group.

In a sparse and low mobility network, traditional multicasting techniques work well; however, if the network is dense and with high mobility, these techniques appear to have low PDR and high control overhead.

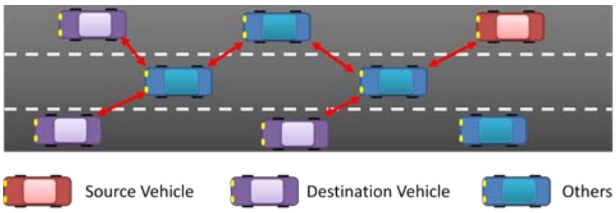


Figure 5. Multicast data delivery in a VANET.

In a high mobility environment, such as a VANET, several multicast variants have been proposed. Geocasting is a location-based multicast routing protocol [13, 14], which leverages position information to deliver packets to all nodes within a specific geographical area, the so-called Zone of Relevance (ZOR) shown in Figure 6. Most geocasting approaches are based on directed flooding, e.g., Location Based Multicast (LBM), which restricts simple flooding over a predefined forwarding zone. Non-flooding geocast approaches basically deliver the packets to the destination area based on unicast; however, it may still use regional flooding within the destination region.

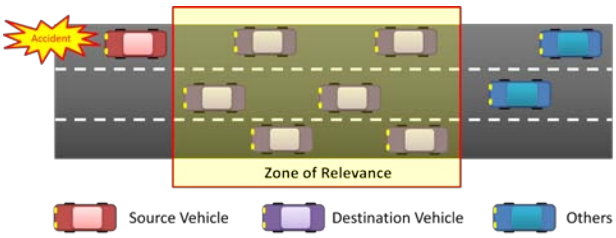


Figure 6. GeoCasting leverages position information to deliver packets to all nodes within the Zone of Relevance (ZOR).

It is worth noticing that in [14], the authors compare different geocasting methods with simple flooding, and the results show that when a network is not congested, simple flooding outperforms geocasting methods in regards to the PDR performance. The redundancy of simple flooding provides more robust delivery when the network is not congested. However, the performance of simple flooding drops significantly in a saturated network.

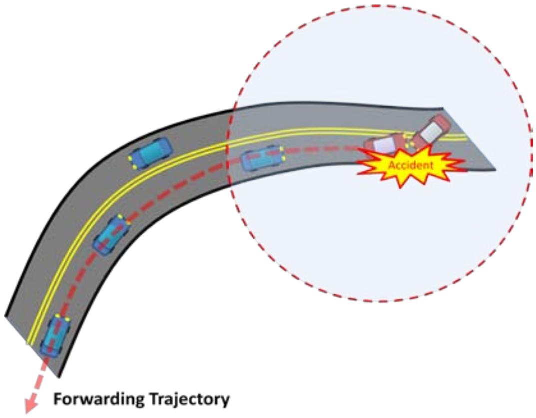


Figure 7. Trajectory-based Forwarding (TBF) in a VANET.

Trajectory-based Forwarding (TBF) [15] is to forward packets along a predefined path (see Figure 7). The path could be defined in different ways, e.g., in terms of functional, equational, and parameter-based representations, etc. The path is encoded and embedded in a broadcasting packet. Each receiver node can calculate if it should rebroadcast the packet based on the embedded path information. By using TBF, a node could save rebroadcasts and limit the broadcasting within the area along a predefined path. TBF can thus be naturally applied to VANETs, since vehicles move along certain paths that can be predefined and included in a digital map.

E. Gossiping

Gossiping is an analogy to rumor spread in a social network. In such a protocol, nodes share the information they have collected and try to collect what they do not have from others. By keeping on exchanging among one another, the information will then be spread to the entire network. Due to the popularity of the peer-to-peer (P2P) applications which use gossiping for file sharing and video streaming, some of the P2P technologies have been modified and brought into the Ad Hoc Networks, especially in VANETs.

BitTorrent is one of the most popular file-sharing protocols [17]. As shown in Figure 8, there are basically three components within a BitTorrent protocol: a web server keeping the torrent files (i.e., the metadata of the sharing files); a tracker keeping track of the information of all participating peers; and a swarm of seeds and leechers, where a seed is a peer that has finished downloading the file but still active for uploading to others and leechers are peers that are still downloading.

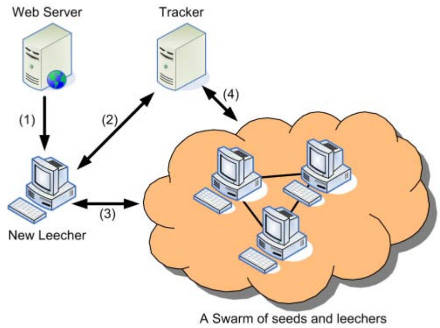


Figure 8. The BitTorrent P2P file sharing protocol.

Also shown in Figure 8, when a new leecher tries to join the torrent, it first connects to a web server to download the torrent file, which contains the file details and tracker location. After that, the new leecher registers its information with the tracker and gets an initial peer list. After the leecher has this initial peer list, it starts connecting to other peers to request exchanges of file chunks.

SPAWN [18] is a BitTorrent-Like content sharing protocol. As shown in Figure 9, when a car arrives at the range of a SPAWN Gateway, the file download process is initiated. After the car leaves the range of the Gateway, certain pieces of the file have been downloaded. Then the car starts to gossip with other cars for collecting the missing pieces and to complete the file download.

