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RESEARCH ARTICLE

Directional Antenna Based Scheduling Protocol for IoT Networks

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Abstract: Contemporary communication networks are the Internet of Things (IoT) networks that can potentially connect millions of devices. However, as these networks expand, issues such as power consumption, throughput, and interference are much more important. In this paper, we present the Directional Scheduling protocol for the constrained 6TiSCH-IoT networks in order to enhance the performance of the network due to the use of directional antennas. The proposed protocol is different from other conventional omnidirectional antenna-based systems, which have low spatial reuse and high interference; it allows multiple nodes to transmit data simultaneously, reducing interference and enhancing throughput. The protocol is decentralized, so every IoT node can locally decide about the time for the next transmission based on local knowledge and thus exclude head-of-line blocking. This paper presents a detailed description of the proposed system model with a focus on the antenna configuration aspect, energy consumption, and the scheduling policy that aims at minimizing power consumption while at the same time achieving high network throughput and low end-to-end delay. Simulation results demonstrate up to 5× higher throughput, 30% reduced end-to-end delay, and a 25% reduction in energy consumption with directional antennas (beam widths of 90 ° and 45 °) compared to omnidirectional configurations, highlighting the enhanced performance and energy efficiency of 6TiSCH for IoT communication. The conclusion reveals that this approach is useful to solve the two main challenges large-scale and IoT networks face, namely, scalability and interference. Further research may examine the application of artificial intelligence techniques to enhance the scheduling and resource allocation functions, in addition to advances in the design of dual-configuration antenna systems, where better performance and lower hardware complexity are sought.

Keywords: 6TiSCH, 6top, distributed algorithm, directional antennas

1. Introduction

The Internet of Things (IoT) has the potential to meet the demands of rapidly evolving wireless technologies, each with distinct infrastructural needs [1–9]. IoT facilitates the connection of heterogeneous networks (such as Wi-Fi, Bluetooth, etc.) [10] to the internet, creating a new paradigm for information analysis and decision-making. However, as these networks expand, challenges such as power consumption, throughput, and interference become increasingly significant [4, 6].

The IEEE 802.15.4e is being proposed as a protocol for IoT, defining the medium access control (MAC) and physical layers of Low-Power and Lossy Networks, which have facilitated increased IoT deployment. One of the five MAC operation modes in the IEEE 802.15.4e protocol is Time Slotted Channel Hopping (TiSCH) [7]. In TiSCH, all IoT nodes use a common schedule to determine the time slot and channel for communication with their one-hop neighbors. However, the standard does not specify how the schedule should be constructed and updated. As IoT becomes integrated into everyday life, IoT-enabled nodes generate high volumes of heterogeneous traffic [8]. The routing and scheduling implemented in this standard directly affect node energy consumption and propagation delay.

Due to the resource constraints of sensor nodes, the Internet Engineering Task Force (IETF) is developing various efficient low-energy communication standards [5]. The IETF 6TiSCH working group outlines a mechanism that combines the high reliability and low-energy consumption of IEEE 802.15.4e TiSCH with the IP protocol. This integration ensures interoperability and smooth application data transmission. The 6TiSCH Operation Sublayer (6top) defines a scheduling function (SF0) that adds or deletes cells between neighboring IoT nodes by monitoring and collecting user data. However, the current implementation of the scheduling function in 6TiSCH operates in an omnidirectional mode.

Using directional antennas can significantly reduce power consumption and minimize one-hop interference with neighboring nodes [9]. Additionally, multiple IoT nodes within the same coverage area can communicate more effectively by enhancing spatial reuse. However, to fully leverage directional transmission, an efficient MAC protocol must be designed to address issues such as deafness and hidden terminal problems.

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The 6TiSCH nodes are synchronized based on a common frame structure along with a transmission schedule. However, the key problem with IEEE 802.15.4e (Figure 1) is that it doesn't specify the time slot scheduling protocol. In this work, a directional antenna-based distributed scheduling is being proposed where every IoT node prepares its schedule in a distributed mode. Since sensor nodes exchange data frequently, an efficient MAC design should be proposed to allocate the time slot for the node intending for communication. Our protocol uses directional antennas for sending and receiving the application data in between one-hop neighbor IoT nodes. This needs to have strict node synchronization during the cell schedule with its neighbor. To address the issue, this paper starts with a discussion of the use of directional antennas in the 6TiSCH network to reduce interference and increase spatial reuse. Later, a distributed scheduling strategy is explored to determine the available slots when a node needs to either send or receive messages from its one-hop IoT neighbor nodes. The main contributions of this proposed work are as follows:

