electronics

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A State-Interactive MAC Layer TDMA Protocol Based on Smart Antennas

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Abstract: Mobile ad hoc networks are self-organizing networks that do not rely on fixed infrastructure. Smart antennas employ advanced beamforming technology, enabling ultra-long-range directional transmission in wireless networks, which leads to lower power consumption and better utilization of spatial resources. The media access control (MAC) protocol design using smart antennas can lead to efficient usage of channel resources. However, during ultra-long-distance transmissions, there may be significant transport delays. In addition, when using the time division multiple access (TDMA) schemes, it can be difficult to manage conflicts arising from adjacent time slot advancement caused by latency compensation in ultra-long-range propagation. Directional transmission and reception can also cause interference between links that reuse the same time slot. This paper proposes a new distributed dynamic TDMA protocol called State Interaction-based Slot Allocation Protocol (SISAP) to address these issues. This protocol is based on slot states and includes TDMA frame structure, slot allocation process, interference self-avoidance strategy, and slot allocation algorithms. According to the simulation results, the MAC layer design scheme suggested in this paper can achieve ultra-long-distance transmission without conflicts. Additionally, it can reduce the interference between links while space multiplexing. Furthermore, the system exhibits remarkable performance in various network aspects, such as throughput and link delay.

Keywords: MAC protocol; ad-hoc network; TDMA; ultra-long-distance communication; interference coordination

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Citation: Li, D.; Nakazato, J.; Tsukada, M. A State-Interactive MAC Layer TDMA Protocol Based on Smart Antennas. *Electronics* **2024**, *13*, 2037. https://doi.org/10.3390/electronics13112037

Academic Editors: Binod Vaidya and Byung Rae Cha

Received: 21 February 2024
Revised: 27 April 2024
Accepted: 1 May 2024
Published: 23 May 2024

1. Introduction

Mobile ad hoc networks, which do not rely on central control devices or infrastructure for establishment, empower devices to connect directly through communication. This facilitates the sharing of resources and information without the need for preplanned or fixed infrastructure configuration. Especially valuable in dynamic or temporary settings, these networks have practical applications in scenarios like military operations, disaster recovery, or mobile device communication [1]. These networks are mobile devices with wireless communication capabilities collaborating interactively, offering benefits like distributed control, dynamic topology, and flexible networking [2,3]. However, they face challenges, including limited transmission bandwidth, scalability issues, and constrained node energy [4].

Smart antenna technology, operating as a physical layer technology within ad hoc networks, employs sophisticated signal processing and control techniques [5]. The primary objective is to dynamically modify antennas' radiation pattern and orientation, adapting them to network conditions' fluctuations. This capability allows smart antennas to optimize signal transmission, improve directionality, and respond effectively to the evolving communication environment within ad hoc networks [6]. Smart antennas in wireless ad hoc networks allow for a significantly extended single-hop communication range and enhanced spatial reuse compared to traditional omnidirectional antennas under equivalent power conditions [7].

In the ad hoc network, the wireless medium remains open and is utilized by multiple nodes. Without proper control over resource acquisition, several nodes might attempt simultaneous access. The Medium Access Control (MAC) protocol aims to establish rules that facilitate efficient and equitable sharing of the shared wireless channel [8,9]. Integrating MAC protocols with smart antenna technology can enhance the system's overall performance, encompassing communication speed, coverage range, and reliability [10]. Consequently, extensive research has been conducted to explore the synergies and advancements offered by this combination [11]. These protocols can be broadly categorized into three types based on different channel access methods [9]. The first is contention-based access MAC layer protocols [6,12,13]. In this approach, wireless nodes compete for channel resources in a contention manner to establish communication. This method eliminates the need for complex time synchronization and spatial scheduling. However, as network load increases, data conflicts and retransmissions significantly increase, leading to a noticeable degradation in system performance. Secondly, there are reservation-based MAC layer protocols, where wireless channel resources are preallocated according to standards such as time, frequency, etc. Typical representatives include Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), and Code Division Multiple Access (CDMA) [14]. Among these, TDMA-based reservation MAC layer protocols commonly employ dynamic slot allocation methods [15–17]. Compared to other protocols, it significantly improves network resource utilization. However, it also introduces issues such as slow network convergence. Thirdly, hybrid access MAC layer protocols integrate contention characteristics and reservation-based protocols [18–20]. An example is the Zebra MAC (Z-MAC) protocol [18], which utilizes the contention-based mechanism for basic channel access and employs the TDMA mechanism to address the performance degradation of contention under heavy network loads. Boarder Node MAC (BN-MAC) in [19] applied several promising models to realize a better performance of the network, which can support the multiple application domains in the realistic world. Energy Efficient MAC (EE-MAC) protocol in [20] introduced an improved MAC protocol that enhances throughput and decreases energy consumption by minimizing idle listening, overhearing, and shortening the preamble size.

TDMA schemes are extensively employed in directional communication because they can establish a transmission schedule devoid of conflicts, thus mitigating issues related to deafness and capture effects [15–17]. However, there are some inherent drawbacks when applying the TDMA protocols with smart antennas for long-distance transmissions in ad hoc networks. These include significant propagation delays, which result in many channel access conflicts. The delay reduces channel utilization and transmission efficiency. To account for the considerable delay during transmission, TDMA mechanisms require nodes in the network to send data in advance. However, this can cause conflicts with adjacent time slots and issues with spatial reuse within a single hop. Additionally, there are limitations in conflict resolution, high control overhead for channel resource reservation, and insensitivity to network scale changes inherent in TDMA-based MAC layer protocols.

To overcome the abovementioned problems, we propose a distributed dynamic TDMA-based MAC layer protocol called State Interaction-based Slot Allocation Protocol (SISAP). This protocol is specifically designed for long-distance wireless ad hoc networks, such as the one illustrated in Figure 1. In this scenario, the nodes in the network are widely spaced apart, and there is a significant wireless transmission delay between them. When combined with smart antennas, the MAC layer in the network is primarily responsible for slot resource allocation, where nodes in the network complete data transmission and reception tasks in corresponding slots according to the latest slot allocation results. At the physical layer, smart antenna technology facilitates wireless signal transmission and reception through beamforming techniques, enabling dispersed nodes in the network to achieve data transmission independently of infrastructure support.

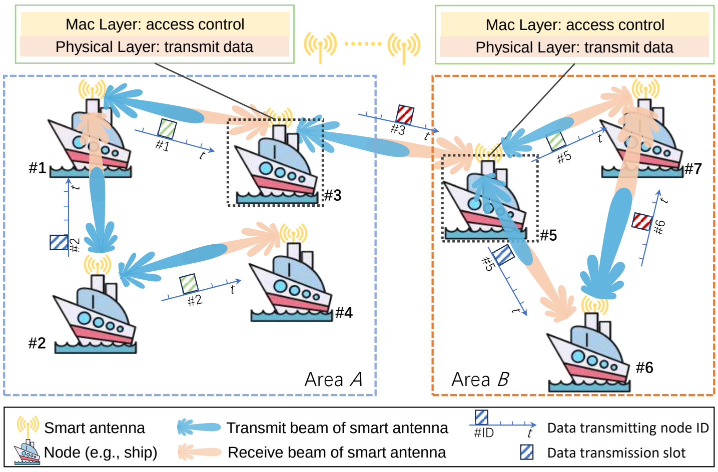


Figure 1. Ad hoc network in this paper.