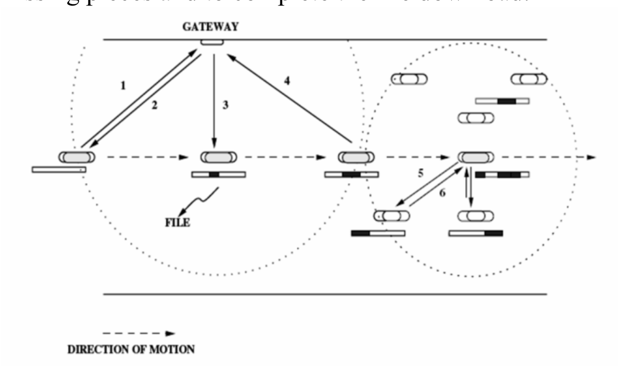


Figure 9. The SPAWN protocol in a VANET [29].

CarTorrent is an implementation of BitTorrent-like content sharing applications built atop the SPAWN protocol [18]. CodeTorrent is a protocol that incorporates network coding into CarTorrent to improve overall thoughput [19].

In the next section, we will introduce the multiple access mechanism used in wireless networks, the network saturation and broadcast storm problem, and the approaches widely discussed to mitigate the broadcast storm problem. We will also introduce a variety of modified flooding schemes that would tremendously reduce the resource consumption.

III. The Network Saturation and Broadcast Storm Problem

It has been shown in a lot literature that, the throughput of standard IEEE 802.11 drops significantly when the network density is high and when the network is saturated. In this section, we first briefly describe the multiple access protocol used in IEEE 802.11-based wireless devices and examine some simple situations that saturate the network; after that, we introduce common approaches for mitigating the broadcast storm problem.

A. Distributed Coordination Function (DCF) of IEEE 802.11

The Distributed Coordination Function (DCF) is the basic mechanism for multiple accesses for IEEE 802.11 based wireless local area network (WLAN). The protocol used in DCF to achieve multiple accesses is called Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). As shown in Figure 10, in CSMA/CA, each node has a backoff counter. A node will transmit a packet when the backoff counter reaches zero. The backoff counter is decremented every "slot time" when the node detects the channel is idle for more than a period of Distributed Inter Frame Space (DIFS). The slot interval equals 9 μs and 20 μs in IEEE 802.11a and 802.11b, respectively. The value in the backoff counter is an integer randomly selected over [0, W-1], where W is called contention window. The selected random number times the slot interval is called the random backoff time. All nodes use this backoff mechanism to contend for the channel.

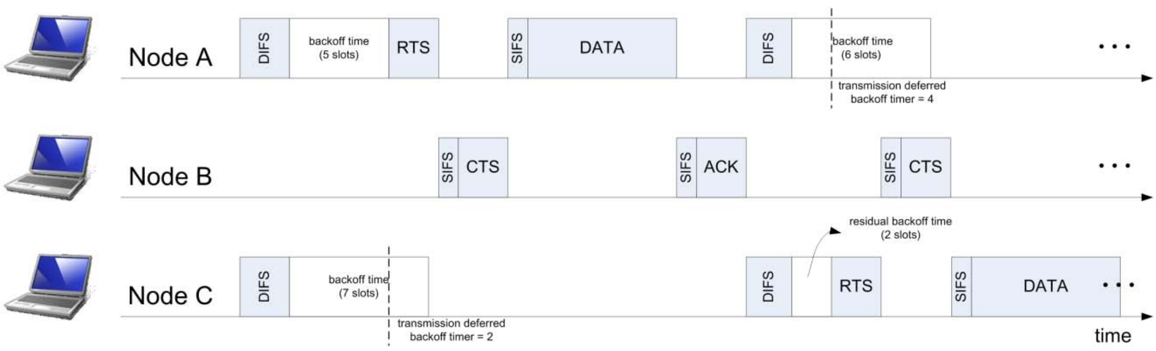
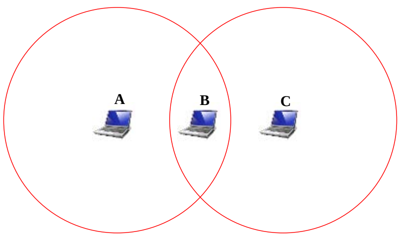


Figure 10. The unicast access mechanism used in a WLAN. (Note that RTS/CTS is optional in the actual data communication and can be disabled under users' preference.)

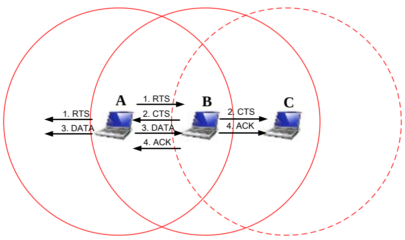
There are two unicast access mechanisms in WLAN: the basic access mechanism and the Request-to-Send/Clear-to-Send (RTS/CTS) access mechanism. The basic access mechanism is a two-way handshake mechanism, while the RTS/CTS access mechanism (as shown in Figure 10 and 11) is a four-way handshake mechanism. In the two-way handshake mechanism, when a source sends out a data packet, the destination is required to respond with an ACK message after a short inter frame space (SIFS), which is 10 μs in 802.11b standard. If the source does not receive the ACK, the collision is considered encountered.

In the four-way handshake mechanism, the source broadcasts an RTS message to its neighbors. When the destination node receives the RTS message, it responds a CTS message after an SIFS. Other nodes that receive the RTS and CTS messages will set a network allocation vector (NAV) timer. The NAV timer maintains a prediction of future traffic on the medium based on duration field of the received RTS or CTS message. This mechanism is also known as virtual carrier-sense.