1) **Directional Scheduling Protocol**: Our protocol incorporates **directional antennas** for **6TiSCH IoT networks**, which significantly improves **spatial reuse**, reduces **interference**, and enhances **network throughput** compared to traditional **omnidirectional antenna-based protocols**.
2) **Decentralized Scheduling**: We present a **decentralized scheduling approach** where each IoT node locally determines its scheduling based on neighboring node information, thus avoiding the **head-of-line blocking** issue that arises in centralized systems.
3) **Energy Efficiency**: Through the use of **directional antennas**, our protocol achieves **energy savings** by reducing unnecessary transmissions and focusing the energy toward the intended target, unlike conventional systems that use **omnidirectional transmission**.

The rest of the paper is organized as follows. Section 2 presents a brief review of literature on IoT-enabled MAC protocols and 6TiSCH scheduling algorithms. Section 3 describes the system model, antenna model, assumptions, and the proposed work. Section 4 explains the simulation results and analysis of the proposed model. Finally, Section 5 presents the conclusion and insights of future work.

2. Related Work

In the following two subsections, the focus is on existing energy conservation techniques and the scheduling algorithm for the IoT networks.

2.1. IoT MAC protocols

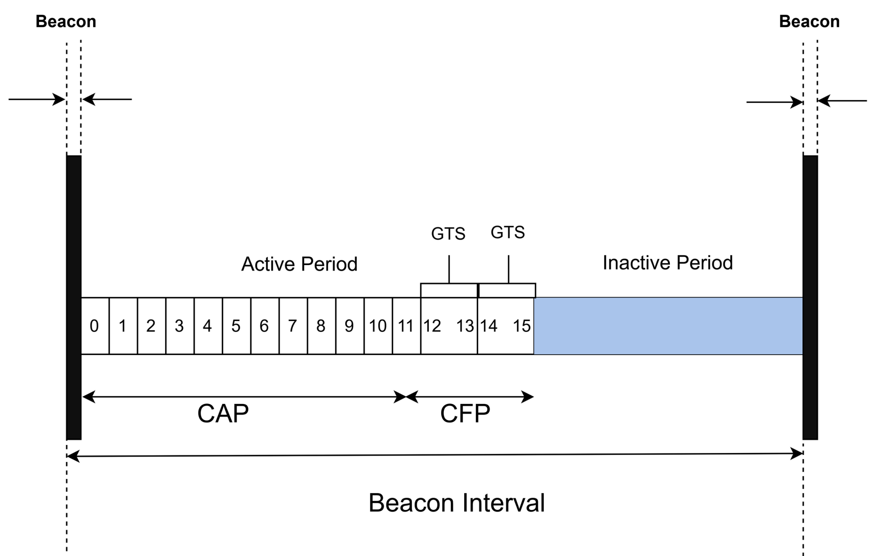
The design of MAC protocols significantly influences communication efficiency, energy management, and security in IoT networks. Several MAC protocols have emerged to meet these diverse IoT application requirements.

Multimedia IoT applications require adaptive MAC protocols capable of managing extensive multimedia-on-demand traffic effectively. Recent studies, such as Nauman et al. [11], have highlighted the significance of dynamic MAC protocols that adapt to varying multimedia traffic, emphasizing quality of service (QoS) and latency minimization. Additionally, Parra et al. [12] address scalability challenges specifically in Direct-to-Satellite IoT scenarios, proposing accurate network size estimation techniques essential for efficient MAC resource management in satellite-based communications.

Security in the MAC layer has also been a critical area of research, with recent approaches leveraging MAC protocol attributes to enhance network security. For instance, Nayak and Bhattacharyya [13] explore MAC protocol-based intrusion detection frameworks tailored to IoT networks, identifying and mitigating potential security threats through MAC-layer analytics. Such integration between MAC protocol operations and security measures contributes significantly to more resilient IoT deployments.

Cross-layer MAC and routing integration is vital for applications demanding high reliability and minimal delay. Kim et al. [14] outline a cross-layer approach that utilizes IEEE 802.15.4 standards to enhance reliability and latency performance in industrial IoT applications. Similarly, Subramanyam et al. [15] investigate cooperative optimization strategies within distributed IoT frameworks,

Figure 1
Superframe structure of IEEE 802.15.4



underlining the benefits of cross-layer cooperation for improved network robustness and energy efficiency.

