Simulation Studies on Barrage Relay Networks

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***Abstract*—Soldier Radio Waveform (SRW) network is a kind of mobile Ad hoc network. It is mostly suitable to tactical or emergency communications. The Time Division Multiple Access (TDMA) control mechanism of Barrage Relay Network (BRN) is used in SRW. To make simulation study on BRN, a group of network models, node models, and process models of BRN are built with OPNET simulation kits. Moreover, the simulation study includes Controlled Barrage Region (CBR), which is a representative application of BRN. The procedures of building CBR and data transmission are implemented. The correctness of these models is proved by extensive simulation experiments and rigorous analyses. These models can be used in both academic study and industrial applications.**

Keywords—SRW, BRN, CBR, OPNET

I. Introduction

Soldier Radio Waveform (SRW) is an important component of the next generation tactical internet of the U.S. army [1,2]. It is one of the key technologies of the joint tactical radio system [3]. Multiple channel access control is the most important and challenging part of SRW system [4]. Nowadays, SRW networks use the technology of Barrage Relay Network (BRN) [5]. BRN is developed by the TrellisWare company of U.S.A as the datalink layer protocol. It is mostly suitable to Mobile Ad hoc NETworks (MANET). BRN is composed of a series of modern waveform processing technologies for cooperative communications [6], such as space-time coding, distributed beamforming, frequency hopping and modern error correction coding, etc. By effectively combining and integrating these techniques, [7] built a test bed for tactical mobile mesh networks and proposed the concept of BRN with [8]. The key idea of BRN lies in the fact that a single link of a wireless network may suffer bad connection due to fading, but multiple fading channels are independent so that the probability that all signal components fade simultaneously is considerably reduced, then ones could improve network connections by leveraging cooperative diversity. Some well-known forms of diversity combating correlated fading channels include spatial diversity, temporal diversity, and frequency diversity. Based on BRN, [9,10] proposed the concept of Controlled Barrage Region (CBR), which pushes BRN forward to specific applications. CBR operates in the way of multiple unicast communication patterns. By using a special type of *buffer nodes*, CBR divides the network region into many separate sectors. A node could only communicate to another node within the same sector, while any communication across the boundary of two sectors will be blocked by buffer nodes. [11, 12] analyzed CBR with the method of Markov chains and proposed a theoretical framework and optimized algorithm. [13] discussed the problem of user capacity of BRN and CBR.

At present, most studies on BRN and CBR are based on theoretical analysis. Simulation studies or test bed based experiments to support theoretical outcomes are still missing. To this end, this article builds a simulation system for BRN and CBR based on OPNET simulation kits. The key problem is to implement the TDMA multiple access control mechanism of BRN and realize the initialization and data transmission procedure of CBR. The simulation system is flexible and extensible. Based on our models, any industrial practitioners or academia researchers could make their own BRN or CBR with different requirements, and only a little of amendment or revise on the App module is needed.

The remainder of this article is organized as follows: In section II, we introduce the principles of barrage relay networks. Still, the network model, node model and process model for BRN simulation system is depicted in detail. In section III, by introducing the fundamental concepts and principles of controlled barrage region, we thoroughly explain the modules and models of CBR simulation system, especially the App module. In section IV, two simulation experiments are done for the built BRN and CBR models. Moreover, the simulation result is analyzed and compared to theoretical analysis. Finally, we summarize the conclusion and briefly give a couple of future studies in section V.

II. Barrage Relay Networks

A. Principles of BRN

At the physical layer, BRN employs a series of robust waveform and signal processing technology to fight against multipath fading and signal collision, including advanced constant envelope modulation, frequency hopping, modern error correction code, adaptive iterative detection, and phase jitter, etc. With these techniques, BRN makes cooperative and collaborative processing to received signals in order to realize the so-called Autonomous Cooperative Communications (ACC). For an MANET application, the most attracting advantage of ACC lies in the effect that when several packets containing same data arrive at a receive node, these packets will not collide or interfere with each other; On the contrary, they form cooperative diversity which greatly improves the probability of correct decoding and message recovery. Therefore,

This work is supported by Natural Science Foundation of Liaoning Province with No. 20170540008.

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BRN eliminates the boring problems of packet collision, hidden terminal, and exposed terminal in traditional wireless networks, and therein saves collision resolve solutions.