In CSMA/CA, collisions could happen because of the same backoff time and hidden node problem. The collision resulting from the same backoff time happens when two or more nodes have the same value in their backoff counters and turn out broadcasting at the same time. As shown in Figure 11, the hidden node problem, happens when node A is sending packet to node B, while node C which is out of node A's transmission range is also sending data to node B. Since node C is not inside node A's transmission range, it does not detect node B to be busy receiving data. In this case, node C is the hidden node that causes the failure of receiving data in node B. The hidden node problem could be avoided by the four-way handshake mechanism. Since nodes that receive the RTS and CTS messages will turn on the NAV timer and will not transmit before the four-way handshake is finished, the hidden node problem is then avoided.



(a) The hidden node problem.



(b) Four-way handshake.

Figure 11. The hidden node problem and four way handshake.

By using the two-way or four-way handshake mechanism, a node can detect if collisions happen. When collisions happen, a mechanism called binary exponential backoff will be adopted to increase the possibility of successful transmission. At the beginning of a transmission, the contention window (W) is initialized as a predefinded minimum value $CWmin$. When collision happens, W is doubled for backoff counter selection, and it can be doubled up to a predefined maximum value $W = CWmax$.

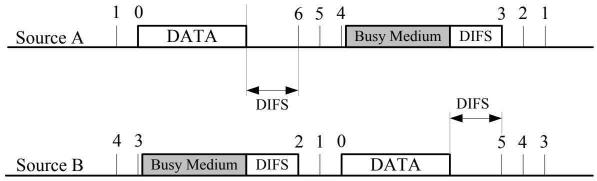


Figure 12. Broadcasting.

Figure 12 shows a conceptual diagram of broadcasting in a wireless ad hoc network where two nodes are competing for the channel. Note that there are basically three characteristics for broadcasting when compared with unicasting based on 802.11 DCF. First, there is no retransmission since the number of receivers would be more than one; it is difficult to coordinate the arrangement of the ACK message. Second, there is no RTS/CTS handshake used to prevent hidden node problems. RTS/CTS works in unicast case, and it is difficult to arrange such kind of mechanism when there are multiple receivers. Third, the contention window size (W) does not change, since the source node does not know if the message is encountering collision or not, there is no exponential backoff used in broadcasting when collisions happen.

B. Network Density and Network Saturation

Let us consider a small scale one-hop network that all the nodes within the network topology are inside the transmission range of one another.

Let N_S denote the number of the broadcasting sources, N_r denote the number of the total nodes, λ denote the packet arrival rate in the sources, and μ_c denote the maximum packet departure rate of the whole system. In a simple flooding, the aggregate packet arrival rate in the neighborhood is $N_s(N_r - 1)\lambda$, since once a source broadcasts, all the rest $(N_r - 1)$ nodes will put the received packets into the queue and wait for rebroadcast. In beaconing, the aggregate packet arrival rate is $N_s\lambda$, because the receiver nodes do not need to rebroadcast the packets. Assuming there are no collision before network saturation, the maximum departure rate of the packet can then be calculated as $\mu_c = 1/T$, where T is packet duration plus a DIFS. Therefore, we know that, in simple flooding, once $N_s(N_r - 1)\lambda > \mu_c$, the network will be saturated since the channel cannot handle the delivery of all the packets in time. Similarly, in the case of beaconing, once $N_s\lambda > \mu_c$, the network will be saturated.

Assuming that the channel is IEEE 802.11b with channel rate equals 1 Mbps and the payload of a data frame is 64 bytes (e.g., for delivering very short status information). T is about 978 μs. Therefore, μ_c is then equal to 1022 packets per second (pps).

In beaconing case, given $\lambda = 10$ pps, when $N_s > 102$, the network will be saturated. In simple flooding case, given $N_s = 5$, $\lambda = 10$ pps, when $N_r > 21$, the network will be saturated.

Considering the case that the payload size is bigger, say 1500 bytes, in beaconing case, with $\lambda = 10$ pps, when $N_s > 8$ the network will be saturated. In simple flooding case, with $N_s = 1$ and $\lambda = 10$ pps, when $N_r > 9$, the network will be saturated.

It is easier to encounter the network saturation when broadcasting by simple flooding. When the payload size of a packet increases, it also increases the probability of network saturation. In addition, when the network is dense, the channel is very easy to be saturated. As mentioned in [22], when the VANETs are widely deployed, the network will mostly work under a saturated condition.

C. Mitigating Broadcast Storm

Basically, the methods for broadcast storm mitigation are to reduce the broadcast redundancy while improve the reliability. The most common technique used for broadcasting is simple flooding. As mentioned earlier, by using simple flooding, all the nodes that receive a new packet will schedule the rebroadcast of the packet. Broadcast storm mitigation methods limit the number of nodes that need to rebroadcast the packets, and at the same time keep or improve the reliability of the broadcasting.

Ni et al. [20] analyze the broadcast storm problem based on redundant rebroadcast, contention, and collision. They introduce several simple methods including counter-based, probabilistic, distance- based, location-based, and cluster-based schemes. Three metrics commonly used for assessing the performance among different methods are: REachability (RE), Saved ReBroadcast (SRB), and Average Latency. *REachability* is defined as the ratio of the number of nodes receving the broadcast message divide by the number of nodes that are reachable. *Saved rebroadcast* is defined as $\frac{(r-t)}{r}$, where r is the number of nodes that receive the broadcast message, and t is the number of nodes that actually transmit the message. *Average latency* is defined as the average time difference between the sending time from the sender and the time the last node finishes its rebroadcasting.