Given the variety and complexity of MAC protocols, Amin et al. [16] provide a comprehensive overview of medium access and radio duty cycling strategies in IoT, revealing essential insights into energy efficiency and performance optimization. Energy harvesting MAC protocols, detailed in Famitafreshi et al. [17], have also gained attention for their potential to extend the lifetime of IoT networks by effectively utilizing ambient energy sources.

Several empirical studies, such as Afroz and Braun [18], explore enhanced variants of existing MAC protocols, including the Extended QX-MAC for IoT-based sensor networks, highlighting performance improvements through empirical validation. Traffic-aware protocols, as studied in Nguyen et al. [19], emphasize priority mechanisms in managing diverse IoT traffic demands, particularly for critical applications such as agricultural IoT, as comprehensively reviewed by Effah et al. [20].

Protocols designed specifically for satellite IoT applications are analyzed in Fernandez et al. [21], discussing on-demand payload strategies crucial for satellite communication efficiency. An integrated intrusion detection and prevention mechanism in the MAC layer, proposed by Krishnan et al. [22], further expands the security landscape by incorporating adaptive features into the MAC protocol design.

A broad review presented in Khisa and Moh [23] discusses the fundamental MAC protocols for IoT, identifying key factors influencing protocol effectiveness across diverse applications. Studies addressing security threats, such as jamming attacks and their impact on MAC-layer performance, are methodically discussed in Kerrakchou et al. [24]. Additionally, energy-efficient and low-latency MAC protocols, essential for real-time IoT applications, are explored comprehensively by Ahmad et al. [25].

Predictive MAC-layer optimization techniques have been advanced in El Houssaini et al. [26], demonstrating the efficacy of predictive analytics for mitigating delays and enhancing MAC performance. Efficient MAC protocols tailored specifically for Unmanned Aerial Vehicle (UAV)-assisted IoT networks are analyzed in Olatinwo et al. [27], highlighting adaptations necessary to accommodate the unique mobility and communication requirements of UAVs.

Cooperation-based adaptive MAC designs, proposed by Mahmud et al. [28], emphasize reliable communications in dynamic IoT environments through cooperative MAC strategies. Scheduling efficiency for the TiSCH mode is critically evaluated in Kim et al. [29], providing insights into multiple slot-frame scheduling mechanisms beneficial for low-power IoT applications.

Scalable and energy-efficient MAC protocol designs, such as the RESS-IoT protocol presented in Ortigueira et al. [30], provide robust frameworks for satellite IoT systems. Network performance metrics relevant to energy efficiency in MAC protocol designs have been systematically reviewed by Engmann et al. [31], underlining key performance indicators for IoT systems. Trust-aware MAC and routing protocols are discussed in Yang et al. [32], highlighting the intersection of security, trust, and efficiency in IoT communications.

Priority-aware MAC protocols adapted for UAV-assisted IoT scenarios are detailed in Khisa and Moh [33], demonstrating how priority-based approaches effectively support time-sensitive data transmission in mobile IoT environments. Analytical assessments of MAC protocols for wireless sensor networks (WSN), as provided in Zhang and Wang [34], deliver critical evaluations necessary for selecting optimal MAC strategies based on specific deployment contexts.

Finally, adaptive MAC protocols employing reinforcement learning techniques, such as the Q-learning-based protocol detailed in Wu et al. [35], showcase advanced artificial intelligence (AI)-driven approaches to dynamically optimize IoT network performance based on real-time conditions and feedback.

These reviewed studies collectively emphasize that successful IoT MAC protocol design should incorporate adaptive scheduling, advanced security mechanisms, cross-layer optimization, scalability considerations, and innovative energy management techniques to fully accommodate the diverse and evolving requirements of IoT networks.

2.2. Scheduling algorithms for 6TiSCH

The 6TiSCH (IPv6 over TiSCH) framework has emerged as a critical solution for deterministic communication in IoT networks, particularly those requiring low latency, high reliability, and energy efficiency. Recent research has substantially contributed toward improving the scheduling mechanisms within 6TiSCH networks.

Rady et al. [36] characterized the performance trade-offs associated with the 6TiSCH minimal scheduling function, highlighting the critical balance required between energy efficiency and latency. Extending this, Rady et al. [37] introduced 6TiSCH, a generalized scheduling framework supporting multiple physical layer configurations for agile networking.