BRN does not use MANET routing mechanism, does not use IPv4 or IPv6 address and gateway, and does not rely on infrastructure. Only the least of network knowledge and resource consumption are needed for BRN running. The Medium Access Control (MAC) protocol of BRN works in the way of TDMA. The time line is cut into many slots. When a relay node receives a packet from its upstream neighbor node, it will forward the packet in the following slot, so principally, BRN uses flooding transmission mechanism based on TDMA slot synchronization.

The Tactical Data Link (TDL), such as Link 16, is another type of tactical internet. Both BRN and TDL use TDMA as MAC protocol and use time slot as the unit of resource assignment. However, the TDMA of TDL is completely different from the TDMA of BRN. In TDL, time slots are assigned to nodes and the assignment may be based on a static or dynamic way. A node can only transmit in the slots it is assigned to and cannot uses the slots for other nodes. The time slot assigning of TDL aims to avoid signal collision in wireless communications, i.e., more than one nodes are not allowed to transmit in the same slot. In other words, only a single node could access wireless channel at a slot, so there is no signal collision at a receiver node. Different from TDL, any node in BRN could transmit at any slot. There is no time assignment in BRN. When a relay node receives a packet at a slot, it will forward the packet at the following next slot, so it is very likely that a receiver node receives multiple packets at a slot from its upstreaming neighbor nodes. While, as mentioned before, owing to the series of waveform and signal processing technology used in the physical layer of BRN, those packets will not collide or interfere with each other; On the contrary, they will generate cooperative diversity benefit, so as to help resolve the original source message.

B. Modeling BRN

In this paper, an BRN simulation network is built in the OPNET simulation environment. See Fig.1. The network contains a pair of source node and sink node, as well as 11 relay nodes. The length of a segment in the network region equals 1.25km, and the communication range of any node is set to 2km, so the BRN performs as a multi-hop network.

The node model, i.e., the protocol stack of BRN node is shown in Fig.2. Besides antenna and wireless transceiver, the protocol stack includes the modules of TDMA and APP. TDMA is the kernel function module of BRN, which realizes the TDMA wireless channel access mechanism. The APP module does not belong to BRN. It depends on different applications. In this section, to be uncomplicated, only a simple APP is given. It is equipped with the functions of source node generating packets, relay node forwarding packets, and sink node receiving packets. In next section, a more complicate APP module for CBR will be given and explained.

TDMA is the kernel function module of BRN. Its finite state machine, i.e., process model, is showed in Fig.3. The state "INIT" represents for initialization procedure, in which the initial values of various variables are given. The state "Tick" is used for time slot division and assigning slot number. The simulation kernel will enter "Tick" periodically. The source node enters the state "Send-PK" at the beginning of every time slot and check whether there are packets in the subqueue waiting for transmission. If Yes, a packet will be taken out from subqueue and sent to transmitter; If No, it does nothing. The state "Rec-PK" works for all nodes to receive packets. When "Rec-PK" receives a packet, it first judge where it comes from by checking the packet stream number. If the packet comes from APP, it is to say the packet is generated by the source node and is waiting for transmission, so "Rec-PK" inserts it into subqueue; If it comes from wireless receiver, it is to say the packet is received from air, then "Rec-PK" transfers it to APP and APP will take over and deal with it. The simulation studies on the BRN network in Fig.1 will be done in section IV.

Fig.1. The network model for BRN.

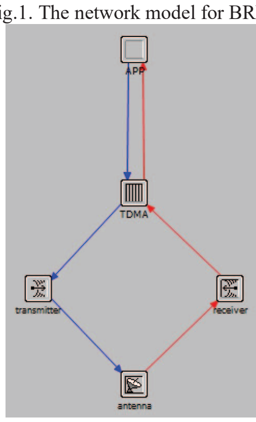

Fig.2. The node model for BRN.

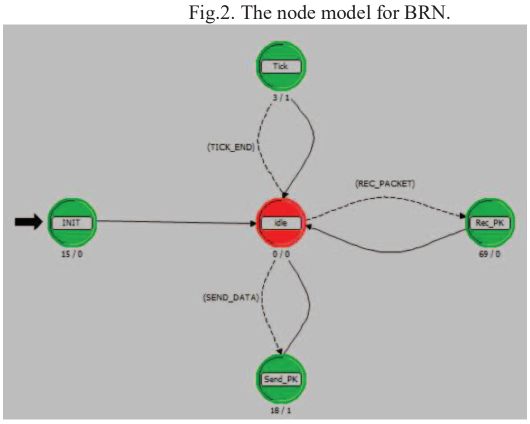

Fig.3. The TDMA process model for BRN.

III. CONTROLLED BARRAGE REGION

A. *Principles of CBR*

A representative application scenario of BRN is CBR, which essentially implements the applications of multiple unicast communications. Specifically, there are a couple of (source-sink) pairs of communication partners and many relay nodes distributed in the network region. These source-sink pairs are separated in space, so it is feasible for them to communicate simultaneously. In other words, there simultaneously exists many unicast flows in the network region. To achieve this goal, CBR divides the whole network region into several unicast sectors and classifies all relay nodes into three types:

1) Internal node: It lies in a unicast sector and forwards packets.
2) Buffer node: It lies between unicast sectors, blocks packets as a wall, and prevents packets from passing through sector borders.
3) External node: It lies in a place far from unicast sector, so does not act as internal node or buffer node.

There are two periods within the CBR working procedure: Contention Logic Channel (CLC) and Data Logic Channel (DLC). CLC is used for initialization and CBR building. In CLC, all relay nodes get or recognize their roles as internal node, buffer node, or external node. DLC is used for data transmission. In DLC, internal nodes forward data packets, buffer nodes block data packets, and external nodes absorb and destroy packets. Therefore, the key point for CBR performing well is to correctly determine the roles of relay nodes in CLC. To build CBR, the source node and sink node utilize the Request To Send (RTS) and Clear To Send (CTS) hand shaking mechanism. Next, we explain the CBR building procedure in detail by introducing CBR modeling.

B. *Modeling CBR*

An CBR network model containing two CBR is shown in Fig.4. Its node model is shown in Fig.5, where the layers below TDMA are as the same to Fig.2, which are kernel components of BRN. CBR_App is the application module for CBR. It is used for the two periods of CLC and DLC. Also, the source and sink modules are used for generating and receiving data packets, respectively.

The finite state machine of CBR_App is shown in Fig.6. Its states and variables are listed in Table. I and Table. II, and its time line advancing is shown in Fig.7.

The work flow of CBR_App is depicted in detail below with respect to Fig.6 and Fig.7.

1) Step 1: Simulation starts running. A source node generates and transmits an RTS packet. When a node receives the RTS, it gets the number of hops between itself and the source node and records the number by a state variable "*d_to_source*". It then revises the packet field "*Hop_count*" with the operation "*Hop_count++*" and forwards the packet. This procedure is repeated until the RTS arrives at a sink node.
2) Step 2: When a sink node receives an RTS packet, it calculates the total number of hops between the source node and the sink node. After $k1$ slots, the sink node generates and transmits an BUF packet into the network; After $k2$ slots, the sink node generates and transmits an CTS packet into the network. If a node around the sink node, i.e., it is one hop distant from the sink node, receives the BUF, it does not forward the BUF packet, but only set the flag bit "*is_buffer*" to 1, so as to mark its role as a buffer node.

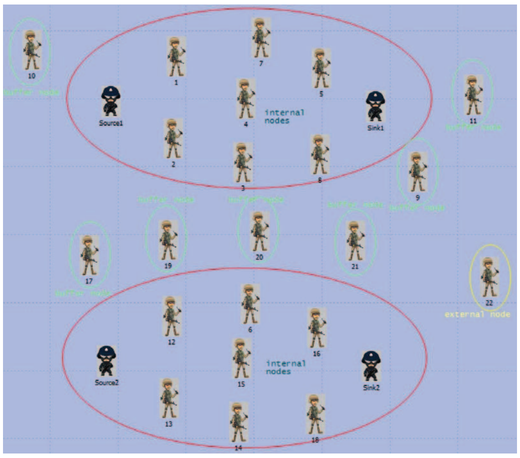

Fig.4. The network model for CBR.

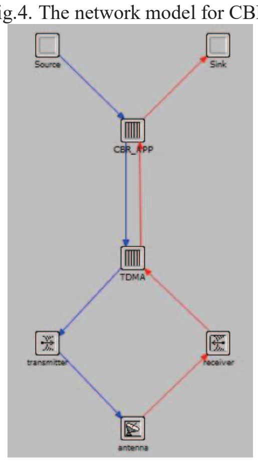

Fig.5. The node model for CBR.

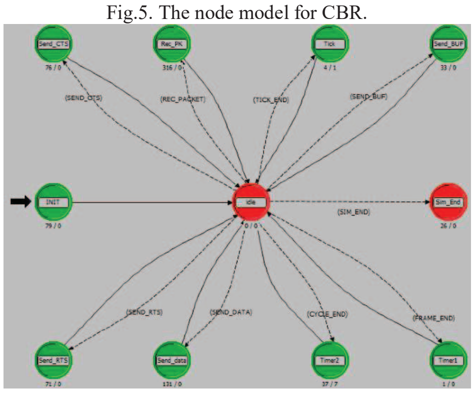

Fig.6. The CBR-App process model

TABLE I. CBR-APP STATES

State	***Function***
INIT	Initialize all variables.
idle	Idle state does nothing.
Sim-END	Represents for simulation end, collects statistics and generates simulation results.
Send-RTS	1. A source node generates and sends an RTS packet to its pairwise sink node. 2. When an internal node receives an RTS packet, it revises the "Hop-count" field and forward the RTS packet.
Send-CTS	1. When a sink node receives an RTS packet, it generates and sends an CTS packet to its pairwise source node after $k2$ slots. 2. When an internal node receives an CTS packet, it revises the "Hop-count" field and forward the CTS packet.
Send-BUF	1. When a sink node receives an RTS packet, it generates and transmits an BUF packet after $k1$ slots. 2. When a source node receives an CTS packet, it generates and transmits an BUF packet after $k3$ slots.
Send-DATA	1. Within the DLC period, a source node generates and transmits a DATA packet. 2. If an internal node receives a DATA packet, forwards it. 3. If a buffer node receives a DATA packet, destroys it.
Rec-PK	1. If the received packet comes from the source module, insert it into subqueue. 2. If the received packet comes from the TDMA module, make different processing according to its type (RTS, CTS, BUF, or DATA).
Timer1	Timer for TDMA frame. A TDMA frame contains M slots.
Timer2	Timer for BRN cycle. BRN cycle is used to refresh and update CBR in mobile topology varying networks. At the end of BRN cycle, it will restart CLC and rebuild CBR.
Tick	Counter for slot. Tick++ after one slot.

TABLE II. CBR-APP VARIABLES

Variable	***Variable type***	***Function***
M	Global variable	The number of slots contained within an TDMA frame. The minimum number is 3.
N	Global variable	Protection period. A bigger value of N corresponds to a larger CBR region and more internal nodes.
slot	Global variable	The duration of an TDMA slot.
CYCLE	Global variable	The duration of an BRN cycle.
$k1$	State variable	When a sink node receives an RTS packet, it waits for $k1$slots before transmitting an BUF packet.
$k2$	State variable	When a sink node receives an RTS packet, it waits for $k2$ slots before transmitting an CTS packet.
$k3$	State variable	When a source node receives an CTS packet, it waits for $k3$ slots before transmitting an BUF packet.

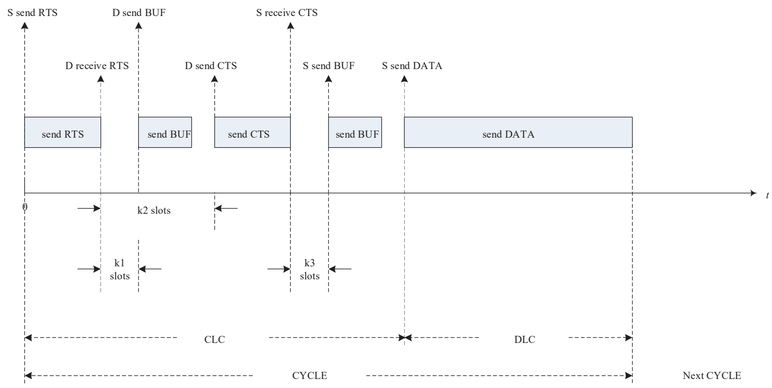

Fig.7. The timing sequence of CBR

3) Step 3: During the period of an CTS packet going backward, if a node receives the CTS, it gets the number of hops between itself and the sink node, and the total number of hops between the source node and the sink node. It records the two numbers of hops by two state variables "*d_to_sink*" and "*d_source_dest*", respectively. Then, it marks its role according to the judgement below.

   $(d\_to\_source + d\_to\_sink) > (d\_source\_dest + N)$?

   If yes, it is a buffer node; Else, it is an internal node.

   It should be noted that the role of "buffer node" and "internal node" are mutually exclusive, i.e., any node cannot be a buffer node and an internal node simultaneously.

   After marking its role, the node revises the packet field "*Hop_count*" and continue sending the CTS packet toward the source node.