A counter-based scheme sets a predefined counter value C_{th}. Once a node that has received the same packet for greater than or equal to C_{th} times, it will stop rebroadcasting the packet, otherwise it will schedule the rebroadcasting. A probabilistic scheme also sets a predefined probability value P_{th}. Once a node that receives a new packet, it will rebroadcast the packet based on P_{th}, i.e. generate a random number P_{test}, if $P_{test} > P_{th}$, then stop rebroadcasting, otherwise schedule the rebroadcast. Simple flooding is a special case of probabilistic scheme with $P_{th} = 1$. Similarly, in distance-based scheme, a distance threshold D_{th} is defined. If the distance between the broadcasting node and the node that receives the packet is less than D_{th}, then the packet will not be rebroadcast, otherwise, it will be rebroadcast.

In a location-based scheme, the node is required to know its position information based on GPS or other positioning devices. Once a node receives packets, it tries to calculate what the additional spatial coverage is when it broadcasts the packet. If the additional coverage is smaller than a threshold A_{th}, then it will not rebroadcast. In a cluster-based scheme, the nodes are organized into clusters based on the Cluster Based Routing Protocol (CBRP) [23]. Basically, all nodes are assigned different IDs and the node with the smallest ID will be the leader of the cluster. The two clusters are connected through gateways. When broadcasting, the gateways are in charge of forwarding the messages between clusters. The leaders are in charge of broadcasting messages to their cluster members. The rest of nodes do not need to rebroadcast the packets. Any of the aforementioned broadcasting schemes can be used in combining with the cluster-based scheme for broadcasting.

It was concluded [20] that if it is a dense network, the counter-based scheme can eliminate many redundant rebroadcasts. If the location information is available for the nodes, then a location-based method is the best choice to eliminate even more redundant rebroadcasts without compromising the reachability.

In addition to Ni et al.'s approaches, William et al. [24] compare in details several neighbor knowledge based schemes by examining the performances of different methods in congested networks, mobile networks, and so on. Neighbor knowledge based schemes are to rebroadcast data based on neighbor information, which can be collected by periodic exchanging of "Hello" messages with neighbors. Once the neighbor information is collected, different methods can be applied to reduce the broadcast storm. In general, all these methods need to jitter the scheduling of rebroadcasting packets to reduce the probability of collisions. Most methods adopt a "Random Assessment Delay (RAD)" timer and keep the packets in the network layer before RAD expires. Once RAD expires, the packets are sent to MAC layer for broadcasting.

One popular neighbor knowledge based methods is called Scalable Broadcast Algorithm (SBA) [25]. The basic idea of SBA is that if all of a node's one-hop neighbors have received the broadcast message, then the node does not need to rebroadcast the message. The SBA consists of two phases: local neighborhood discovery and data broadcasting. The nodes first exchange "Hello" messages with its neighbors. All nodes include their neighbors' information into the "Hello" message, so that each node can collect neighbor's information within two-hops. Every time when a node receives a broadcast packet, it will update the *covered set* table based on the sender. Once the node finds all its neighbors have been covered, it will not rebroadcast the message.

Based on the comparative simulation results, it was concluded [24] that the increased network density can disproportionately hurt the performance of probabilistic and counter-based methods in terms of saved rebroadcasts. The schemes utilize RAD need to adaptively adjust RAD to avoid suffering from congestive networks. In mobile environment, some neighbor knowledge based schemes can suffer from outdated neighbor information and result in performance degradation.

As addressed in [24] that since a probabilistic scheme uses a predefined probability threshold, when the density of the network increases the number of rebroadcasting nodes also increases rapidly. There are subsequent researches, which propose methods to adaptively adjust the rebroadcast probability based on the neighbor information. Zhang et al. [26] propose an adaptive probabilistic approach that the rebroadcast probability is adjusted based on the number of times the packet is received. Hanashi et al. [27] propose an adaptive method that the rebroadcast probability is updated based on the number of the neighbors, n. To be more specific, the rebroadcast probability p is set to $\max(P_{min}, P_{max}^{n})$ with (P_{min}, P_{max}) being empirically set as (0.4, 0.9).

To improve the broadcast efficiency, Tonguz et al. [28] propose weighted p-persistence, slotted 1-persistence, and slotted p-persistence schemes. In the weighed p-persistence scheme, the rebroadcast probability is adjusted based on D/R, where D is the distance to the source and R is the transmission range. In the slotted 1-persistence scheme, the nodes broadcast based on distance weighted delays. In the slotted p-persistence scheme, the nodes broadcast based on distance weighted delays and a predefined probability p. By applying these schemes, after receiving a packet, the farthest node could rebroadcast the received packet first. The broadcast messages are then expected to be delivered more efficiently. It was claimed [28] that by using the slotted p-persistence scheme the broadcast redundancy and packet loss ratio are significantly reduced in the highway network scenarios. As to the performance of the proposed schemes over two-dimensional topology, even though not much improvement of packet loss ratio was observed, their schemes can be used to assist finding routes with fewer hops.

In summary, most proposed schemes for mitigating the broadcast storm problems are based on heuristic approaches. Moreover, the payload size of the packets are assumed small most of time and the networks are far from saturation. In the following section, we will introduce a mathematical model for describing the dynamic behavior of broadcasting. Based on this modeling, an improved method to deal with network saturation with large packet sizes (e.g., for multimedia packets) in high density network will be introduced.