Adaptive scheduling was explored by Lee [38], who proposed cell negotiation techniques to dynamically allocate network resources based on real-time conditions. Chang et al. [39] provided insights into MSF implementation and standardization challenges within the IETF, emphasizing scalability improvements. Ha and Chung [40] introduced traffic-aware routing methods to optimize network efficiency and load balancing in industrial IoT scenarios.

Tanaka et al. [41] introduced YSF, a scheduling function designed explicitly to minimize latency for industrial IoT applications. Similarly, Kotsiou et al. [42] proposed the Low-Latency Distributed Scheduling Function to reduce delays in distributed IoT systems.

Elsas et al. [43] reviewed recent advances in multi-modal industrial IoT networks, emphasizing adaptive and efficient scheduling solutions. Kumar and Kolberg [44] proposed DeSSR, a decentralized broadcast-based scalable scheduling solution for IoT networks, addressing scalability and decentralization challenges.

Fahad et al. [45] investigated multi-queue priority-based scheduling to enhance IoT network performance, particularly in scenarios demanding differentiated service quality. Pratama et al. [46] leveraged Q-learning methods to develop low-latency, distributed scheduling algorithms enhancing responsiveness in dynamic network conditions.

Righetti et al. [47] critically analyzed the CoAP congestion control strategies over 6TiSCH networks, providing insights into congestion mitigation and efficient resource utilization. Pradhan et al. [48] presented low-latency autonomous scheduling for industrial IoT, significantly improving real-time communication capabilities.

The scheduling of distributed renewable energy resources in IoT systems was explored by Nengroo et al. [49], highlighting energy-aware scheduling's role in sustainable IoT network operation. Amiri et al. [50] proposed efficient anycast mechanisms for 802.15.4-TiSCH networks, further advancing IoT communications reliability.

Rady et al. [51] examined heterogeneous slot durations in 6DYN, demonstrating improved scheduling flexibility and performance in diverse IoT deployments. Righetti et al. [52] evaluated autonomous and adaptive scheduling techniques, emphasizing their importance for IoT networks operating under variable traffic loads.

Energy efficiency strategies in Software-Defined Networking (SDN)-enabled IoT were discussed by Rout et al. [53], integrating scheduling approaches into the SDN framework. Azimian et al. [54] presented cross-layer scheduling and routing techniques, improving end-to-end QoS.

Josbert et al. [55] focused on SDN-driven industrial networks, demonstrating how scheduling functions within the SDN architecture significantly enhance IoT operational efficiency. Orozco-Santos et al. [56] proposed TiSCH multiflow scheduling to guarantee QoS in critical industrial IoT applications.

Distributed channel-ranking scheduling was addressed by Amezcua Valdovinos et al. [57], improving the adaptability of channel allocation strategies. Jabandžić et al. [58] developed dynamic multichannel time division multiple access (TDMA) slot assignment algorithms, enhancing the robustness of 6TiSCH scheduling under varying channel conditions.

Tanaka et al. [59] designed a comprehensive scheduling function suite, systematically addressing diverse application requirements within 6TiSCH networks. Finally, Claeys et al. [60] assessed the Transport Layer Security handshake's performance in 6TiSCH networks, linking security considerations directly with scheduling performance.

Collectively, these studies represent substantial advancements in 6TiSCH scheduling algorithms, emphasizing adaptive, flexible, and efficient approaches tailored to meet the demanding communication and operational requirements of modern industrial and critical IoT applications.

2.3. Review on directional antennas

Directional antennas have become critical components in wireless communication, particularly in IoT and emerging network technologies, due to their capacity for improving energy efficiency, reducing interference, and optimizing spatial reuse. Recent literature demonstrates significant innovations across diverse aspects of directional antenna designs and applications.

Marco di Renzo et al. [61] explored reconfigurable intelligent surfaces, demonstrating their potential to dynamically optimize wireless environments, thereby significantly enhancing network reliability and efficiency. Rahman and Ryu [62] introduced an IoT sensor network leveraging electronically steerable parasitic array radiator antennas, significantly reducing energy consumption through dynamic beam steering.

Arnaoutoglou et al. [63] developed a miniature, all-polarization antenna optimized for beamforming and direction-of-arrival estimation, facilitating accurate localization in compact IoT devices. Pourahmadazar et al. [64] focused on novel planar IoT antenna developments, showcasing compact, multidirectional radiation patterns optimized for IoT integration. Bhakhar and Singh Chhillar [65] proposed dynamic multi-criteria scheduling for directional antenna-based IoT networks, optimizing throughput, latency, and efficiency.