The network nodes in this system adopt a receive-align mechanism to address the challenges of significant delays in ultra-long-distance transmissions. Nodes in the network send data in advance. Time slots are allocated based on node state information, which enhances spatial reuse and prevents conflicts of advancement between adjacent time slots. This approach effectively mitigates interference between links. The time slot allocation method uses a "request-response" approach coupled with a distributed dynamic time slot allocation algorithm that can adapt to changes in the network environment. Hence, the major contributions are as follows:

- Proposing a dynamic MAC layer protocol with a flexible frame structure that can adapt to changes in network size.
- Addressing the issue of excessive delays over long distances by requiring nodes to align the reception of data packets with the beginning of time slots. Additionally, resolving conflicts arising from advance transmission in adjacent time slots based on node state information.
- Introducing an interference avoidance strategy to mitigate interference between wireless links effectively.
- Employing a distributed dynamic time slot allocation based on the "allocate blocks first, then allocate fragment slots" strategy. This approach ensures fairness while maintaining the aggregation of allocated transmission slots for specific requesting nodes. This strategy reduces the frequency of beam direction switching, lowering node power consumption and theoretically minimizing end-to-end latency in the system.

The paper is structured as follows: Section 2 summarizes the related works. Section 3 includes the detailed design of the MAC protocols, which covers the network requirements and the MAC layer protocol. We evaluate the performance of the MAC protocol with simulation in Section 4. Finally, Section 5 concludes the paper.

2. Related Works

In this section, we will include the related works and the problem formulation.

A reservation-based access MAC layer protocol based on TDMA usually uses dynamic slot allocation methods. One such protocol is the [21]. This study proposes a Unifying Slot Allocation Protocol (USAP), which assigns or releases time slots when nodes join or leave the network. However, USAP needs to provide enough slots to allocate for all nodes in the network, which leads to low channel utilization as the number of unassigned slots increases with an increase in the number of nodes in the network. In [22], the authors introduce an Adaptive Slot Allocation Protocol (ASAP) to improve channel utilization by considering the autonomous behavior of nodes. It proposes an adaptive TDMA protocol that increases the frame length as the number of nodes increases, but this can lead to underutilization of channel bandwidth. In [23], the authors present an Extended ASAP (E-ASAP) that allows each node to minimize the frame length by providing more detailed information in the ASAP control packet. This drastically improves channel utilization. However, when the frame length halves, some nodes may need to reselect the slots, and some idle slots may exist during topology changes, which negatively affects the throughput performance. According to a research study by Zhu, C. et al. [24], another protocol for TDMA slot allocation is presented. This protocol involves a five-phase reservation process that uses a contention-based random selection among nodes within a two-hop neighborhood. This method has been proven to significantly reduce dynamic TDMA slot conflicts, which makes it an ideal choice for large and mobile networks. However, it has some drawbacks, such as increased complexity, overhead, and delay with each running cycle, which harms throughput. Additionally, this protocol only supports omnidirectional antennas and does not facilitate point-to-point data transmission within the network.

As technology advances, the directional TDMA-based MAC protocol has significantly improved special reuse efficiency and flexibility [7,25–30]. The primary process for managing channel resources consists of three parts: neighbor discovery, reservation, and data transmission. In [25], Zhang, Z. et al. introduced the Directional Transmit and Receive Algorithm (DTRA), a classical synchronous protocol for directional ad hoc networks. This distributed protocol can dynamically assign slots to links based on traffic demand. However, the proportion of data transmission and the frequency of time-slot allocation in DTRA is relatively low. To minimize the influence of the propagation delay, in [27], the authors introduced guard spaces in mini-slots. This method can help reduce the impact of propagation delays. However, it might lead to a waste of channel resources. In [26], Cha. et al. proposed a protocol designed to reduce end-to-end delay in multi-hop networks. In the network, before the start of a session, all the relay nodes on the path from source to destination reserve consecutive time slots to deliver a packet within one data transmission phase. This approach can effectively reduce the latency of data transmission across multiple-hop links. Nevertheless, if a multi-hop link persistently occupies channel resources, it may cause an imbalance in the allocation of channel resources among links in the network. The slot allocation process involves combining the time slots available to both the transmitter and receiver to meet the communication needs of the nodes in the network [28]. This determination of available time slots can increase network efficiency and reduce communication link conflicts to a certain extent. In a recent study [30], the authors proposed a novel mechanism to reallocate the slots by categorizing them into four states to achieve fair resource allocation. However, the determination of the available time slot states does not consider the direction of link data transmission, which can negatively impact network performance.

The TDMA protocol can be divided into two groups based on how channel resources are allocated, namely, the centralized-based [31] and the distributed-based [32–36]. In the centralized scheme, a master node manages the scheduling of channel resources to maximize network efficiency. However, if the master node fails, the entire network is at risk of disruption, which could compromise network stability. On the other hand, distributed schemes are better suited for dynamic networks, but they require a significant exchange of control messages to achieve distributed slot allocation. For example, the algorithm proposed in the study [32] demonstrates improved link delay and fairness performance by incorporating functions for requesting and releasing free time slots and load balancing. However, achieving fair distribution requires nodes to exchange two-hop neighbor information, increasing control overhead. Ultimately, the significant exchange of control messages results in elevated control overhead and reduced channel resource utilization.

Interference issues can occur in wireless communication links due to the broad main lobe of antennas. To address this problem, a complex TDMA-based protocol is employed, as outlined in [37]. Jakllari et al. introduced the idea that nodes translate RTS and CTS signals before data transmission to prevent interference. However, this approach does not consider interference during the reservation phase. In [17], the authors provide an interference avoidance strategy. This strategy involves communication nodes sharing a list of slots susceptible to interference. Each node updates its list based on received data about definite slot states. However, since the network environment is dynamic, a delayed update of slot lists can result in interference within the network. Table 1 illustrated the advantages and disadvantages of related works mentioned in this section.

Table 1. Advantages and disadvantages of related works.

Aspects	Ref.	Pros.	Cons.
Dynamic slot allocation	[21–23]	Dynamic assign and release slots.	Low channel utilization.
	[24]	Low dynamic TDMA slots conflicts.	Higher complexity, overhead, and latency.
Directional TDMA-based MAC protocol	[25]	Dynamically assign slots to links based on traffic demand.	A low portion of data transmission and slot allocation frequency.
Propagation delay	[26]	Reduce end-to-end delay in multi-hop networks.	Cause imbalance in the allocation of channel resources among links.
	[27]	Using mini-slots to reduce the impact of propagation delay.	Wesatage of channel resource.
Determination of available slots list	[28]	Achieve fair resource allocation.	Ignore the direction of link data transmission.
Centralized distributed	[31]	Centralized network: The master node can maximize network efficiency.	If the master node fails, the entire network risks disruption.
	[32–36]	Distributed network: suited for a dynamic network.	High control overhead.
Interference avoidance	[37]	Prevent interference by transmitting special data.	Do not consider interference during the reservation phase.
	[17]	Prevent interference by sharing a list.	Delayed updates of slot lists can result in interference within the network.

In ultra-long-distance ad hoc networks, meticulous consideration of the substantial transmission delay of wireless signals is imperative to ensure precise communication synchronization among nodes. We assume a scenario wherein a node within the network is situated at a distance of 10 km. Under the assumption that wireless signals propagate at the speed of light, the propagation delay of such wireless signals can be calculated by Equation (1).

$$t = \frac{d}{v} = \frac{10\ \text{km}}{3 \times 10^6} = 33\ \mu\text{s} \tag{1}$$

The duration of wireless data transmission is estimated to be 33 ms. However, when factoring in the processing delay of a data packet in hardware devices, which amounts to approximately 100 ms, and comparing it with the duration of a time slot set at 200 ms, it becomes evident that the significant transmission delay of wireless signals cannot be disregarded. To solve the problem, we employ a method of pre-transmitting data and synchronizing the start of time slots at the receiving end to mitigate the propagation delay of wireless signals. However, this approach can potentially introduce conflicts due to anticipation between adjacent time slots. Hence, addressing and preventing conflicts arising from the adjacent slots is imperative. Moreover, the unique characteristics of wireless links in ad hoc networks can lead to interference when attempting spatial reuse. Consequently, channel resource allocation algorithms must mitigate interference between different links.

The MAC protocol design not only tackles these challenges but also ensures dynamic and efficient utilization of channel resources. To achieve a more practical MAC protocol, we employ the TDMA scheme to combine the interaction of different node states. The problems mainly lie in the frame structure's design, the node states definition, how to cooperate with the node states to solve the propagation delay advance compensation, and the slot allocation algorithm.

3. System Model and MAC Protocol

3.1. Assumptions

Before describing a new MAC protocol, we list the assumptions and conditions our works rely on and capitalize on as follows.

- All nodes in the network have the same equipment and use smart antenna technology in their physical layer.
- The nodes in the network are accurately synchronized.
- All neighboring nodes within the network have symmetrical relationships.
- Nodes in the system can only communicate with a single neighbor at any given time. However, multiple pairs of nodes can communicate simultaneously during the same time slot, achieving spatial reuse.

3.2. MAC Protocol Design

3.2.1. Frame Structure

The network is divided into superframes, each consisting of N frames with a duration of 1 s. Each frame contains M slots, and nodes use TDMA to access the channel within each frame. The initial K frames are designated for monitoring purposes, facilitating network synchronization, access, and the discovery of various network clusters. The remaining $N - K$ frames operate on a TDMA basis and are responsible for slot allocation, establishing and maintaining the network topology, transmitting upper-layer business data, and broadcasting packets. The TDMA frame includes P time slot allocation and $N - K - P$ data transmission frames. Each slot allocation frame is allocated to a central responding node to complete local slot allocation within its one-hop neighbor range. Thus, P nodes can be distributed within each superframe to perform slot allocation work within their local area. During the data transmission frames, nodes transmit business data based on the slot allocation results. Figure 2 illustrates the structure of the superframe. As a decentralized distributed self-organized network, nodes periodically employ a "request-response" approach to allocate channel resources. The receiving end determines the final slot allocation results. The allocated slots will used to send data to the slot allocation (SA) node. This process can significantly reduce the frequency of node information exchanges during the channel resource allocation process. The SA frame is divided into five parts: synchronization, time slot request, data transmission, slot allocation answer, and guard time slots. The specific function of each part within the frames is as follows.

- Synchronization: This involves sending synchronization control packets in every frame to ensure that the nodes in the network are synchronized. Although it is a crucial process component, it is not the primary element of slot allocation.
- Time slot request: Within each time slot allocation frame, a specific node is designed for the current time slot allocation. The neighboring node (requesting node) of the current time slot allocation node sends a slot allocation request (SAR) to it using directional transmission and reception methods.
- Data transmission: During this phase, the slot allocation node (responding node) computes the time slot allocation and transfers data to other nodes concurrently. On the other hand, requesting nodes exclusively transmit data in this phase.
- Slot allocation answer (SAA): The responding node provides feedback regarding the slot allocation results and related information to each requesting node. The related information includes the request order of the next time for the requesting node and angle information for neighboring nodes, which will be utilized in Section 3.3. The angle information is formed by any two neighboring nodes with the responding node as the vertex. A responding node has U neighbors, resulting in a total of $\binom{U}{2}$ possible combinations of angle information. Finally, the requesting nodes receive the result directionally.

- Guard time slots: Two persistent guard time slots are implemented between each segment to prevent confusion caused by transmission delays that may occur at different stages.

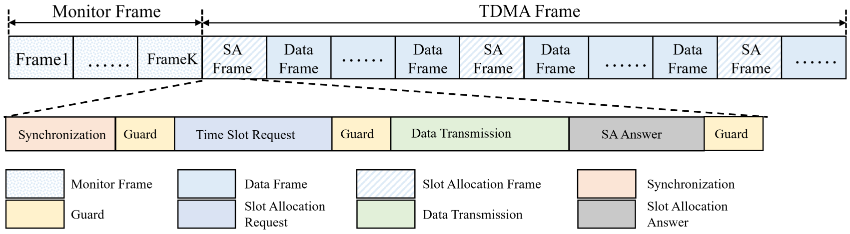


Figure 2. Superframe structure.

3.2.2. The Time Slot Request

After setting up the network, each node completes synchronization, discovers neighbors, and measures information. In the next dynamic time slot allocation phase, the neighbors send a SAR to the current slot allocation node. The SAR data include the states of all the slots in the transmission section and the number of slots needed to communicate with the slot allocation node. Since SAR transmission and reception use directional antennas, both the sending and receiving nodes must know when and where to handle the SAR signal. In cases where a node, like Node A, acts as the slot allocation node for the first time, its neighbors are unaware of the timing to transmit the SAR to Node A. Under such circumstances, both the sending and receiving Node A will disregard slot allocation at that moment. Node A will finalize the next cycle's slot request order information. Alternatively, suppose a node has previously served as the slot allocation node. In that case, both its neighbors and the node itself possess information about the sequence for transmitting the SAR derived from the content of the last slot allocation result.