IV. MODELING BROADCASTING BEHAVIOR

In this section, we introduce a discrete Markov model that is well-known for modeling standard IEEE 802.11 unicast behavior, and has also been extended to model the broadcast behaviors. This discrete Markov model was originally proposed in [29, 30] to model the dynamic behavior of the DCF of IEEE 802.11. Ma et al. [31] further extend this discrete Markov model and apply it to the broadcasting scenario. In addition, the consecutive freeze process (CFP) [49], which causes consecutive transmission of packets right after a transmission, is also modeled. Based on [29, 30, 31], a simplified interpretation on the modeling is presented.

A. Modeling the backoff mechanism within a node

Let us assume the channel is ideal, i.e., the channel is error free and there is no hidden node problem and no consecutive free process (CFP). As mentioned above that in a standard IEEE 802.11, when broadcasting, the node has a fixed contention window without retransmission, nor exponential backoff. To model backoff mechanism within a node in a broadcasting scenario, a discrete Markov model with constant states can be adopted. Each state of this discrete Markov chain represents a backoff counter value.

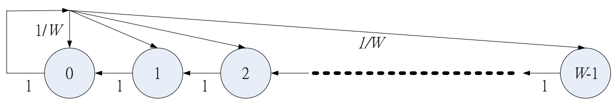


Figure 13. The discrete Markove model for modeling backoff in broadcasting.

Let $k \in [0, W-1]$ denote the states of this discrete Markov chain. Let $b(t)$ denote the random process representing the backoff time counter, which is initially chosen over $[0, W\text{-}1]$ uniformly with probability $\frac{1}{W}$, and then decrements at every time slot when the idle time of the channel is more than DIFS. The following relationship can be derived from the model above.

$$P\{b(t)=k\} = P\{b(t-1)=k+1\} + \frac{P\{b(t-1)=0\}}{W}, \quad k < W-1 \qquad (1)$$

$$P\{b(t)=W-1\} = \frac{1}{W} P\{b(t-1)=0\}, \qquad k = W-1 \qquad (2)$$

The steady state probability p_k for a node with k remaining time slots before being allowed to tranmit (broadcast) can be derived by limiting equations above.

$$\lim_{t\to\infty} P\{b(t)=k\} = p_k = \frac{(W-k)}{W} p_0 \qquad (3)$$

Since $\sum_{i=0}^{W-1} p_i = 1$, p_0 can then be solved as (4).

$$p_0 = \frac{2}{W+1} \qquad (4)$$

At any time slot, the node being at state 0 has the steady state probability of p_0, which is the transmission probability a node could transmit (broadcast) data at any given time slot.

B. Modeling the dynamics among n nodes

Once we know the behavior of a node, we can model the dynamics among n nodes. Given a wireless ad hoc network, where all the n nodes are within one-hop neighboring range. Let n_t be the number of transmitting nodes, then the probabilities that no one is transmitting (P_x) and at least one node is transmitting (P_t) can be calculated by the following equations.

$$P_x(n) = P\{n_t = 0\} = (1 - p_0)^n \tag{5}$$

$$P_t(n) = P\{n_t \geq 1\} = 1 - (1 - p_0)^n \tag{6}$$

The probability (P_s) that a node successfully transmits a packet can also be calculated:

$$P_s(n) = P\{n_t = 1\} = np_0(1 - p_0)^{n-1} \tag{7}$$

The probability (P_c) that a node experiences a collision can then be expressed as (8).

$$P_c(n) = P\{n_t > 1\} = 1 - P\{n_t = 0\} - P\{n_t = 1\} \tag{8}$$

In standard IEEE 802.11, the transmission probability p_0 is solely a function of contention window size (W) according to (4). Since the transmission probability is a constant depending on W, when the number of nodes contending for the same channel increases, more collisions will happen with degrade network reliability.

Two performance metrics, the packet delivery ratio (PDR) and the normalized throughput (S'), are used to assess the performance of different methods. As discussed previously, the PDR is defined as the ratio of the number of successful delivered packets to the number of the total packets transmitted, and can be calculated as

$$PDR(n) = \frac{P\{n_t = 1\}}{\sum_{i=1}^{n} i \cdot P\{n_t = i\}} = (1 - p_0)^{n-1} \tag{9}$$

The throughput (S) is defined as the total number of bits of successfully delivered packets divides by the time elapsed for the transmission. The throughput can be expressed as (10).

$$S = \frac{P\{n_t = 1\}L}{P\{n_t = 0\}\sigma + P\{n_t = 1\}T_s + P\{n_t > 1\}T_c} \tag{10}$$

where L is the payload size in bits; σ denote the time for a slot time; T_s denote the average time the channel is sensed busy by each node during a successful transmission, and T_c denote the average time the channel is sensed busy because of a collision. Since we assume the channel is ideal and no hidden node problem is present. The collisions are only due to the same backoff time; therefore, $T_s = T_c = T$ (as defined in Figure 14).

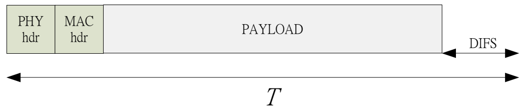


Figure 14. Structure of a transmission period of the broadcast packet.

We then define the normalized throughput as

$$S' = \frac{P\{n_t = 1\}L/R_c}{P\{n_t = 0\}\sigma + P\{n_t \geq 1\}T} \tag{11}$$

where R_c is the data rate of the broadcasting. In our modeling and simulation, we set $R_c = 1$ Mbps.

C. Adaptive Contention Window

Since we know that the choice of contention window size (W) affects the results of the system. In [30], Bianchi et al. also proposed a method to decide the optimized contention window size for WLAN, which can be easily applied to the wireless ad hoc networks. More specifically, to maximize the throughput based on the optimal transmission probability, we perform $\frac{dS'}{dp} = 0$ where p is the transmission probability and thus we have

$$(1 - p)^n - T_\sigma\{np - [1 - (1 - p)^n]\} = 0 \tag{12}$$

where $T_\sigma = T/\sigma$, i.e. T measured in slot times. Assuming that $W \gg n > 1$,

$$(1 - p)^n \approx 1 - np + \frac{n(n-1)}{2}p^2 \tag{13}$$

Substituting (13) into (12), we can derive the optimal transmission probability (p_0^*) that achieves maximum throughput as follows.

$$p = p_0^* \approx \frac{\sqrt{2}}{n\sqrt{T_\sigma}} \tag{14}$$

From (4), the approximate value of the optimal contention window size can then be expressed as

$$W^* \approx n\sqrt{2T_\sigma} \tag{15}$$

If the packet duration and number of competing neighbor nodes are known, the optimal contention window can be derived from (15). Assuming that the packet duration is known, to achieve maximum throughput, the contention window size needs to be adjusted based on the number of competing nodes, n. There are relatively few papers discussing the adaptive contention window approaches in wireless ad hoc network; however, it is noted that techniques used in wireless local area network could still be applicable to wireless ad hoc networks. In the following, we will summarize some researches which are related to approaching maximum throughput for WLANs.

In [32, 33], the authors pointed out that the performance of 802.11 standard can be much inferior from the theoretical throughput limit, and an appropriate tuning of the backoff algorithm by changing contention window size (W) can significantly increase the throughput. To approach the maximum throughput, one needs to estimate the number of competing neighbor nodes. There are methods being proposed to estimate the number of competing nodes n. In [29], the number of busy slot times was used to infer n. In [34], the number of competing nodes n was expressed as a function of the collision probability encountered on the channel, and an extended Kalman filter equipped with change detection mechanism is proposed to estimate the number of competing nodes. In [35], a Bayesian approach was proposed to optimize the backoff parameters of the DCF based on the predicted distribution of the number of competing nodes.

Due to the difficulty and complexity of estimating the number of competing nodes, alternative methods without estimating the number of competing stations have been proposed. In [36], the authors pointed out that when $n \geq 4$, the product $n \cdot p_0^*$ can be very close to asymptotic value, where p_0^* is the optimal transmission probability as defined in (14). It is also shown that $n \cdot p_0^*$ is the tight upper bound of slot utilization (SU), which is defined as $SU = \frac{\text{number of busy slots}}{\text{number of availabe slots}}$. Based on this observation, Asymptotically Optimal Backoff (AOB) is proposed. The basic idea of AOB contains two steps. The first step is to estimate the SU. In the second step, only when SU is less than or equal to $n \cdot p_0^*$, then the broadcast transmission is enabled in the node.

In [37, 38], the authors used the number of consecutive idle slots, $\bar{C}_i$, between two attempts of transmissions as an effective indicator of choosing the contention window size to minimize the cost for a successful transmission. The optimized number of consecutive idle slots, $\bar{C}_i^{opt}$, is calculated in advance. If the number of competing nodes is known, then the optimal $\bar{C}_i^{opt}$ is chosen as the target number of idle slots, $\bar{C}_i^{target}$. If the number of competing nodes is unknown, an observation that this number can converge quickly to an asymptotic value, $\bar{C}_{i\infty}^{opt}$, which can then be used to approximate $\bar{C}_i^{target}$. Based on the value of $\bar{C}_i^{target}$, a method called idle sense is proposed. The basic idea of idle sense is that if $\bar{C}_i < \bar{C}_i^{target}$ the contention window should be increased; otherwise, the contention window should be decreased.

In [39], the observation, which is also mentioned in [32], that the collision probability is independent of the number of competing nodes when the optimized throughput is achieved can be used to create a simpler algorithm. The optimal collision probability is derived *a priori*. Based on monitoring the collision probability, the transmission probability can thus be tuned toward the optimal transmission probability, therefore, the knowledge of the number of competing nodes is no longer required.

In this section, we introduced a discrete Markov chain to model the backoff mechanism within a node. After the modeling of a single node, the dynamic of n nodes was easily formulated. An adaptive contention window method for optimizing the throughput was then introduced. The derivation of the adaptive contention window size gives a sense to the choice of Random Access Delay (RAD) in mitigating broadcast storms.

V. Proposed Method

As discussed in the previous section, the channel is very easy to be saturated in a dense 802.11 network and the subsequent collisions increase significantly. Even though the optimal contention window can be derived in (15), however, the algorithm for estimating the number of competing nodes n is usually complicated. In this section, we aim to create a simple algorithm that significantly improves the performance in a dense network.

It is intuitive that if the channel idle probability P_{idle} is high, it is less likely broadcasting the packet will cause collision. On the other hand, if the channel idle probability is low, broadcasting the packet will more likely to cause collisions. Therefore, we can adaptively adjust the transmission/broadcast probability based on the channel idle probability to improve the performance. More specifically, the transmission probability $P_0(n,t)$, which governs whether a node can transmit/broadcast the data at time t, with n competing nodes, is modified as

$$P_0(n,t) = p_0 \cdot \tilde{P}_{idle}(n,t-1) \quad (16)$$

where the weighting term $\tilde{P}_{idle}(n,t)$ represents an exponential moving average of measured channel idle probability $P_{idle}(n,t)$ at each time instance, i.e.,

$$\tilde{P}_{idle}(n,t-1) = (1-\alpha)\tilde{P}_{idle}(n,t-2) + \alpha P_{idle}(n,t-1) \quad (17)$$

where α is a smoothness control factor.

It can be shown that the measured channel idle probability $P_{idle}(n,t)$ can be theoretically and recursively approximated by

$$P_{idle}(n,t-1) = \frac{P_x'(n,t-1)\sigma + P_t'(n,t-1)T_{DIFS}}{P_x'(n,t-1)\sigma + P_t'(n,t-1)T} \quad (18)$$

where σ denotes the time duration for one slot, T_{DIFS} is the time duration for a DIFS, and T denote the packet duration, as shown in Figure 14. The probability $P_x'(n,t)$ that no one is transmitting and the probability $P_t'(n,t)$ that at least one node is transmitting at a given time slot of the proposed idle probability based method can be inferred from (5) and (6), i.e.,

$$P_x'(n,t-1) = \left(1 - P_0(n,t-1)\right)^n \quad (19)$$

$$P_t'(n,t-1) = 1 - P_x'(n,t-1) \quad (20)$$

Equations (16)-(20) are for calculating the values in the theoretical and recursive modeling. In the actual implementation, W is used for deciding p_0, α is used for filtering, and n is not needed in the implementation since $P_{idle}(n,t)$ is measured from the real channel condition without any theoretical approximation, i.e., only (17) is used. More specifically, in the simulations, $\tilde{P}_{idle}(t) = \tilde{P}_{idle}(n,t)$ was estimated recursively based on the following equation.

$$\tilde{P}_{idle}(t+\Delta t) = min\left(\left(1-\frac{\Delta t}{T_o}\right)\cdot \tilde{P}_{idle}(t) + \frac{\Delta t}{T_o}\cdot b, 1.0\right) \quad (21)$$

where Δt is the sampling time for channel status, and

$$b = \begin{cases} 0, & \text{if channel is busy.} \\ 1, & \text{if channel is idle.} \end{cases}$$

The value of T_o was set to 1000 time slots, and Δt to 1 time slot in the simulation.

The algorithm of the proposed idle probability based method is shown as follows:

> Periodically update channel idle probability $\tilde{P}_{idle}$ based on (21)
> On Backoff timer expires:
> Generate a random number p_r over [0,1]
> if $p_r < \tilde{P}_{idle}$ transmit the packet
> else entering re-backoff

In the re-backoff process, the node enters another backoff state with the same contention window size.

VI. Modeling and Simulation Results

In this section, we compare the modeling and simulation results of three different approaches: the standard IEEE 802.11, the optimal contention window with n given, and the proposed idle probability based method. The modeling results are based on the derivation in Sections IV and V. To verify the modeling results, we conducted our simulations over NS2. Without loss of generality, the simulations are conducted for single hop wireless ad hoc network with a saturated scenario over a $50 \times 50m^2$ network topology. The network scenario was generated using *setdest* in NS2. The number of nodes in the topology range from 10 to 100 with increments of 10. The transmission range is set to 100 meters, and the carrier sensing range is set to 250 meters. The capture effect was turned off and the EIFS was disabled. And, the broadcast was performed at a basic rate of 1Mbps.

In this simulation, the packet arrival rate to a node is 500 packets per second (pps). The nodes start broadcasting at 0.1 second and the simulation ends at 20 seconds. The data were collected and analyzed after 20 seconds. The contention window size (W) is set to 64 in the simulation. In the modeling and simulation, we use two different payload sizes, 64 bytes and 1500 bytes, to represent safety messages and multimedia packets.

The performance metrics used in the simulation are calculated as follows:

- Packet Delivery Ratio (PDR): average number of packets received in each receiver node.

$$PDR = \frac{1}{N_r}\sum_{i=1}^{N_r}\frac{n_p(i)}{N_p} \quad (22)$$

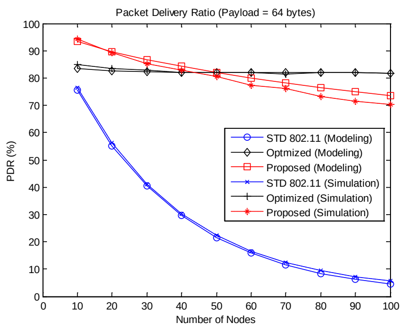
  where N_r is the total number of the nodes, $n_p(i)$ is total number of packets received by the i-th receiver node, and N_p is the total number of the packets transmitted.

- Normalized Throughput (S'):

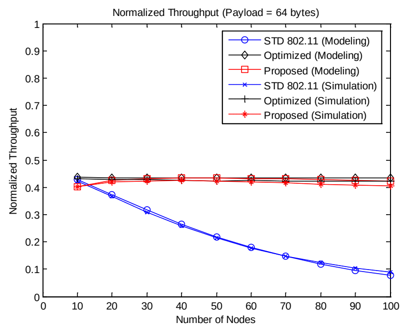
$$S' = \frac{N_s \cdot L}{T_e \cdot R_c} \quad (23)$$

  where T_e is the simulation time, R_c is the data rate used for broadcasting, i.e. 1 Mbps in the simulation, L is the payload size in bits, and N_s is the total number of successful transmissions.

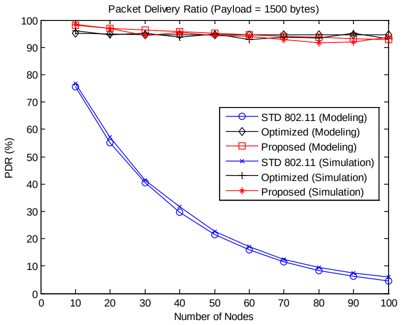
Figure 15 shows the modeling results and the NS2 simulation results. The curves for different methods are listed in the legend. The NS2 simulation results are shown to be very consistent with the modeling results. The slight difference of the PDR performance between modeling and simulation for standard IEEE 802.11 is believed to be caused by the consecutive freeze process. And the difference of the PDR performance for the proposed method is due to the fluctuation of the measured channel idle probability. The differences are also observed in the normalized throughput.



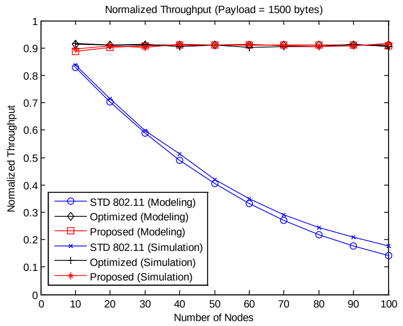
(a) PDR (Payload size = 64 bytes)



(b) Normalized Throughtput (Payload size = 64 bytes)



(c) PDR (Payload size =1500 bytes)



(d) Normalized Throughput (Payload size = 1500 bytes)

Figure 15. (a) PDR with payload = 64 bytes. (b) Normalized Throughput with payload = 64 bytes. (c) PDR with payload = 1500 bytes. (d) Normalized Throughput with payload = 1500 bytes.

Both modeling and NS2 simulation results show that by simply feeding back the channel idle probability, the results can be improved significantly, especially when network density becomes higher and payload sizes become bigger. The PDR of the proposed method is significantly higher than the default IEEE 802.11 standard method as the network density increases. When the number of neighbor nodes is 100, the PDR of the proposed method is more than seven times of the default IEEE 802.11 method with payload size being 64 bytes. When the payload size increases to 1500 bytes, the PDR of proposed method is more than 9 times better than the standard IEEE 802.11 method. The normalized throughput of the proposed method is very close to the theoretical bounds, as shown in Figure 15 (b) and (d), especially when the payload sizes increase.

It is shown that the PDR and normalized throughput of the proposed method increases with the payload size. When the payload size equals 1500 bytes, the PDR of the proposed method is more than 90% and the normalized throughput is about 90%. This indicates that the proposed method would be suitable for multimedia data exchanges.

The proposed method can easily be combined with simple broadcast storm mitigation approaches, such as the counter-based approaches, to achieve more reliable broadcasting. In addition, the proposed mechanism can also be applied to beaconing and gossiping among hundreds of nodes with high throughput and PDR.

Moreover, in our simulation, we adopted the two-ray ground refection model. However, as shown in literature, simulations conducted over different propagation models would have different results [22]. In reality, the performance would be different from the simulation results in some ways, especially in a city area that buildings block most of the radio transmission and create heavy hidden node problems. More realistic simulations and real-world experiment should be conducted to assess efficiency and effectiveness of the proposed algorithm.

The researches for mitigating broadcast storm are mostly based on heuristics, while the researches for maximizing throughput in WLAN provide a lot of mathematical foundation. With the network density is expected to be higher, the combination of both researches would facilitate more reliable multimedia broadcasting over the dense ad hoc networks. Our proposed method is not to substitute the existing approaches, but to show a simple method could effectively perform near optimal results and facilitate the combination with the broadcast storm mitigation approaches.

VII. Conclusions

The recent major focus of the ad hoc networks is on VANETs, which have quite different characteristics comparing with MANETs. The high mobility makes a VANET difficult to adopt traditional routing protocols for data communications. Therefore, broadcasting is becoming a predominant technology for message exchange in VANETs. Even though the current focus of the research in VANETs is on safety applications, the multimedia applications would be feasible with the higher available bandwidth installed.

However, even though the bandwidth could be increased, the network is still easy to be saturated, especially when the density of mobile devices is getting higher and the packet size becomes bigger, and when redundant packets flood the network. As mentioned in [22], after the VANETs are deployed the nodes would operate in a saturated condition most of the time. When a network is saturated, significant collisions happen when nodes operate under the standard IEEE 802.11. In this article, we identify the problems and introduce a simple technique to mitigate the problem.

To better understand the broadcast nature, we introduce a well-known mathematical model used for modeling unicast of a WLAN but extended to the broadcast scenario. By applying the mathematical models, observations in different researches could easily be modeled and incorporated. Based on the model, we tested a simple idle probability feedback algorithm, which appears to perform significantly better than the standard 802.11.

The proposed idle probability based method significantly outperforms the standard IEEE 802.11, especially when the payload size and network density increase. The PDR of the proposed method is more than 90% and the normalized throughput is about 90% when the payload size equals 1500 bytes, therefore, our proposed method can be suitable for multimedia data exchange.

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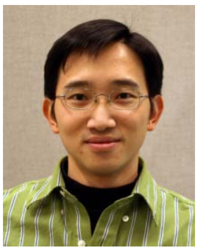

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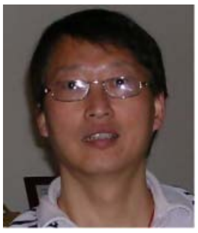

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