4) Step 4: When a source node receives an CTS packet, it gets the total number of hops between the source node and the sink node and records the number by a state variable "*Distance_S_D*". After $k3$ slots, the source node generates and transmits an BUF packet. If a non-internal node around the source receives the BUF, it marks itself as a buffer node.

   In step 2 and step 4, the parameters $k1$, $k2$, and $k3$ are given by the formulas as below.

$$k1 = max(0, N\text{-}1) \tag{1}$$
$$k2 = max(1, N) + 2 \tag{2}$$
$$k3 = N \tag{3}$$

5) Step 5: After the four steps above, the CLC procedure is complete. All network nodes get its roles as buffer node, internal node, or none of them. In the last case, it is marked as an external node. Step 5 is the DLC procedure. A source node sends DATA packets with the period of M slots. If an internal node receives a DATA packet, it forwards the DATA in the next slot. If a buffer node receives a DATA packet, it destroys the packet. Finally, the DATA packet will arrive at the pairwise sink node. Since the value of M is set by M>3, two consecutive DATA packets will not collide at any node. ■

If the network is static with fixed topology, then it keeps sending DATA in DLC, i.e., step 5, until all source data have been sent out; Otherwise, if the network is mobile with variable topology, the network should set a CBR refreshing period "*CYCLE*" to update the roles of nodes. The length of "*CYCLE*" is up to topology changing rate. When the "*CYCLE*" timer is time out, the network should restart CLC by repeating step 1 – step 4 again.

IV. Simulation Experiments

A. Simulation Experiment on BRN

This experiment is designed to check and affirm the functionality of BRN shown in Fig.1. The parameter settings are as follows.

The communication range of a node: 2 km.

Length of slot: 0.1 s.

Period for a source node sending DATA packet: 1 s.

Simulation duration: 10 minutes.

The simulation result is shown in Fig.8. The number of sending packets "*PK_SENT*" is equal to the number of receiving packets "*PK_RCVD*", which shows there is no packet loss during simulation network running. Further, the packet delay statistics "*PK_DELAY*" measures the propagation delay between source node sending packet and sink node receiving packet. In this simulation experiment, the network topology is fixed, so packet delay is constant, which takes the value of 0.400056 second. This result could be analyzed theoretically as following. In Fig.1, according to the parameter setting communication range = 2km, the sink node is approximately 5 hops distant from the source node. It is to say the sink node can only receive packets sent from 4-hop nodes, including the nodes 6, 7, 11 in Fig.1. Since the slot duration is set to 0.1s, the number of four TDMA transmission consumes 4 slots delay, i.e., 0.4s. Plus the propagation delay in the 5th hop, the total delay should be a little larger than 0.4s, which complies with the simulation result.

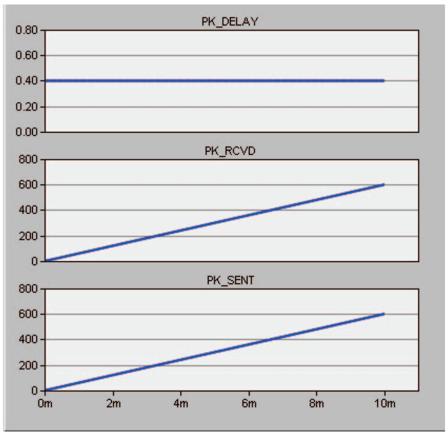

Fig.8. The simulation result of BRN

B. Simulation Experiment on CBR

Simulation network is shown in Fig.4. The network region is a square with the size of 10km*10km. The communication range of a node is set to 2km. There are two CBRs in the network, with pairwise source nodes and sink nodes, marked by Source1, Sink1, Source2, Sink2. By running simulation, it is confirmed that the nodes 9, 10, 11, 17, 19, 20, 21 are buffer nodes, the node 22 is an external node, and others are internal node. This result is in accordant with the network topology in Fig.4, so ensures the functionality correctness of our models and algorithms.

V. Conclusion and Future Work

Barrage relay network is a promising technology for mobile Ad hoc networks. It will play a significant role within the applications of tactical communications and emergency communications. In future, the studies on barrage relay network will be done on many facets, including theoretical framework, analysis tools, simulation and testing systems, device and applications development, etc. Based on OPNET simulation tools, this article builds many simulation models for BRN and CBR, including network models, node models and process models. The simulation results conform to theoretical analysis, which ensures the correctness of building models. These models provide “take & use” services for network industry users, and help academic researchers understand BRN and CBR. They could easily make further studies on BRN and CBR based on our work.

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