3.2.3. The Dynamic Update of The Node's States

The functionality of distributed dynamic slot allocation at the MAC layer relies on the interaction of state information between the nodes. Each node in the network has different states to their neighbors in different time slots during the data transmission section. To ensure smooth transmission, nodes need to update the slot states in the local states table (lnsTAB) before sending SAR data and after receiving SAA data. Based on the determined time sequence, the slot states of nodes can be classified into three categories: transmission/reception state, occupancy state, and blocking state.

The network node, such as Node A, updates lnsTAB slot by slot before transmitting SAR data to the slot allocation node. The following steps are taken.

Step 1: Transmission/Reception State

Transmission: In the current slot, the node sends data (without necessarily specifying transmission to Node A).

Reception: In the current slot, the node receives data (without necessarily specifying reception to Node A).

Idle: In the current slot, the node is doing nothing.

Step 2: Occupancy State

Occupancy: Following Step 1, detection and assessment are performed on the determined "transmission" state slots. If the node has already been allocated for transmission to a node other than Node A in the current slot, that slot's "transmission" state is updated to "transmission occupied". This ensures that slot allocation results will not interfere with the allocation results of other nodes when they act as slot allocation nodes. This guarantees that the slot allocation results are conflict-free.

Step 3: Blocking State

In the MAC protocol, nodes use a reception alignment approach to manage the significant transmit delay during long-distance communication, as illustrated in Figure 3. In Figure 3, ΔT_1 and ΔT_2 represent the data packet transmission lead times for slots 1 and 2, respectively. However, there are situations where the advance of adjacent time slots may lead to conflicts, as indicated by the overlapping region in Figure 3. To cope with this problem, we adopt the blocking states.

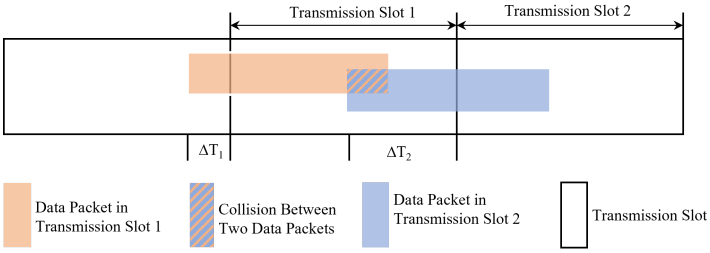


Figure 3. The schematic illustration of advance conflicts in adjacent time slots.

After confirming the transmission/reception states, in order to avoid conflicts in the adjacent time slot advancement, we will determine the blocking states of the "Idle" time slots in Step 1.

For the "Idle" time slots, based on the different states of the two adjacent time slots and the neighbor topology information, the blocking states are determined one by one. Considering the impact of the actual system transmitter having to send in advance according to the signal propagation delay, the blocking states can be categorized into four different scenarios based on the states of time slots. The determination process of the states of the time slot is illustrated in Table 2.

Table 2. The rules for determining the blocked state of *i* time slot table.

Number	Slot ($i-1$)	Slot i	Slot ($i+1$)
1	Reception	Transmission blocking	Reception
2		Transmit-receive blocking	Transmission
3		Transmit-receive blocking	Transmission occupied
4		Transmission blocking	Idle
5	Transmission	$\Delta_i > \Delta_{i-1}$, Transmission blocking	Reception
		$\Delta_i \leq \Delta_{i-1}$, Idle	
6		$\Delta_i \leq \Delta_{i-1}$ and $\Delta_i \geq \Delta_{i+1}$ Reception blocking	Transmission
		Transmit-receive blocking	
7		$\Delta_i > \Delta_{i-1}$, Transmit-receive blocking	Transmission occupied
		$\Delta_i \leq \Delta_{i-1}$, Reception blocking	
8		$\Delta_i > \Delta_{i-1}$, Transmission blocking	Idle
		$\Delta_i \leq \Delta_{i-1}$, Idle	
9	Transmission occupied	Idle	Reception
10		Reception blocking	Transmission
11		Reception blocking	Transmission occupied
12		Idle	Idle
13	Idle	Idle	Reception
14		$\Delta_i \geq \Delta_{i+1}$, Reception blocking	Transmission
		$\Delta_i < \Delta_{i+1}$, Transmit-receive blocking	
15		Reception blocking	Transmission occupied
16		Idle	Idle

Δ_i is transmission lead time of slot *i*.

3.3. The Interference Self-Avoidance Strategy

The adoption of the SISAP protocol, along with the use of smart antennas, allows for special reuse in the system. However, due to the directional transmission and reception of the signals, interference may occur between different links sharing the same time slot.

For instance, in Figure 4, when Link1 and Link2 transmit data at the same time slot, it can result in an overlap between the transmission lobe of Link2 and the receive lobe of Link1. This interference from Link2 may cause the signal-to-interference-plus-noise ratio (SINR) for Node A in the current time slot to deteriorate, leading to packet loss.

To avoid interference, we adopt the interference self-avoidance strategy (IAS). We introduce a new definition of the "transmission blocking" state, which refers to a situation in the distributed time slot allocation process where a requesting node aims to transmit on a specific time slot that is already occupied by several wireless links in the network (denoted as the set L). If the requesting node's occupation of this time slot for transmission could potentially interfere with the reception nodes of at least one hop link in set L, the requesting node classifies the state of that time slot as "transmission blocking".

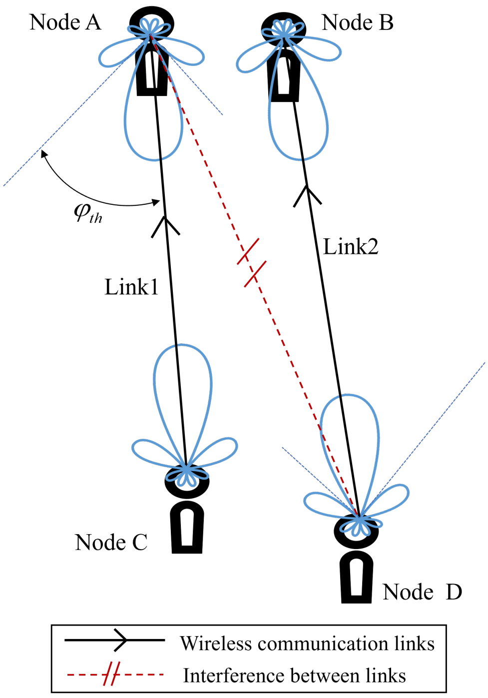


Figure 4. Interference between links under spatial reuse.

We establish a link interference information table (liiTAB) in Table 3 that contains sets of valid links in the network for each time slot, relative angle information, and other pertinent details. The requesting node refers to the liiTAB when determining the "transmission blocking" states. This table includes information about all neighbors within the one-hop communication range of the requesting node, which is maintained by the requesting node. The requesting node refers to the liiTAB when determining the "transmission blocking" states.