Chu and Chun [66] developed SNR threshold scheduling methods to optimize IoT uplink network performance. Bang et al. [67] explored the secrecy sum-rate of directional antenna-equipped IoT networks, highlighting security benefits derived from directional communication techniques. B R and Manjanaik [68] introduced decentralized large antenna-array scheduling solutions using hierarchical consensus methods, enabling scalability in massive IoT networks.

Rohit et al. [69] introduced graph-based aggregation and attention mechanisms optimized for directional antenna deployment, significantly enhancing IoT network performance. Chu et al. [70] presented joint active and passive beamforming strategies to enhance data rates and energy efficiency. Zhang et al. [71] proposed MASSnet, a deep-learning-based multiple-antenna selection approach optimized for IoT performance.

Yahya et al. [72] developed dual-band GPS/LoRa antennas specifically tailored for IoT deployments, improving dual-mode IoT device communication efficiency. Giordani et al. [73] reviewed directional antenna applications and future technologies toward 6G networks, emphasizing beamforming and smart antenna deployment. Gil-Martínez et al. [74] introduced fast frequency scanning metasurface antennas, significantly improving spectrum agility and beam-steering efficiency.

Bhardwaj et al. [75] presented printed monopole antennas optimized for next-generation IoT applications, highlighting compact form factors and enhanced directionality. Dwivedi and Prasad [76] designed security enhancement scheduling models for IoT networks with directional antennas, emphasizing privacy and secure communication.

Liu et al. [77] proposed optimal scheduling methods for integrated IoT-Fog-Cloud systems, ensuring low latency and reliable directional communication. Hazra et al. [78] developed cooperative transmission scheduling and computation offloading techniques for directional antenna-equipped IoT networks, optimizing computational efficiency and latency reduction.

Goudarzi et al. [79] focused on scheduling IoT applications in edge and fog computing environments, leveraging directional antennas for efficient resource allocation and reduced interference. Hussain et al. [80] designed compact, sub-GHz tunable antennas optimized for frequency agility in IoT networks, enhancing network adaptability and spectral efficiency.

Yassine et al. [81] introduced a four-sided matching game model for energy-efficient directional antenna scheduling, maximizing performance in energy-constrained IoT networks. Achar [82] presented Neural-Hill, an innovative algorithm for efficient directional antenna scheduling, emphasizing neural network-driven optimization strategies.

Faenzi et al. [83] introduced methods for designing dual-polarized metasurface antennas, enhancing polarization flexibility and communication performance in IoT scenarios. Bodehou et al. [84] developed direct numerical inversion techniques for efficient directional antenna design, ensuring high-performance beam steering.

Finally, Martínez Rosabal et al. [85] examined methods for minimizing worst-case energy consumption in directional antenna-based IoT networks, emphasizing robust and energy-conscious antenna design and network operation.

Collectively, these references reflect the expansive developments in directional antenna technology, emphasizing adaptive beamforming, intelligent scheduling, security enhancement, energy efficiency, and optimized design strategies tailored to meet the diverse requirements of contemporary and future IoT deployments.

3. Research Gaps in IoT MAC Protocols and 6TiSCH Scheduling

Despite advancements in MAC protocols for the IoT and the development of 6TiSCH scheduling algorithms, several research gaps persist:

1) **Energy Efficiency:** Balancing energy conservation with performance remains challenging, especially in heterogeneous IoT environments with devices having varying energy constraints and communication requirements.
2) **Scalability:** Many protocols struggle to accommodate the massive number of devices anticipated in future IoT deployments, leading to increased collisions and reduced throughput.
3) **Quality of Service (QoS):** Ensuring consistent QoS across diverse IoT applications is difficult, particularly with varying data rates, latency requirements, and reliability standards.
4) **Security:** Integrating robust security measures into MAC protocols without significantly impacting performance or energy efficiency remains an ongoing challenge, given the resource constraints of many IoT devices.
5) **Mobility Support:** Current MAC protocols often lack effective mechanisms to handle device mobility, leading to increased packet loss and communication delays in dynamic IoT environments.
6) **Interoperability:** Achieving seamless communication among diverse devices and networks with different MAC protocols is essential for widespread IoT adoption but remains a significant hurdle.
7) **Standardization:** The absence of universally accepted standards for IoT MAC protocols hampers compatibility and integration across various platforms and applications.
8) **Dynamic Topologies and Traffic Patterns:** In 6TiSCH networks, centralized scheduling approaches require prior knowledge of network topology and traffic, leading to slow adaptation in dynamic environments with sporadic traffic. Distributed methods offer better adaptability but may not achieve optimal scheduling due to limited local information.
9) **Collision Avoidance in Distributed Scheduling:** Algorithms like On-the-Fly (OTF) dynamically allocate bandwidth based on local information, which can result in collisions due to unawareness of other nodes' schedules.
10) **Latency in Hash-Based Scheduling:** Hash-based scheduling methods classify node traffic and determine time slots via hash values, potentially leading to high latency despite low communication overhead.
11) **Energy Consumption in Dense Networks:** Protocols like the Decentralized Broadcast Scheduling Algorithm reduce collisions by sharing local schedules, but in dense networks, this leads to increased energy consumption.
12) **Cross-Layer Optimization:** There is a lack of integrated approaches that consider interactions between scheduling at the MAC layer and routing decisions at the network layer, which is crucial for overall network performance.

Addressing these gaps is crucial for the development of efficient, reliable, and secure IoT systems.

Table 1
Notations

Symbol	Meaning
N	number of nodes in the network
n_i	i^{th} node in the network
V	$V = n_0, n_1, ...n_N$ are the sensor nodes with n_o as the root node
R_i	radius of communication
$D_{x,y}$	Direction of the node

4. System Model

4.1. Antenna model

In this work, a switched beam antenna is used, as it supports a fixed and highly directive beam for data transmission. The beam width θ is set to 90 ° to point in four directions for simplicity; however it can be changed to M directions. An IoT node switches from one beam to another visiting all the beams is defined as sweeping. Neighbor node position is evaluated based on the direction of arrival. All the nodes in the network are equipped with directional antennas. Thus, the proposed scheduling protocol can achieve reduced node energy consumption by maximizing the concurrent transmissions with minimal interference. It is noteworthy that each and every IoT node will maintain a cell-allocation matrix (to keep track of cell information) and a directional antenna beam matrix.

IoT nodes (sender) start scheduling their one-hop neighbor nodes based on local information (cell availability) and broadcast their schedule information to local neighbors. Neighbor nodes that receive schedule information from the sender will update their cell-allocation matrix and directional beam matrix. With this, nodes that are in the communication range of the sender will know about the antenna beam that is going to be used for directional transmission.

In current WSN hardware, each node is equipped with a half-duplex transceiver. This leads to two categories of conflicts: (i) primary conflict, which occurs when a node attempts to transmit and receive simultaneously, and (ii) secondary conflict, which occurs when a node receives multiple transmissions [86].

For secondary conflict, let us assume that the sink location is fixed and sensor nodes are deployed within the IoT network. Once the sensor nodes are battery powered, how exactly synchronization happens among the one-hop neighbor nodes is a challenging task. To achieve this, nodes that are switched ON will listen in all directions to receive the scheduling update from the one-hop neighbor nodes. Later, data transmission will be broadcast with the directional antenna toward the direction of the sink.

4.2. Communication and computation delays

In the proposed model, the minimum rate of upload between two nodes i and j is given by $ru_{i,j}$. The maximum delay at any given node is defined as

$$D^u = max\left(\frac{|B_i|}{ru_{i,j}} + \zeta_i^u\right)\forall i \in V \tag{1}$$

where $|B_i|$ is the total number of bits to be transmitted in up-link and down-link at a given node and ζ_i^u is the channel access time. Similarly, the minimum rate of download between two nodes j and j is given by $rd_{j,i}$. The maximum delay at any given node is defined as

$$D^d = max\left(\frac{|B_i|}{rd_{i,j}} + \zeta_i^d\right)\forall i \in V \tag{2}$$

The computation time per iteration at a node depends on the size of the learning model, the CPU cycles to execute one unit of data is denoted by χ_i, and the size of dataset S_i. The number of CPU cycles needed to execute is $(\chi_i.S_i)$, given all the data.

4.3. Directional energy consumption

The energy consumption at node i is a function of channel state, directional transmission rate, and the bandwidth. The wireless channel between the nodes i and j is given by signal-to-noise ratio (SNR) γ_{ij} defined as

$$\gamma_{ij} = \frac{P^r_{ij}.|hij|^2}{N_0.W_{ij}}, \tag{3}$$

where P^r_{ij} is the received power at i, $|hij|$ is the channel fading, N_0 is spectral density, and W_{ij} is the bandwidth. Also, the path loss for distance of d_{ij} is α $(2 \leq \alpha \leq 6)$. Thus, received power is attenuated with respect to transmission as follows $P^r_{ij} = P^t_{ij}.\omega.d^{-\alpha}_{ij}$. The transmission rate from node i to j given SNR is defined as

$$ru_{i,j} = W_{ij}\log_2(1 + \upsilon\gamma_{ij}) \tag{4}$$

where $\upsilon = -1.5/\log(5.BER)$ BER is the bit error rate; the transmitted power can be written as

$$P^t_{ij} = \frac{N_0.W_{ij}}{g_{ij}}\left(2^{\frac{r_{ij}}{W_{ij}}} - 1\right) \tag{5}$$

where g_{ij} is the channel gain that is defined as

$$g_{ij} = \upsilon.\omega.d^{-\alpha}_{ij}.|h_{ij}|^2 \tag{6}$$

The total energy consumed at node i to send data of length B_i to node j is

$$E_{ij} = \frac{P^t_{ij}.|B_i|}{rij} \tag{7}$$

4.4. Design objectives

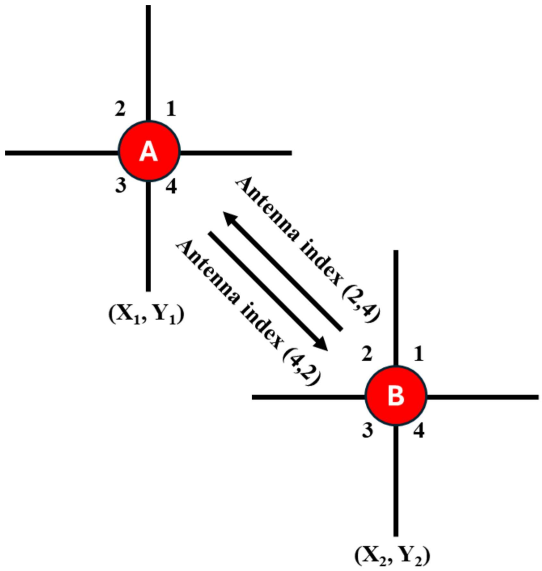
Minimal Schedule Length: The primary design objective is to make use of concurrent transmissions, increasing the spatial reuse by minimizing the interference to reduce the schedule length.

Minimizing Energy Consumption: Two popular techniques for maximizing the network lifetime in resource-constrained WSN are (i) transmission power control and (ii) radio activity. Nodes can transmit with optimal power instead of maximum power, and instead of keeping the radio active all the time, intelligent scheduling between sleep and active states is archieed using duty cycles.

4.5. Network model

In TiSCH, enhanced beacons (EBs) are broadcast by the coordinator for network formation. Then, interested nodes scan for the EB messages and reply with EB message to show their presence. In this model, we consider a 6TiSCH network with tree topology built using the Routing Protocol for Low-Power and Lossy Network. We consider a time-slotted IEEE 802.15.4-2015 network, where the nodes operate in a distributed manner. The network can be defined as $G = (V, E)$, where $V = n_0, n_1, ...n_N$ is the set of nodes in the network. Here, n_0 is the sink, E denotes the link between the nodes, R_i denotes the communication radius, and $D_{x,y}$ denotes the direction of the node (see in Table 1). Sensor nodes monitor various events and forward them to the sink node. In the proposed work, the antenna works in directional mode for data transmission and omnidirectional mode for data collection. **Node directional matrix** avoids interference from neighbor nodes accessing the same channel. Every node knows its own location. By the exchange of local information, the node calculates the antenna direction and index number of neighbor nodes using the global position system (GPS), as shown in Figure 2.

Figure 2
Directional antenna discovery for neighbor node



Directional interference in a channel is avoided through modified Request To Send (RTS) and Clear To Send (CTS) messages, which include index of antenna and angle of arrival information. Due to this, directional data transfer with efficient transmit power is archived.

Node Channel Matrix

The primary objective of the node channel matrix is to avoid collisions and reduce power consumption.

$$M = \begin{bmatrix} V^{[K]}_{[1,1]} & \cdots & V^{[K]}_{[1,C^{[1]}]} \\ \vdots & \ddots & \vdots \\ V^{[K]}_{[K,1]} & \cdots & V^{[K]}_{[K,C^{[K]}]} \end{bmatrix} \tag{8}$$

Node Directional Matrix

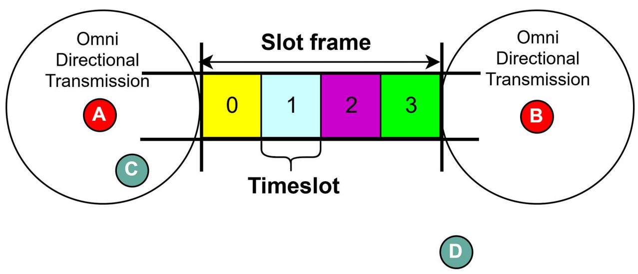
We design a node directional matrix (9) containing $D_{x,y}$ to avoid interference with neighbor directional data transmission on the same channel.

$$M = \begin{bmatrix} D_{1,2} & \cdots & D_{1,K} \\ \vdots & \ddots & \vdots \\ D_{K,1} & \cdots & D_{K,K-1} \end{bmatrix} \tag{9}$$

4.6. Directional transmission

In the above scenario (Figure 3), we assume four nodes A, B, C, and D using one channel trying to have communication with

Figure 3
Omnidirectional TiSCH transmission from node A to node B; node C and node D are in waiting state



each other. Node A wants to communicate with node B, while node C also wants to communicate with node D. Node pair (A,B) is in need of four time slots and is scheduled to transmit in channel 1's four time slots to start its omnidirectional transmission, while node pair (C,D) must wait for next cycle for transmission. Omnidirectional transmission prevents surrounding nodes that are in its interference range from transmitting. With the use of directional transmission (see Figure 4), Node C, which is intending to transmit in the other direction, is allowed to start its transmission. Thus, in directional transmission nodes, both the node pairs can access the channel simultaneously, increasing the spatial reuse and reducing the waiting time.

4.7. Node scheduling

The data delivery rate is constrained by the rate at which the sink can accept the data. High priority is given to one-hop neighbors as they are busy all the time. The scheduling of one-hop neighbors is adjusted based on the packet arrival rates. A top-subtree TS(r) is defined as one whose root r is a child of the sink, and it is said to be eligible if r has at least one packet to send. Any given node has to identify the slots through which it can send information and the slot from which it can receive information; for the selected time slot, the node needs to decide a channel offset. Nodes around the sink are prioritized based on the min buffer size and high available bandwidth. Nodes for which the sink is in the directional transmission range have two modes of operation.

5. The Proposed MAC Model

Hybrid MAC with synchronous TDMA-CSMA/CA is designed to schedule the sensor nodes for directional data transmission.

5.1. Synchronous scheduling

Our proposed model in Figure 5 is based on a tree topology consisting of one parent node and multiple child nodes, as shown in Figure 6. The protocol includes two periods: synchronous scheduling and asynchronous data transfer. Our main idea is to schedule nodes based on the timer value, which is calculated based on the number of packets remaining (buffer size). Many-to-one communication employed in sensor nodes suffers from a congestion problem called the funneling effect. So, one of the primary objectives is to keep the sink node busy. The synchronous scheduling period is divided into three TDMA slots 0, 1, 2 of equal length. In slot 0, nodes at level 1 are scheduled to start the timer. In the Figure 5, node $n2$ timer expires first; hence, it sends RTS to the root node $n0$. Next, $n0$ broadcasts CTS to its neighbor nodes $n1, n2, n3$. Upon receiving CTS from the root node $n0$, $n2$ sends a NAV signal to its child nodes, indicating that it is in sending mode. Next, node $n1$ timer expires; it has listened to the CTS for $n2$ node from $n0$, so it changes its mode to receiving mode and broadcasts to its neighbors its availability. Similarly, node $n3$ changes to receiving mode and informs its availability to its child nodes. As the slot 1 begins, all the nodes level 2 will start their timer; $n4$ timer expires first, and it sends RTS to $n1$ node, which is in receiving mode. Node Math input error sends CTS to all its child nodes, $n4, n5$, and upon receiving the CTS, $n5$ understands $n1$ is busy and changes its mode to receiving mode. Similarly, the procedure is followed for all the remaining nodes till all the possible links are scheduled.

5.2. Single channel omnidirectional case

In this scenario, as shown in Figure 7, nodes $n0, n1, n2, n3$ are in the interference range of one another, and they are operating with omnidirectional antennas with one available channel. