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Research on Communication Stability of Inter-Cannonball Network Based on OPNET

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Abstract: In modern warfare, achieving strikes against military targets commonly involves utilizing methods such as fire coverage and missile precision guidance. While effective, fire coverage requires significant ammunition support, and missiles can be costly. Therefore, an intelligent strike solution can be an effective way to address these challenges. The inter-cannonball wireless communication network provides a solid foundation for inter-cannonball networking and joint strikes. The synergy improves the strike's range and precision, ensuring own safety and destroying the enemy's core with success. In this paper, the reliability of inter-cannonball group communication is studied. The vast array of activities and short striking distance of cannonballs make wireless networking between cannonballs a technological challenge. For this unique communication environment, the network of cannonballs is discussed, the self-organizing structure model of the network is proposed, the corresponding node topology is established, the protocol framework of inter-cannonball communication is presented, and the simulation parameters of the communication network are set. On this premise, discrete event simulation is performed by using the OPNET program to validate the impact of failure rate and node movement speed on the inter-cannonball network communication reliability. And the main performance indices of the inter-cannonball communication system are derived. The simulation results indicate that it can maintain basic communication stability, with wireless LAN delays of less than 100 ms, even when the node failure rate reaches 20%. The simulation verification method, on the other hand, overcomes the limitations of the real environment, optimizes the design phase, reduces research costs, and accelerates the development of intelligent cannonballs.

Keywords: intelligent cannonball; communication stability; OPNET; routing protocol emulation; inter-cannonball network; mobile ad hoc networks

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1. Introduction

On the Russo-Ukrainian War battlefield, it can be seen that advanced munitions are one of the keys to creating an asymmetric firepower advantage [1]. To perform successful and intelligent strikes against enemy units while decreasing self-damage and enhancing attack accuracy, it is vital to guarantee that the munitions have the capacity to hit properly and destroy effectively. Intelligent cannonball grouping with coordinated strikes is one potential solution. This is the most effective way for combat units to improve their battlefield survivability, reduce the amount of ammunition, and achieve the intended operational objectives [2]. There is minimal communication and coordination between cannonballs, and the tactic of fire coverage is still used to accomplish the target's destruction. Future warfare will include the development of intelligent artillery rounds to provide swift, intelligent strikes.

Relevant data show that ammunition consumption can be reduced by at least 20% when attacking with the support of cannonballs [3]. To obtain the first opportunity in future wars, fight the enemy effectively, and protect themselves, it is very important to develop intelligent cannonball technology to bridge the gap between foreign and domestic technology [4,5]. Due to the vast array of activities and short striking distance of artillery rounds of intelligent cannonballs, high communication stability is required, and the theoretical issues for communication mechanisms and engineering methods need to be clarified [6,7].

The inter-cannonball ad hoc network is a wireless mobile network established through automatic connection of the other nodes, which does not rely on ground command stations or satellites [8,9]. In such a network, each node operates not only as a host but also as a router; nodes transmit information to each other through multiple hops when the destination node is not within the communication range.

Ad hoc network is a multi-hop centreless network. When there are mobile nodes in this network, it becomes mobile ad hoc network (MANET). Since MANET is self-organizing, self-healing, and vandal resistant, it is ideal for special external situations such as natural disasters, military areas, and communication in locations without radio infrastructure.

MANETs differ significantly from both fixed networks and ordinary mobile networks. First, inter-channel interference, changes in transmitting power, and node movement methods, as well as changes in the number of communication network nodes can all cause dynamic changes in MANET network topology. Second, ad hoc networks are formed in the absence of other network facilities, and mobile nodes complete their tasks using routing protocols and fixed algorithms. Again, because wireless communication distance is limited, a node requires an intermediate node to forward messages to nodes outside its communication range, thus requiring multiple hops. Finally, centralized control is a single point of contact for everything, whereas self-organizing networks use distributed network control, which is more resistant to destruction than centralized control.

The adaptability of the MANET architecture and its dynamically distributed topology are well-suited for the environment of inter-cannonball networks [10,11]. Furtherly, this brings security issues in the communication network, and there have been numerous studies to compensate for this shortcoming [12–16]. However, inter-cannonball networking still faces many obstacles due to the cannonballs' large flight distances and severe node losses.

The various strike modes are compared in Figure 1. The fire coverage mode requires more ammunition; precision-guided strikes can save ammunition resources. Due to missiles being costly, it is not a good solution when facing low-cost targets; inter-cannonball grouping can attack cost-effective targets in concert.

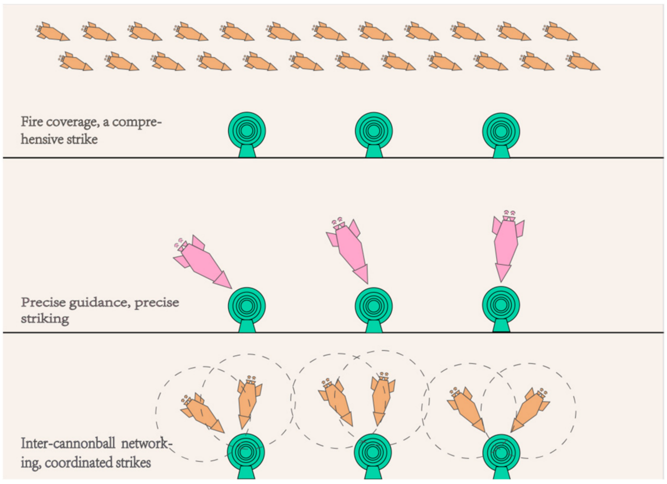


Figure 1. Comparison chart of striking methods.

Wu et al. [17] focuses on self-organizing networks in a satellite-denied environment. This research investigates the relative distance and velocity between munitions and constructs the trilateration localization integrated (TLM) with multidimensional scaling (MDS) algorithm to accomplish cooperative localization of three-dimensional, airborne, networked weapons in an ad hoc network. It boasts greater localization precision and a quicker convergence rate than the conventional approach. This accomplishes node localization in the inter-cannonball network, but the lack of inter-cannonball information exchange prevents it from achieving sophisticated cooperative strikes.

Yi et al. [18] present an innovative three-dimensional guiding approach based on clock synchronization algorithms to guide the munition for cooperative attack by computing the munition's normal phase acceleration in both horizontal and vertical planes. This solution overcomes the issue of non-connection and even communication interruption in cooperative guiding of loitering munitions induced by packet loss and delay. However, the change in attack target after the original one gets destroyed is not considered.

Terminal-sensitive cannonballs are primary stage intelligent cannonballs that use end guidance to strike area targets. Uncertainty in the intersection state between it and the target makes it difficult to calculate the laser return energy. In [19], the authors provided a novel calculation technique for laser echo power based on a laser circumferential scanning detection mechanism, establishing a calculation function for the laser echo power reflected off the ground target's surface. The terminal-sensitive cannonball only has ballistic end guidance, which cannot realize the cooperative strike of multiple munitions against multiple targets, and here lies the advantage of the inter-cannonball network, which can develop strike strategies through inter-cannonball communication and realize a cooperative strike.

Disaster area network (DAN) suffers the same issues of node loss and communication stability with inter-cannonball networks. However, with a shorter life duration, the inter-cannonball networks are less demanding in terms of energy-efficient communication. To combat the impacts of topology changes in node networks and provide dependable and energy-efficient communication, it is required to enhance latency, decrease overhead, limit energy consumption, preserve mobility, and boost bandwidth for multimedia applications. Jahir et al. [20] studied several routing protocols and compared their properties in terms of latency, overhead, throughput, topology, and mobility models.

The performance of MANET is significantly affected by network node mobility and resource limits, where node mobility impacts link stability and node resource constraints may lead to congestion. Chen et al. [21] came up with a topologically adaptive ad hoc on-demand multipath distance vector (TA-AOMDV) routing protocol that takes into account node resources, such as remaining energy, available bandwidth, and queue length of nodes, as well as the probability of connection stability, and simulated several scenarios on the NS2 platform. In high-speed node networks, the findings indicate that on-demand multipath routing protocols have considerable promise for supporting quality of service. This paper examines the effects of node speed, data rate, and number of nodes on network communication, but disregards the effect of node failure rate.

A stable communication network is a foundation for achieving inter-cannonball information sharing and completing coordinated strikes. For the characteristics of the inter-cannonball network: with the high failure rate of cannonball nodes, extensive movement range, and short striking distance, we establish the network topology and provide the protocol framework of its communication network and obtain the influence consequence of failure rate and node movement speed on the inter-cannonball communication network. The communication network architecture can meet the fundamental requirements under the harsh environment. Figure 2 depicts the flowchart of the research procedure.

The structure of this paper is as follows: Section 1 gives background information on inter-cannonball ad hoc networks. Section 2 gives the theoretical model of the inter-cannonball communication network and explores mathematically the node coordinates, communication distance, and communication parameters. To lay the groundwork for future study, Section 3 examines the features of routing protocols and picks the proper routing protocol for the inter-cannonball self-organizing network based on the characteristics of the network itself and simulation findings. In Section 4, the OPNET simulation program is introduced, the impact of node failure on routing is described, the final node topology model is shown, and the required simulation parameters are explained. In Section 5, the node movement speed and failure rate are used as variables to examine their effects on communication stability. Simulation analysis is conducted for harsh environments to determine the key technical indicators for the viability of inter-cannonball self-organizing network communication. Section 6 of this paper outlines the study outcomes and future work.

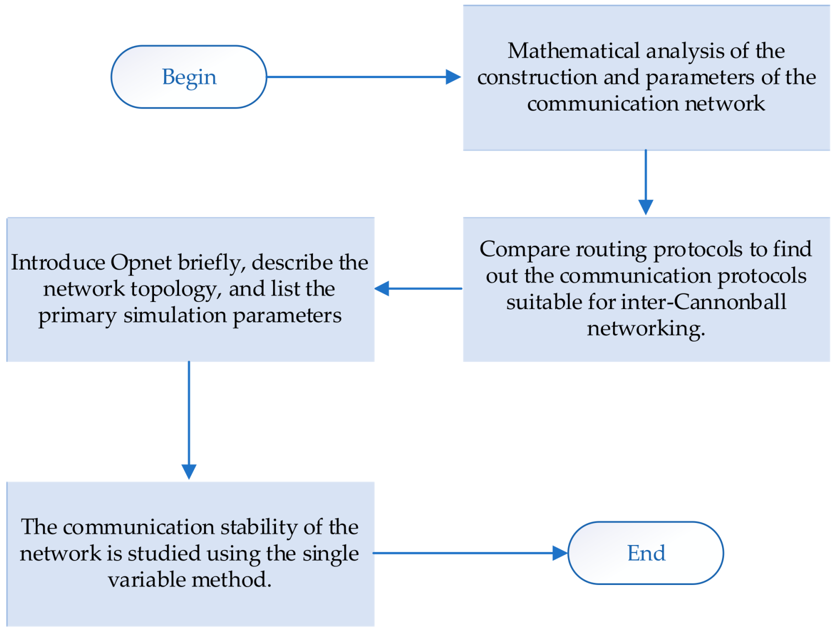


Figure 2. Flowchart of the research procedure.

2. Theoretical Modelling

2.1. Network Topology Modelling

In order to obtain the impact on the routing and stability of the communication system in the event of multiple node movements and failures, 36 ad hoc nodes are set up in the network topology with a spacing of 10 km between surrounding nodes. It is observed whether the communication network could maintain basic communication capability in the event of 20% of the nodes being disturbed.

It is essential to maintain smooth network communication within an effective communication range. The output power of the transmitting node and the sensitivity of the receiving node are the main influencing parameters. Under ideal conditions where radio waves are not reflected, scattered, or absorbed, the formula for calculating the wireless communication distance is [22]:

$$\mathrm{Loss}(\mathrm{dB}) = 32.44 + 20LgD(\mathrm{km}) + 20LgF(\mathrm{MHz}) \tag{1}$$

where $Loss(\mathrm{dB})$ is the transmission loss, $D(\mathrm{km})$ is the transmission distance, and $F(\mathrm{MHz})$ refers to the carrier frequency.

Figure 3 shows the schematic diagram of the coordinate system. The geodetic coordinate system of point P is represented by $(B,\ L,\ H)$, while the spatial rectangular coordinates are represented by $(X,\ Y,\ Z)$, where B is the geodetic latitude, L is the geodetic longitude, and H is the geodetic height [23,24].

The geocentric coordinate system is adopted to describe the ad hoc network node location, and the coordinates $(B,\ L,\ H)$ of any one node location can be expressed as:

$$\begin{cases} B = \arctan\left[\frac{Z}{\sqrt{(X^2+Y^2)}}\left(1-\frac{e^2N}{N+H}\right)^{-1}\right] \\ L = \arctan\left(\frac{Y}{X}\right) \\ H = \frac{\sqrt{(X^2+Y^2)}}{\cos B} - N \end{cases} \tag{2}$$

$$N = \frac{a}{\sqrt{1 - e^2 \sin^2 B}} \tag{3}$$

$$e = \sqrt{\frac{a^2 - b^2}{a^2}} \tag{4}$$

In Equation (2), N is the radius of curvature in prime vertical, and e is the first eccentricity. In Equation (3), a is the equatorial radius, and in Equation (4), b is the polar radius. For ease of representation, this is usually converted to a spatially right-angled coordinate system by the following conversion equation:

$$\begin{cases} X = (N + H)\cos B \cos \mathrm{L} \\ Y = (N + H)\cos B \sin \mathrm{L} \\ Z = [N(1 - e^2) + H]\sin B \end{cases} \tag{5}$$

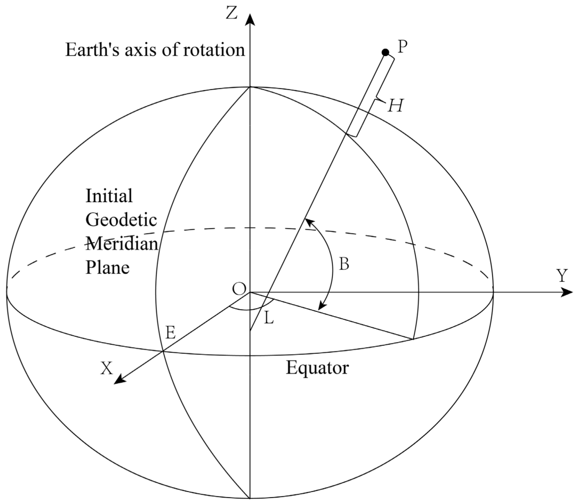


Figure 3. Geocentric coordinate system.

2.2. Modelling of Analytical Methods

In order to analyse the route establishment process, real-time data transmission and network overhead of the communication network are established. We collect and analyse the number of hops per route, route discovery time, wireless LAN delay, and throughput parameters from the modelling simulation data [25,26].

Throughput is usually expressed as the amount of data sent and received by a node per unit of time and is defined as:

$$X = \frac{C}{\tau} \tag{6}$$

where C is the total number of tasks completed, and τ is the total time taken to complete these tasks. For statistical convenience, the number of packets that successfully reach the destination node and are received at the upper layer is used as the throughput data.

The inter-cannonball ad hoc network is a more delay-sensitive network, where the delay $\overline{D}_{\mathrm{E2E}}$ is the sum of the delays of all links on the established route, defined as follows:

$$\overline{D}_{\mathrm{E2E}} = \frac{\sum D_{i,\mathrm{E2E}}}{N_{\mathrm{R}}} = \frac{\sum (t_{i,\mathrm{R}} - t_{i,\mathrm{S}})}{N_{\mathrm{R}}} \tag{7}$$

where $t_{i,\mathrm{S}}$ and $t_{i,\mathrm{R}}$ are the time when messages are sent from the source node and received at the destination node, respectively, and N_{R} denotes the total number of messages received by the destination node. Considered the most dominant transmission delay, let the propagation delay from the source node to the destination node be D_{SD}^{Pro}. Then, it is expressed as:

$$D_{SD}^{\mathrm{Pro}} = \frac{L_{SD}}{c} \tag{8}$$

where L_{SD} denotes the path length from *node_S* to *node_D*, and c denotes the propagation speed of the signal over the channel. Using the geocentric coordinate system, we know that at any moment, the link length between two neighbouring nodes V_i and V_j is:

$$\mathrm{dis}(V_i, V_j) = \sqrt{\left(X_i^t - X_j^t\right)^2 + \left(Y_i^t - Y_j^t\right)^2 + \left(Z_i^t - Z_j^t\right)^2} \tag{9}$$

where (X_i^t, Y_i^t, Z_i^t) and (X_j^t, Yj, Z_j^t) are the coordinate positions of *node_i* and *node_j* at moment t, respectively. The route between *node_S* and *node_D* can be represented by the set of links $E_{SD} = \{(V_S, V_i), (V_i, V_n), \ldots, (V_j V_D)\}$, then the length of the route is:

$$L_{\mathrm{SD}} = \mathrm{dis}(V_{\mathrm{S}}, V_i) + \mathrm{dis}(V_i, V_n) + \cdots + \mathrm{dis}(V_j, V_{\mathrm{D}}) \tag{10}$$

Combining Equations (9) and (10) yields an expression for the path length from *node_S* to *node_D* as:

$$\begin{aligned} L_{\mathrm{SD}} = \; & \sqrt{(X_{\mathrm{S}}^t - X_i^t)^2 + (Y_{\mathrm{S}}^t - Y_i^t)^2 + (Z_{\mathrm{S}}^t - Z_i^t)^2} \\ & + \sqrt{(X_i^t - X_n^t)^2 + (Y_i^t - Y_n^t)^2 + (Z_i^t - Z_n^t)^2} \\ & + \cdots\cdots \\ & + \sqrt{\left(X_j^t - X_{\mathrm{D}}^t\right)^2 + \left(Y_j^t - Y_{\mathrm{D}}^t\right)^2 + \left(Z_j^t - Z_{\mathrm{D}}^t\right)^2} \end{aligned} \tag{11}$$

3. Routing Protocol Modelling Analysis

Ad hoc routing protocols are mostly split into two groups based on the driven model: table-driven and on-demand routing protocols. Table-driven routing protocols require each node to maintain a routing table that reaches every other node on the network. The on-demand routing protocol searches for a route only when the node needs to transmit data, and only the route that actually completes the data transmission will be recorded and maintained by the routing table [27].

When a node has data to transmit, the latency of table-driven routing will be modest as long as a route exists, but it takes a large amount of overhead to maintain the route so that routing updates may keep up with network topology changes as much as feasible. By not constantly broadcasting routing information, on-demand routing conserves some network resources. However, while transmitting data, if there is no route to the target node, the data must be stored until route discovery, resulting in a modest increase in message delay.

Considering the instability of the inter-cannonball ad hoc network communication link and the bandwidth consumption of the routing protocol, the on-demand routing protocol is more in line with the design requirements. At present, the two more common on-demand routing protocols are dynamic source routing (DSR) and AODV routing protocol [28].

3.1. Routing Protocol Comparison

DSR is a network routing protocol based on the notion of source routing that is self-organizing. As a sort of on-demand routing, the DSR protocol does not need individual nodes to constantly maintain the whole network structure. When a source node delivers data, the message header will contain the source node's entire routing information to the destination node, and the data will be forwarded depending on this routing information. Two parts comprise the whole of the DSR networking procedure: route discovery and route maintenance [29].

If the source node does not have a path to the destination node during the route discovery phase, the DSR protocol will enable a flooding mechanism to broadcast route request information (RREQ) to neighbouring nodes. Neighbouring nodes that receive the request will then broadcast it again, and so on, until a path to the destination node is discovered. When a destination node or an intermediary node having a path to the destination node is discovered, the node passes the route reply message (RREP) in the same manner in the opposite direction and returns the path information to the source node. The source node now has the entire route to the destination. If a link is broken during route maintenance, the intermediate node will send the source node a route error message (RERR). The source node will examine its cache and use the remaining cached pathways or re-enable route discovery [30].

DSR employs the notion of source routing to decrease the overhead associated with route finding and prevent routing loops. However, since each piece of data must contain the whole route information, this produces an increase in message overhead during transmission. AODV, on the other hand, communicates by constructing a dynamic routing table, which is maintained by each node [31]. Therefore, AODV is more efficient than DSR when the number of nodes is high and the network topology changes often. In Section 3.2, the AODV communication protocol will be detailed.

Due to the large range of node movement and the high rate of node destruction in the inter-cannonball self-organizing network, the network topology is unstable; therefore, the effect of node failure rate communication stability must be studied. We build a communication network with 50 fixed nodes (speed is 0) and configure routing protocols as DSR and AODV, respectively. Four nodes are set to be damaged at 10 min and 20 min each, and four nodes to be restored at 30 min, for a total simulation time of 40 min.

The simulation results for the average routing hops under the above conditions is shown in Figure 4. AODV has a lower number of routing hops compared to DSR, because it is more targeted to the destination node and only performs route search activities when data transmission is taking place. Therefore, the effectiveness of the search is increased.

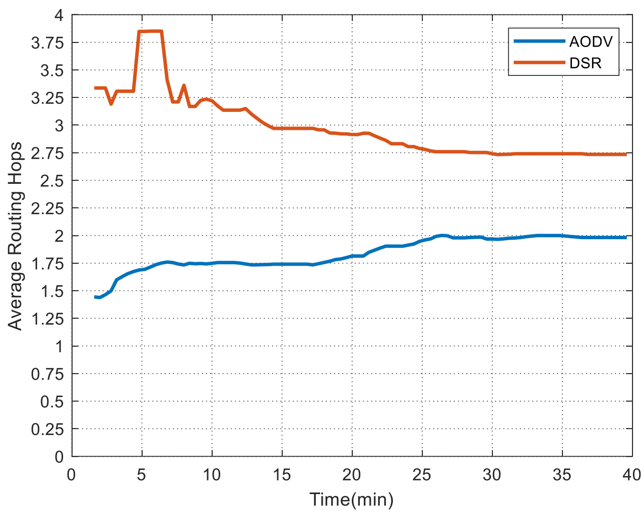


Figure 4. Comparison of average routing hops for AODV and DSR routing protocol.

A comparison on the wireless LAN delay of AODV and DSR is shown in Figure 5. AODV completes information transfer through route request, route answer, and route delivery between nodes. Each node maintains its own routing information. The DSR protocol uses source routing and stores a large amount of routing information in the packet header, which causes a difference in their wireless LAN delay.

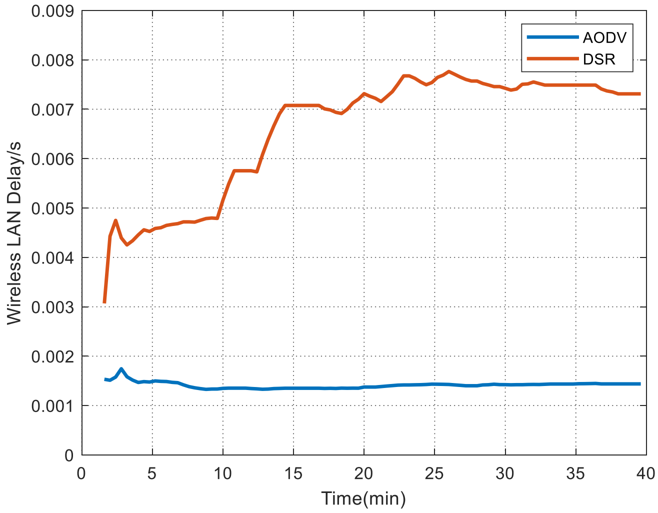


Figure 5. Wireless LAN delay comparison of AODV and DSR routing protocols.

The AODV routing protocol is more suitable for the inter-cannonball ad hoc network. It is scalable, does not require real-time maintenance, and can effectively avoid routing loops, which meets the needs of inter-cannonball ad hoc networks.

3.2. AODV Routing Protocol

The AODV protocol implements route discovery and route maintenance between nodes through four types of packets: RREQ, RREP, RERR, and active route detection (HELLO) packets. When data is forwarded between communication network nodes, the source node sends out the data packet, which is forwarded by the intermediate node, and the destination node receives the data packet and performs related processing [32].

Incremental sequence numbers are set in AODV protocol messages to avoid routing loops, which are situations where the metric value of a route counts to infinity due to the formation of loops when data is forwarded between nodes [33]. The serial number of the packet lets the node know what the old and new status of the packet is. This makes it easy for the node to do routing maintenance. If there is a route between the source node and the destination node, the data forwarding process can start directly; otherwise, the source node will start the route discovery first.

Figure 6 illustrates the process of AODV route establishment, where *node*_1 is the source node and *node*_3 is the destination node. The source node will first send RREQ messages in multicast form to other nodes within the communication range of the node, at which time the intermediate node receiving the RREQ packet will establish or update the reverse route to the source node [34]. If the RREQ message reaches the destination node, or if it reaches the existence of a sufficiently new, intermediate node with a routing table to the destination node, it will unicast the RREP message to the source node. Otherwise, the intermediate node will continue to forward RREQ messages for route finding to the destination.

The AODV protocol periodically broadcasts the HELLO message to confirm the connectivity of the communication link. If a route has not been used within the “active route timeout”, or if the next hop of a valid route is not reachable due to node movement or failure, the route is invalid. In this case, the RERR message is broadcast by the node, informing other nodes that the IP address of the node is not accessible and deleting the routing table associated with the unreachable node. Then, the source node restarts the route discovery process.

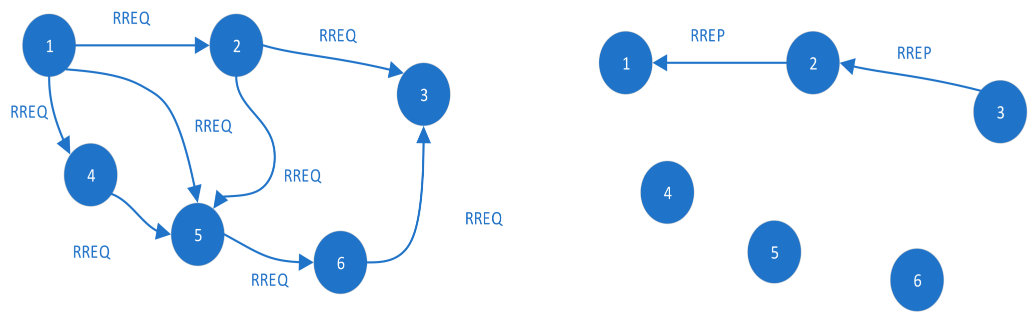


Figure 6. The AODV routing protocol route discovery process, where circles indicate nodes and numbers represent node indices.

4. Modelling Scene Setup

4.1. Introduction to OPNET

OPNET Network simulator is a tool to simulate the behaviour and performance of any type of network [35–37]. Originating from Massachusetts Institute of Technology (MIT), it enables predictive network performance management and simulation, thanks to its accurate analysis of the performance of complex networks.

OPNET consists of three modules, that is, ITDecisionGuru, Modeler, and Modeler/Radio, which are nested in layers. Among them, ITDecisionGuru has only the function of simulation and analysis; Modeler adds the function of library building based on the former; and Modeler/Radio adds support for mobile satellite and satellite communication. Modeler, the first commercial product of OPNET, is also the most widely used one. Its main features are as follows:

(a) Hierarchical modelling mechanism.

The three-layer modelling mechanism of OPNET is shown as Figure 7, which al-lows multiple scenarios to be set up in the network layer for comparing the simulation results of different design solutions.

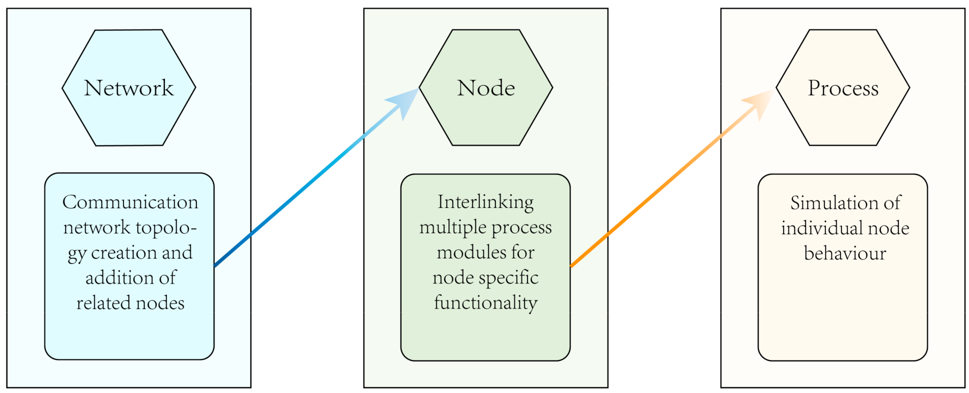


Figure 7. OPNET three-layer modelling mechanism.

(b) FSM (finite state machine) programming.

The process layer combines FSM and C/C++ to model the behaviour and functionality of processes. The relevant execution actions are performed by specific trigger conditions. Users can also rewrite the process module to customize its functionality according to their needs.

(c) Flexible statistical tools.

In terms of data collection, OPNET has its own information collection process module that provides common statistics. If users have other requirements, they can customize the probe into any position in the network to collect the required data. OPNET can graphically organize the collected data and correlated data in a planar rectangular coordinate system for easy observation by the user if there are other needs.

(d) Full support for protocol programming.

OPNET comes with many network protocol models and library functions. For existing models, you can directly set external variables and then simulate them. If you want to change the protocol, you can develop and improve it based on the original model.

4.2. OPNET Scene Modeling Configuration

This paper focuses on inter-cannonball network communication, with emphasis on the changes in network characteristics when nodes move over the air and when failures occur. First, we build a simple fixed node ad hoc network as shown in Figure 8. All nodes use AODV routing protocol to construct a data transmission connection between *node*_0 and *node*_35, and then setup *node*_7 to be damaged after 500 s in order to monitor the change in communication link after node damage.

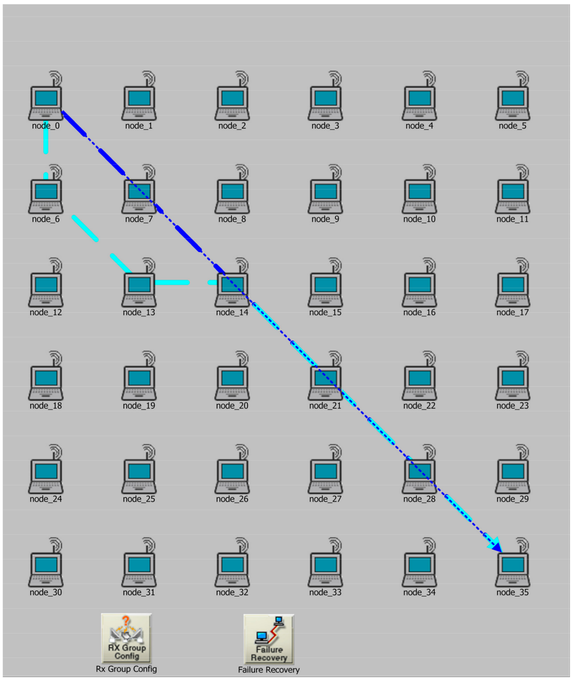
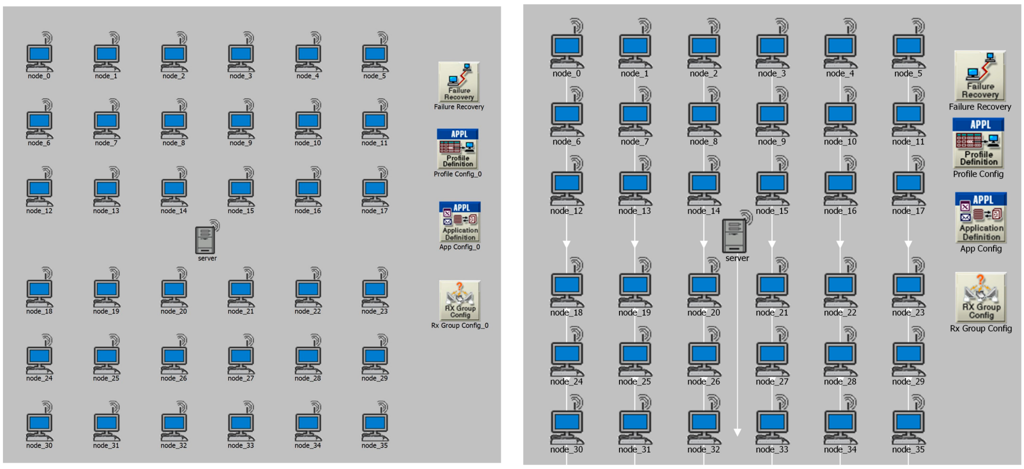


Figure 8. Changes in routing after *node*_7 is damaged.

As shown in Figure 8, dark blue and light blue represent the paths before and after the node damage, respectively. The AODV protocol selects the routing table *node*_0-> *node*_7-> *node*_14-> *node*_21-> *node*_28-> *node*_35 with a routing hop count of 5 once the simulation begins. After 500 s, *node*_7 is damaged and the original communication route is compromised, thus *node*_0 will retry the route discovery and send RREQ packets to the nodes in communication range in order to circumvent the injured node. When *node*_14 receives the RREQ packet, it returns the RREP packet since it has a routing table to *node*_35, and a new routing table is successfully constructed between *node*_0 and *node*_35. The routing table changes to *node*_0-> *node*_6-> *node*_13-> *node*_14-> *node*_21->*node*_28->*node*_35, and the route hop count rises to 6. The inter-cannonball self-organizing network is similarly based on this paradigm, but it is not a fixed data connection and needs routing modifications for network topology changes.

We set the scenario as an ideal environment, where all nodes are at the same level when moving in the air, with a total of 36 cannonball nodes and one FTP service node at the beginning. The minimum spacing between cannonball nodes is 10 km, and the communication frequency is 2401 MHz. To ensure that the nodes can communicate with each other, the ideal environment is assumed, and the reception sensitivity is −95 dB. In this environment, according to Equation (1), $Loss(\text{dB}) = 120$ dB, then the minimum transmit power should be set to 25 dBm, corresponding to 0.316 W. Considering the retention margin, the node's transmit power is set to 0.4 W.

In order to compare the effects of node mobility and survival rate on the communication network, we build two networks as shown in Figure 9, where all fixed nodes are used on the left side, and all mobile nodes are used on the right side with white arrows showing node movement trajectories, and the rest of the simulation settings are the same.



(**a**) (**b**)

Figure 9. Comparative fixed and mobile node network topology in terms of (**a**) fixed node, (**b**) mobile node.

We set all communication nodes to use the AODV protocol, used the FTP data service, set the data transfer file size to 2 Mbit, and performed concurrent data transfer every 5–10 s [38]. The backend traffic start time was 60 s, and the simulation time was 30 min. To speed up the simulation, the Rx Group Config node was utilized to set the maximum communication distance between communication nodes to 15,000 m. The simulation parameters are presented centrally in Table 1.

Table 1. Simulation parameter table.

Model Parameters	Parameter Description	Parameter Setting
Simulation scene size	The size of the range in which the node can be moved during simulation	100 km × 100 km
Number of nodes	Number of nodes present in the simulation scenario	36
Maximum communication range	Maximum communication distance between two nodes	15 km
Routing protocol	Routing protocols used by communication nodes	AODV
Transmission power	Transmitting power when the node transmits information	0.4 w
Data size	Size of transmitted packets	2 Mbit
Backend traffic start time	Delay in the start time of background traffic as specified in the traffic browser	60 s
Total simulation time	The total simulation time set	30 min

In order to observe the failure rate and the impact of different cannonball speeds on network communication, the node movement trajectory in the mobile node simulation is given, and the node speed is used as a variable. It is set that *node*_7, *node*_10, *node*_19, and *node*_22 fail ten minutes after the simulation starts, and the ad hoc network reaches a 10% failure rate at this time. Twenty minutes later, *node*_15, *node*_20, *node*_25, and *node*_28 fails. At this time, the failure rate reaches more than 20%, and the node failure continues until the end of the simulation. We may deduce the link between inter-cannonball network communication stability with fault rate and node shift speed based on these simulation findings.

5. Results and Discussion

Due to the high mobility of ad hoc nodes and the damage that will occur as time advances, the ad hoc network needs to perform new route discovery during data transmission to ensure smooth communication lines. By studying the effects of damage and movement of nodes on routing and network communication, we can determine the interference resistance of inter-cannonball self-organizing networks. The delay within 100 ms has little impact on the self-organizing communication system, so when the node failure rate reaches 20%, the delay still does not exceed 100 ms, and it means that the communication network stability meets the requirements. Simulation scenarios were used to compare the impact of node shift speed and error rate on the communication network.

In order to explore the effect of the node failure rate of the communication network on the communication stability, Figure 10 shows the simulation comparison before and after the node failure of the inter-cannonball self-organizing network. To improve the efficiency of simulation, we collect the average value of simulation data over a period of time. The blue curve is the simulation result when there is no failure, from which we can see that the data is smooth at this time, the communication is stable, and the wireless LAN delay is kept below 10 ms after the stable route is established. The red curve shows the simulation results when the failure occurs within the specified time, and the node damage rate reaches 10% and 20% at 10 and 20 min, respectively. As the node failure rate rises, route hops, route discovery time, and wireless LAN delay rise, while system throughput drops.

The increase in the number of hops per route and route discovery time is because AODV initiates routes on demand, so it needs to bypass the damaged nodes to find routes again. According to Equation (8), the wireless LAN delay will become larger due to the increase in the data transmission distance, while the decrease in the number of nodes will reduce the overall throughput of the system. In Figure 10, the offset of the red curve relative to the blue curve is greater between 20 and 30 min than that between 10 and 20 min. The impact of a node failure rate of 20% is greater than that of a node failure rate of 10%. It represents that the communication network is more severely harmed, and communication must bypass a large number of failed nodes.

Figure 11 depicts the results of a comparison and study of the difference between the communication indices at three different moving speeds. Considering that the different moving speeds of the cannonball nodes may affect the effectiveness and reliability of the communication system, we compared and studied the difference between the communication indices at three different shift speeds. To better compare trends, the gathered data are averaged, and the pictures are divided into global plots on the left and local plots on the right. Comparing the system's properties at the three node movement speeds reveals that as node movement speed rises, the average route-finding time grows until it is about the same. This suggests that the quicker the nodes move, the longer it takes to construct a stable route, but that it has less influence on the stability of the communication after the route has been established.

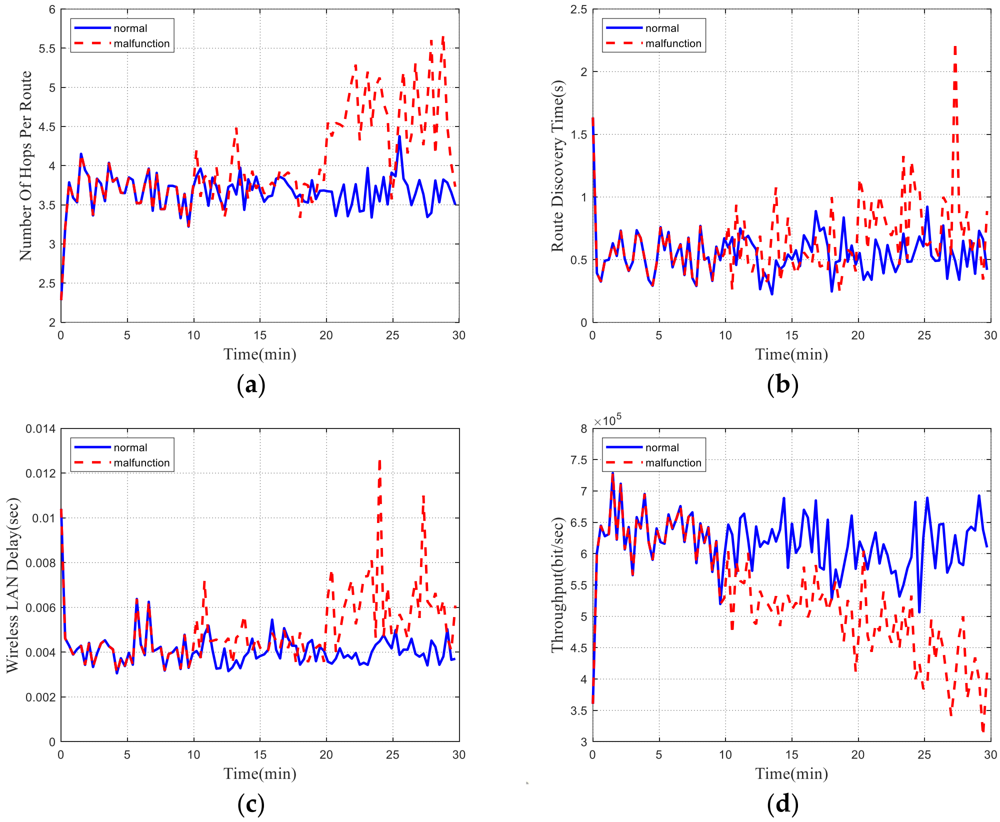


Figure 10. Comparative simulation data before and after node failure in terms of (**a**) number of hops per route, (**b**) route discovery time, (**c**) throughput, (**d**) wireless LAN delay.

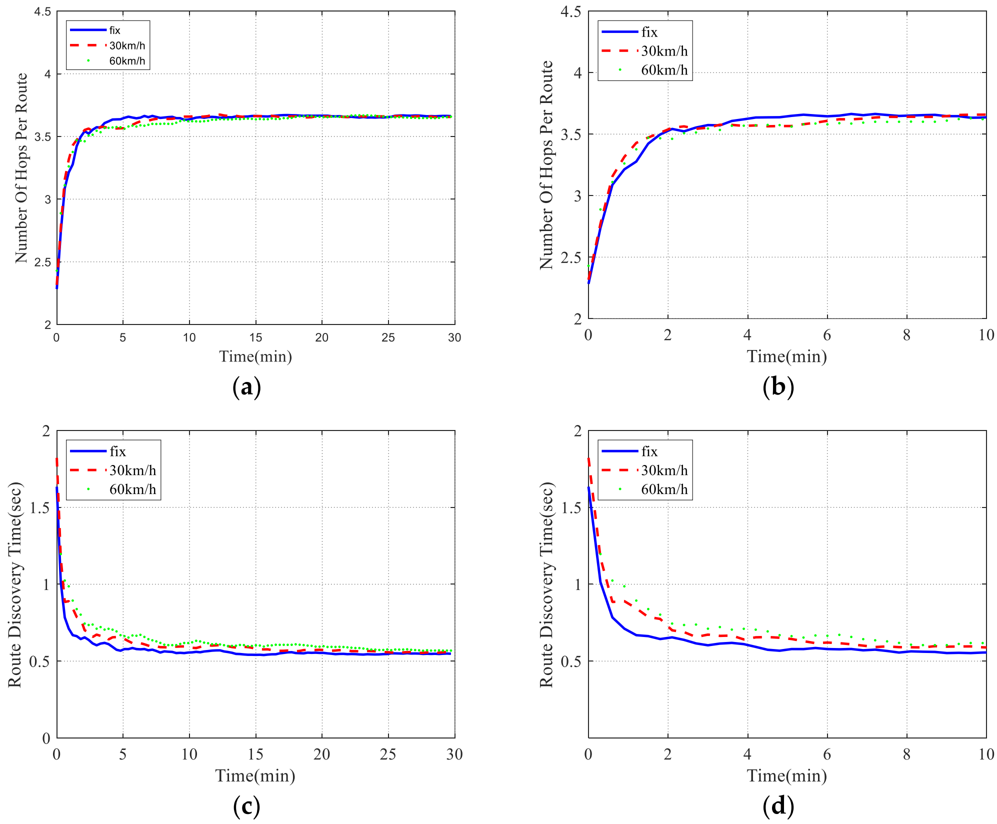


Figure 11. Effect of different speeds on communication stability. (**a**) number of hops per route, (**b**) local enlargement of a, (**c**) route discovery time, (**d**) local enlargement of c.

Figure 12 shows the simulation results of nodes moving at 90 km/h and having failed nodes at the specified time, where the node reaches 10% failure rate at 10 min and 20% failure rate at 20 min. Compared to 10 min, the increase in the number of hops per route, route discovery time, and wireless LAN delay is greater at 20 min. The maximum data delay is still less than 100 ms, so the network still meets the basic communication requirements.

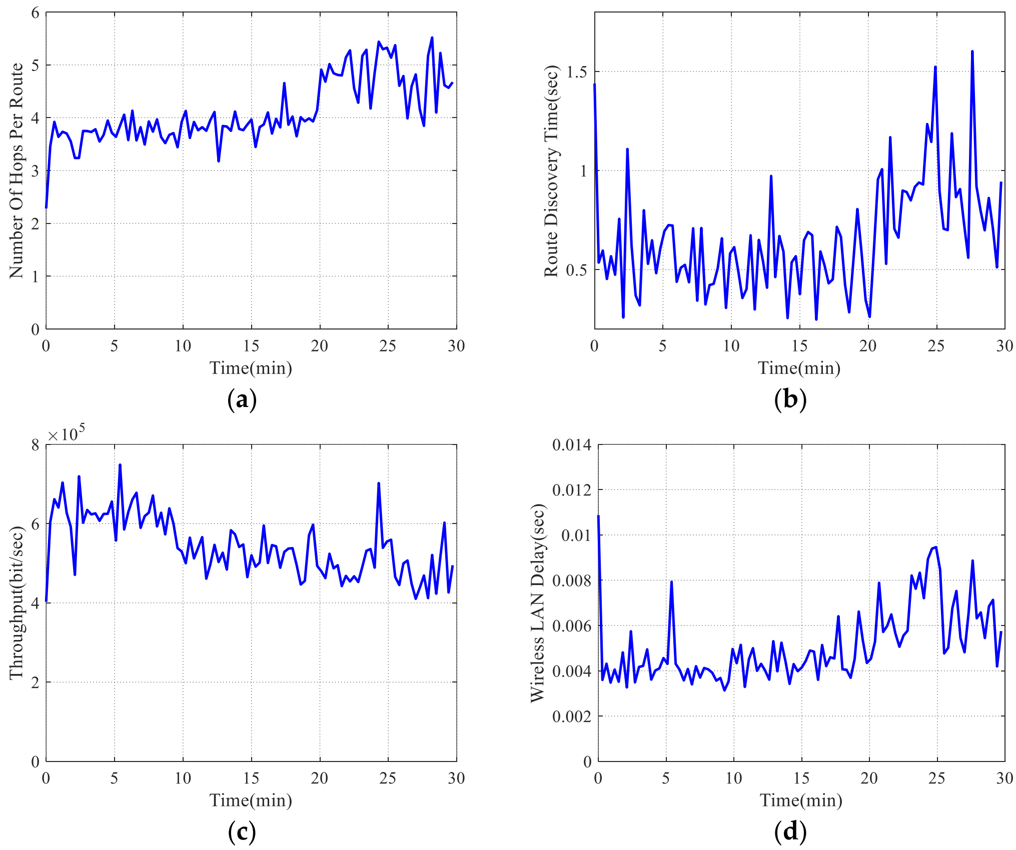


Figure 12. Harsh environment simulation. (**a**) number of hops per route, (**b**) route discovery time, (**c**) throughput, (**d**) wireless LAN delay.

6. Conclusions and Future Works

The reliability of inter-cannonball network communication is investigated in this paper. The inter-cannonball network communication allows numerous cannonballs to work together to strike the target, which may boost the effectiveness of the strike and save strategic resources. Due to cannonball properties and military strike application requirements, the topology of inter-cannonball communication network nodes changes frequently. To investigate the dependability of the communication network, we constructed and simulated the communication system for the mobility and failure rate of the inter-cannonball self-organizing network and assessed the impact of these two factors on the communication stability of the system.

Based on the simulation results, the impact on the reliability of the communication network is minor when the node damage rate reaches 10%; then, when the rate increases to 20%, the reliability of the network is clearly reduced. Moving node speed, on the other hand, has less influence on steady-state aspects of network communication than failure rate, whereas moving node speed has a greater influence on the pre-construction communication routing stage. The stability time of a network grows as network speed increases. Despite the fact that the route discovery time and wireless LAN latency increase when the movement speed or node damage rate rises, the communication network satisfies the essential communication criteria and demonstrates the viability of inter-cannonball group communication.

Based on the findings of this paper, more research is being planned. First, the communication network investigated in this research employs flat routing; layered routing will be implemented in the future. The communication network is designed to have a greater reach and more nodes while maintaining communication stability. In addition to the control information, the data supplied by the intelligent cannonball also contain environmental monitoring data. The control information is prohibited from having a bit error rate (BER); however, the environmental information may have a modest BER range. The associated data processing algorithm will be built at a later date.

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