- Node ID: It stands for the different nodes in the network differentiated by ID.
- Latest time slot allocation results: They stand for the latest slot allocation results of the different neighboring nodes when they serve as the slot allocation nodes. It is assumed that the data transmission section compromises M slots.
- Neighbor relative angle information: It represents the angle size formed with two different neighboring nodes, considering the corresponding node (in different rows) as the vertex. The angle sizes are classified as either "large" or "small" (considered "large" if greater than half of the main beam width). This characterization represents the "wide" or "narrow" angles between two neighboring nodes. When a node has U neighboring nodes, the maximum number of angle combinations for neighbor angle information is $\binom{U}{2}$.

Table 3. Link interference information table (lliTAB).

Node ID	Latest Time Slot Allocation Results					Neighbor Relative Angle Information			
Node A,B...,U	Slot 0	Slot 2	...	Slot M-1	Slot M	1	2	...	$\binom{U}{2}$

Finally, according to the description above, the proposed Algorithm 1 illustrates the progress in determining the presence of interference. We define the local node as $Node_k$.

Algorithm 1 The algorithm for interference self-avoidance.

Input: The local node's states Table (lnsTAB), and the link interference information table (liiTAB).
Output: The update of the local node's states Table (lnsTAB).

for *neighbor* $Node_i$ in *lnsTAB* **do**
  for $slot_j$ in *transmission section* **do**
    if $statue\ of\ slot_j \in [Transmission, Reception\ blocking, Idle]$ **then**
      for $links_p$ *of* $slot_j$ in *liiTAB* **do**
        if *The sending node of* $link_p$ *is* $Node_k$ or *The receiving node of* $link_p$ *is* $Node_i$ **then**
          continue;
        else
          Look up the $Angle_\alpha$ formed by taking the receiving node at $link_p$ as the vertex in relation to the transmitting node of $link_p$ and $Node_k$, within the *liiTAB*;
          if $Angle_\alpha$ is *large* **then**
            Look up the $Angle_\beta$ formed by taking the $Node_k$ as the vertex, in relation to the receiving node of $link_p$ and $Node_i$, within the *liiTAB*;
            if $Angle_\beta$ is *large* **then**
              continue;
            else
              The state of the $slot_j$ to $Node_i$ within the *lnsTAB* ← *Transmission blocking*;
            end if
          else
            The state of the $slot_j$ to $Node_i$ within the *lnsTAB* ← *Transmission blocking*;
          end if
        end if
      end for
    end if
  end for
end for

3.4. The Slot Allocation Algorithm

The node determines slot states before allocating time slots for the next cycle. In this scenario, it sends it to the next distributed time slot allocation node, Node A. During the slot request section, nodes send the SAR data to Node A if they are its neighbors. After Node A receives all the SAR data from its neighbors, it combines its node status table with the SAR data to determine the final available slots. Node A then uses the slot allocation algorithm to output the final result.

Determining the available slots for both Node A and its neighbors can be divided into three steps. Firstly, Node A determines the available time slots for each requesting node based on the "slot states" field information received in the SAR. Time slots with "Idle", "transmission", or "reception blocking" states are considered available and can be used to send packets to Node A. Secondly, based on the node states information in the lnsTAB relative to each requesting node, Node A determines the available time slots. Time slots with “Idle”, “reception”, or “transmission blocking” statuses are available and can be used to receive data from the corresponding requesting nodes. Finally, if a particular time slot is available for both the requesting node and Node A, then the time slot is available for the “request-response communication node pair”.

The provided Algorithm 2 outlines the slot allocation process. Firstly, we initialize local variables: the set of the numbers of available time slots for communication node pairs corresponding to each requesting node as determined by response node statistics Y:$\{y_0,y_2,\ldots,y_{M-1}\}$, and the set of remaining unallocated time slots for each requesting node P:$\{p_0,p_1,\ldots,p_{M-1}\}$, and the set of ratios representing the proportion of remaining unallocated time slots to the total number of requests for each requesting node S:$\{s_0,s_1,\ldots,s_{M-1}\}$, where $s_i = p_i/q_i$, and the set of the expected number of time slots to be allocated for each requesting node A:$\{a_0,a_1,\ldots,a_{M-1}\}$, where $a_i = x_i \times \eta$.

Then, for the slot allocation algorithm, the result of the slot allocation directly influences the operating mode of the physical layer. The allocation for a given requesting node is intentionally designed to be contiguous to avoid frequent switching of the underlying antennas and reduce end-to-end latency. The slot allocation node first records the time slot blocks with contiguous available time slots. To ensure fulfillment of all the requesting nodes, a percentage η represents the proportion of the desired time slots to each node's total number of requests. The slot allocation node then assigns blocks of required slot numbers in descending order. Ideally, a slot block matching the required time slots is allocated. If not, the allocation proceeds by assigning smaller slot blocks individually. When a slot is allocated to a neighboring node, it will be removed from all the available communication pairs. After allocating slot blocks, some available slots may remain. In such cases, the slot allocation node assigns the remaining slots based on specified priorities. These priorities are determined by the percentage of remaining unallocated time slots to total requested time slots, with descending priority based on requested time slots, available time slots, and node ID. The allocation is performed incrementally, prioritizing the highest priority node according to this reference criterion.

The time complexity of the algorithm for a single network channel resource allocation process depends on the maximum number of neighbors in the network nodes and the number of data transmission slots in the frame. In the worst-case scenario, when no slot block is available for allocation, the slot allocation nodes need to scan each slot individually to complete slot allocation for all neighbors. In this case, the time complexity of the algorithm is $O(m \cdot n)$, where m is the maximum number of one-hop neighbors for each node, and n is the number of slots used for each allocation. As the network scale increases, since the channel resource allocation process is only related to the number of slots and the number of neighbors, the time complexity of the slot allocation process will not increase. The algorithm complexity will greatly increase for routing protocols used in the upper layers of the network to filter neighbors and maintain network topology.

After completing the slot allocation process, the node responsible for allocation broadcasts the results data (SAA). This information can be received by neighboring nodes directionally. Each node updates its states table for the responding nodes according to the slot allocation information parsed from the SAA data. If a particular time slot is allocated to a requesting node, the state for that time slot is modified to “transmission” to the slot allocation node. Otherwise, the states of the time slots remain unchanged. The slot allocation node determines the states of each time slot individually. If a time slot is unallocated, the node retains the previous state. Otherwise, if a slot is allocated to a requesting Node P, the state is updated to “reception” for the Node P. The outcome of a distributed time slot allocation takes effect one frame after the current time slot allocation frame, during which nodes must complete updating the states.

Algorithm 2 The algorithm for slot allocation.

Input: The number of the slot requesting nodes M, and the set of requesting node IDs sorted in descending order of requested time slots X:$\{x_0,x_1,\ldots,x_{M-1}\}$. For requesting nodes, defining the set of available time slot numbers G:$\{G_0,G_1,\ldots,G_{M-1}\}$, and the set of time slot numbers requested Q:$\{q_0,q_1,\ldots,q_{M-1}\}$, and the proportion of the desired number of time slots to the total number η.

Output: The set of the slot allocation result for each requesting node R:$\{R_0,R_1,\ldots R_i,\ldots,R_{M-1}\}$. R_i corresponds to the allocation result for x_i.

for $i \leftarrow 0$ to $M-1$ **do**
  According to the order of X, G_i sequentially determines the set of available time slot blocks B_i:$\{B_0,B_1,\ldots B_k,\ldots,B_{n_{blk}-1}\}$ for the nodes. B_K is a time slot block composed of consecutive or single time slot numbers. Let L_i:$\{l_0,l_1,\ldots,l_{nblk-1}\}$ denote the number of time slot numbers in each time slot block of B_i, and n_{blk} be the number of time slot blocks in B_i;
  for $k \leftarrow 0$ to $n_{blk}-1$ **do**
    if $l_k == a_i$ **then**
      $R_i = B_k$;
      Remove the time slot numbers in R_i from each node's corresponding $G_m(0 < m < M-1)$, and update the respective y_m, p_m, s_m;
    end if
  end for
  if No blocks' size equals to a_i **then**
    for k$\leftarrow$ 0 to $n_{blk}-1$ **do**
      if $l_k > a_i$ **then**
        R_i = the first a_i time slot numbers of B_k;
        Remove the time slot numbers in R_i from each node's corresponding $G_m(0 < m < M-1)$, and update the respective y_m, p_m, s_m;
      end if
    end for
  end if
  if ! blocks' size $\geq a_i$ **then**
    Sort the time slot blocks in B_i in descending order based on the values of L_i;
    for $k \leftarrow 0$ to $n_{blk}-1$ **do**
      size += l_k;
      if *size* $\leq a_i$ **then**
        Append B_k to R_i;
      else
        break;
      end if
      Remove the time slot numbers in R_i from each node's corresponding $G_m(0 < m < M-1)$, and update the respective y_m, p_m, s_m;
    end for
  end if
end for

4. Simulation

In this section, we conducted simulation verification using the NS2 platform to test the performance of intelligent antennas and spatial reuse effects. The simulation utilized a typical mesh topology structure with eight nodes. Each node was interconnected, forming a fully directed graph, as depicted in Figure 5.

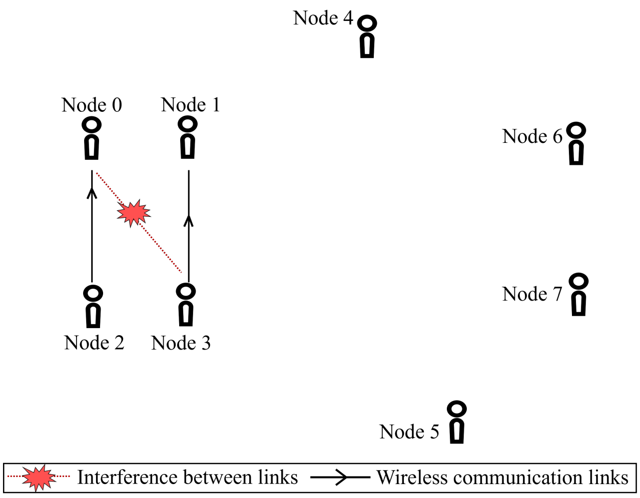


Figure 5. Network topology diagram.

The diagram in Figure 5 shows eight nodes placed inside a mesh that measures 1600 m × 1600 m. Each node can reach any other node in one hop. The network topology is such that each node is a neighbor to every other node. Node information and superframe details are shown in Table 4.

Table 4. Node and superframe configuration.

Items	Configuration Parameters
Transport layer protocol	User Datagram Protocol (UDP)
Traffic Generator	Constant Bit Rate Generator (CBR)
Routing protocol	Destination-Sequence Distance Vector (DSDV)
System queue type	Lost tail queue
Antenna Type	Omnidirectional and Directional Antenna
Number of frames in each superframe	50
Number of monitor frames in each superframe	1
Number of TDMA frames in each superframe	49
Number of time slots in each frame	100
Number of time slots for data transmission in each TDMA frame	85

All the nodes in the network are equipped with Constant Bit Rate (CBR) generators, which are used to send/receive data packets to/from the other 7 nodes, resulting in a total of 56 links within the network. CBR data transmission is initiated at 8 s, and the simulation duration is 55 s. The simulation results are evaluated based on various performance metrics, such as the IAS effectiveness, throughput within the network system, and end-to-end delay.

4.1. The Interference Self-Avoidance Strategy

A simulation system was designed to test the IAS on network performance. The network configuration was set as shown in Figure 5. In some local regions, such as nodes 0, 1, 2, and 3, link interference could exist between links $2 \to 0$ and $3 \to 1$. Enabling the IAS was expected to improve network throughput performance slightly at the MAC layer. The simulation was conducted to compare network performance with and without the IAS.

To ensure enough network margins and better visualization of changes in throughput for each node, we set different CBR transmission rates for nodes. Each node is linked to seven CBR generators of the same rate, which transmit business data to the seven neighboring nodes. The details of the CBR parameters associated with each node can be found in Table 5, and each node transmits data packets with a size of 1020 Bytes.

Table 5. CBR parameter settings.

NodeID	0	1	2	3	4	5	6	7
Data rate/Mbps	0.604	0.564	0.524	0.484	0.444	0.404	0.364	0.324

4.1.1. Slot Allocation Results

Tables presenting the slot allocation results for time slots 15, 16, and 17 during the 45–48 s round in a 55 s simulation are displayed in Table 6 (without IAS) and Table 7 (with IAS).

Table 6. Timeslot allocation results without IAS.

The Slot Number	Slot Allocation Results	Special Reuse	Total Number of Links	Number of Interfered Links
15	$\mathbf{2 \to 0, 3 \to 1, 6 \to 5, 7 \to 4}$	4	230	17
16	$\mathbf{2 \to 0, 3 \to 1}$, $6 \to 5$	3		
17	$2 \to 0$, $4 \to 1$, $7 \to 5$	3		

Table 7. Timeslot allocation results with IAS.

The Slot Number	Slot Allocation Results	Special Reuse	Total Number of Links	Number of Interfered Links
15	2→0, 4→3, 5→1, 7→6	4	231	4
16	2→0, 5→1	2		
17	2→0, 3→5, 4→7, 6→1	4		

In Table 6, certain links are highlighted to indicate that they are affected by interference from other links using the same time slot. This causes their SINR to fall below the minimum required for reception, resulting in the loss of data packets transmitted by these links in the current time slot. By comparing the slot allocation situations in Tables 6 and 7, we can observe a significant reduction in mutual interference between links after activating the IAS, proving its effectiveness. In Table 7, we can see simultaneous communication for the links $2 \rightarrow 0$, $4 \rightarrow 3$, $5 \rightarrow 1$, and $7 \rightarrow 6$ in time slot 15, achieving maximum spatial reuse within a one-hop range in the network. The columns "Total number of links" and "Number of interfered links" in Tables 6 and 7, respectively, represent the total number of communication links and the number of links affected by interference during the simulation period from 45 s to 48 s. The tables indicate that before the activation of the IAS, the network allowed a total of 230 communication links, out of which 17 instances suffered significant internal network interference, leading to packet loss at the receiving nodes. However, with the IAS functionality activated, the network supported a total of 231 occurrences of communication links, with only 4 links encountering network interference, resulting in packet loss at the receiving nodes. This represents a decrease of 13 occurrences compared to before IAS activation.

4.1.2. Throughput

(A) Network throughput

Figure 6 compares network throughput before and after the activation of IAS.

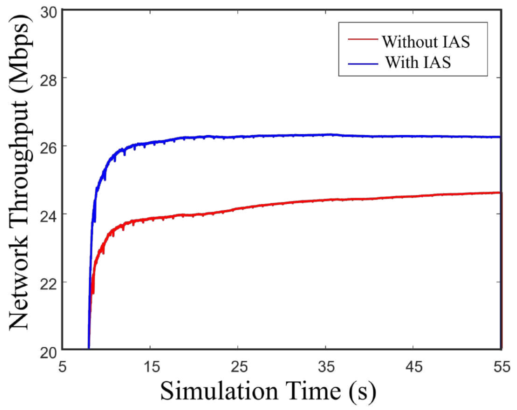


Figure 6. Network throughput comparison with/without IAS.

The theoretical ratio P of the data layer transmission rate to the MAC layer transmission rate can be calculated by considering the addition of a MAC layer overhead to the IP layer data packets, which is defined in the Formula (2):

$$P = \frac{R_{IP}}{R_{MAC}} = \frac{IP_{pktSize}}{IP_{pktSize} + MAC_{overHead}} \tag{2}$$

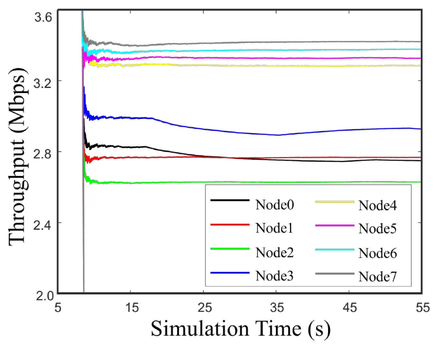
where R_{IP} is the rate at which IP packets are transmitted, and $IP_{pktSize}$ represents the size of the IP packet data. Additionally, the $MAC_{overHead}$ refers to the MAC overhead added to the IP packet in this specific network, the $IP_{pktSize}$ is 1020 bytes, and the $MAC_{overHead}$ is 33 bytes. When transmitting data using a CBR, the network throughput can be calculated using Equation (3).

$$Thr_{IP} = (0.604 + 0.564 + 0.524 + 0.484 + 0.444 + 0.404 + 0.364 + 0.324) \times 7 = 25,984 \text{ kbps} \quad (3)$$

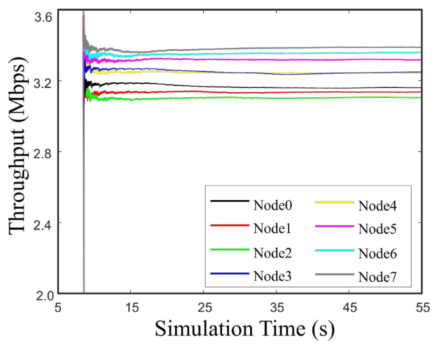
When we consider the ratio P defined in Formula 2, we find that the throughput of the MAC layer is 26,824 kbps. Based on the simulation results from Figure 6, we can see that the network's stable throughput before enabling the IAS is approximately 24,570 kbps. However, when the IAS is enabled, the throughput increases to around 26,200 kbps, resulting in a notable improvement of approximately 1630 kbps. This amounts to a performance improvement of around 6.634%, close to the maximum achievable network throughput of 26,824 kbps. The slight discrepancy may be due to unicast data packets in the network that do not contribute to throughput but still occupy link transmission time slots.

(B) Node throughput

Figure 7a,b illustrate the network node throughput before and after IAS activation respectively.



(**a**)



(**b**)

Figure 7. Comparison of node throughput without/with IAS. (**a**) Without IAS. (**b**) With IAS.

By comparing Figure 7a,b it is evident that the activation of the IAS function has significantly improved the throughput of Nodes 0, 1, 2, and 3. When visually inspected, the network topology depicted in Figure 5 shows that these nodes are positioned near small angles between the connecting links. The qualitative analysis aligns with the simulation outcomes, where the activation of the IAS function is observed to alleviate interference issues and improve the throughput of Nodes 0, 1, 2, and 3.

4.2. The Overall Performance of Network

Based on the network topology in Figure 5 and the traffic generation design, CBR generators are employed at each node to send/receive data packets to/from the other seven nodes. The CBR rate is set at 1522.063 kbps for each node. During this period, nodes activate IAS. A comparative analysis of the network's overall throughput, latency, and other performance metrics is conducted through simulation.

4.2.1. Throughput

In the case of TDMA channel access, theoretical network throughput without spatial reuse can be expressed by Equation (4):

$$Thr = Phy_{rate} \times n_{slot} \times \eta \tag{4}$$

where Thr is the theoretical throughput of the network, and Phy_{rate} is the maximum payload size of the physical layer in a single TDMA slot, and n_{slot} represents the number of the data transmission time slots in one second, and η is the data payload utilization efficiency. In the current simulation scenario, the maximum payload size of the physical layer in a single TDMA slot is 994 bytes, and in a TDMA frame, there are 85 time slots and 49 TDMA frames per second. we consider the value of η in the network to be 100%. From Formula (4) and the network parameters, the network's throughput without spacial reuse is 994 × 8 × 85 × 49 = 33,120.080 kbps. The theoretical value of network throughput with spatial reuse is 1522.063 × 8 × 7 = 85,235.528 kbps. When considering the ratio η defined in Equation (2), the throughput of the MAC layer is 87,993.178 kbps. Figure 8 depicts the network throughput comparison between spatial reuse and theoretical throughput without spatial reuse. The simulated network throughput with spatial reuse measures around 81,880 kbps, demonstrating an 81,880÷33,120.080 ≈ 2.472 times increase compared to the theoretical values without spatial reuse in the simulation results. Figure 9 depicts the throughput of nodes in the network. It can be observed that the throughput of the eight nodes remains relatively consistent, fluctuating within the range of [9000, 10,800] kbps when the network stabilizes.

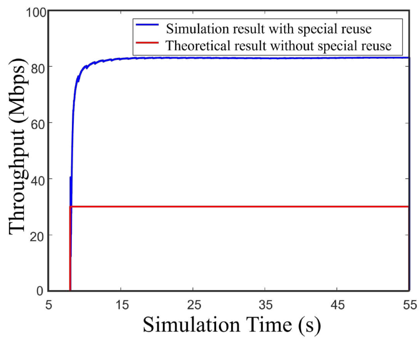


Figure 8. Network throughput.

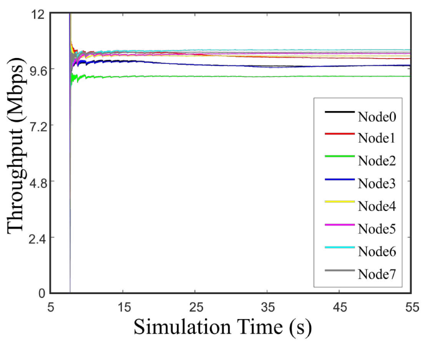


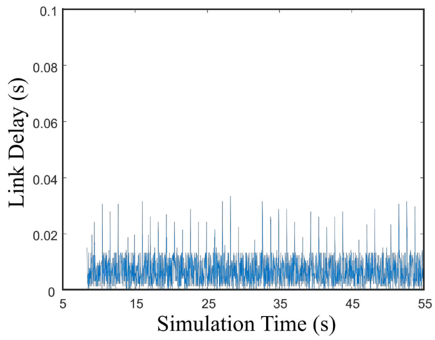
Figure 9. Node throughput.

4.2.2. Network Delay

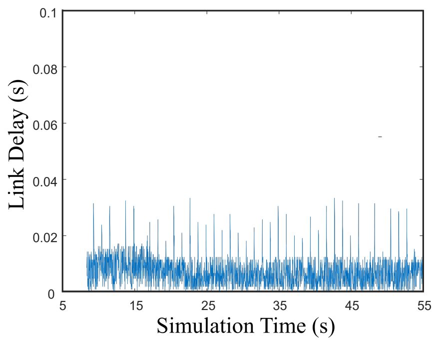
In the simulation, latency refers to the delay from when an IP packet is transmitted from a port in the sending-side network layer until it is completely received at a port in the receiving-side network layer. It includes the entire process duration. The general formula for calculating end-to-end latency during the transmission of IP packets in the network is represented by Formula (5).

$$\tau_{delay} = \tau_p + \tau_l + \tau_q + \tau_t \tag{5}$$

where the τ is the end-to-end during the transmission of the IP packet, and τ_p is the total processing delays incurred by various devices, and τ_l refers to transmission delay. τ_q refers to the time elapsed from when a data packet enters the internal buffer queue of a device until the moment it is dequeued, and τ_t is the propagation delay. Figure 10a,b show the end-to-end delays for two of the 56 links. The results for the remaining 54 links are similar. Figure 11 illustrates the Cumulative Distribution Function (CDF) of the two link delays shown in Figure 10a,b.



(**a**)



(**b**)

Figure 10. Two links delay in the network. (**a**) Link: node4 → node3. (**b**) Link: node5 → node4.

During the simulation process, it was found that the worst-case scenario occurs when the IP packet arrives at the MAC layer at the beginning of a listening frame, which occurs once per second. This results in a delay of approximately 20 ms. However, the overall impact of link latency at other times is relatively low under the influence of τ_p, τ_l, τ_q and τ_t. The simulation results in Figure 11 indicate that over 90% of data packets in the network experience latency below 0.015 s, and almost all the packets experience latency below 0.02 s, which demonstrates that the network nodes can conduct normal communication without any issues.

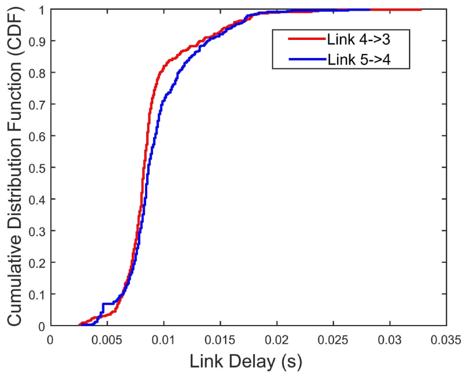


Figure 11. CDF of link delay.

5. Conclusions

This paper proposed a TDMA-based reservation MAC layer protocol (SISAP). This protocol defines a frame structure that meets the functional requirements of self-organizing networks, ensuring real-time communication among nodes in the system. It adopts a receive-align working mode to address experimental issues in ultra-long-distance transmission. The processing node states in this mode effectively avoid signal transmission advance conflicts between adjacent time slots.

Simultaneously, the protocol employs a "request-response" slot allocation scheme, intelligently handling slot requests, allocation, and responses to adapt to the upper layer's constantly changing business needs while efficiently utilizing channel resources. The protocol enables long-distance transmission and spatial reuse at lower power consumption with support from smart antenna technology and interference self-avoidance techniques.

The results of using the NS2 network simulation platform for protocol simulation demonstrate that the protocol exhibits high slot allocation efficiency and low end-to-end latency in environments with dynamically changing business requirements. It can intelligently allocate slot resources according to node demands, maximizing spatial reuse and presenting a self-organizing network system that operates autonomously and efficiently. In the paper, for a more intuitive assessment of algorithm performance, we primarily employ a "with and without" comparative analysis for the interference self-avoidance strategy. For overall network performance, we primarily compare it with theoretical network values, lacking experimental analysis comparisons with relevant literature. In future work, we will continue to explore research in related areas. Specifically, our focus will be on developing an efficient method to ensure the continuity of available time slots. We have decided to utilize the DSDV routing protocol directly for simulation purposes, recognizing its potential impact on future network performance. To enhance network performance, our goal is to integrate the channel allocation algorithm with a high-performance routing protocol. Furthermore, we will conduct comparative analyses with existing literature to validate network performance and continually refine our research efforts.

Author Contributions: Conceptualization, D.L.; methodology, D.L.; software, D.L.; validation, D.L.; formal analysis, D.L. and J.N.; investigation, D.L. and J.N.; resources, M.T.; data creation, D.L.; writing—original draft preparation, D.L. and J.N.; writing—review and editing, D.L., J.N. and M.T.; visualization, D.L., J.N. and M.T.; supervision, J.N. and M.T.; project administration, M.T.; funding acquisition, J.N. and M.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by JST ASPIRE Grant Number JPMJAP2325, Japan.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest. The founders had no role in the design of the study, in the collection, analysis, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

ASAP	Adaptive Slot Allocation Protocol
CBR	Constant Bit-Rate generator
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
DSDV	Destination-Sequence Distance Vector
DTRA	Directional Transmit and Receive Algorithm
E-ASAP	Extended Adaptive Slot Allocation Protocol
FDMA	Frequency Division Multiple Access
IAS	Interference Self-Avoidance Strategy
liiTAB	link information table
MAC	Media Access Control
SA	Slot Allocation
SAA	Slot Allocation Answer packet
SAR	Slot Allocation Request packet
SINR	Signal-to-Interference-plus-Noise Ratio
SISAP	State Interaction-based Slot Assignment Protocol
TDMA	Time Division Multiple Access
UDP	User Datagram Protocol
USAP	Unifying Slot Allocation Protocol
Z-MAC	Zebra MAC

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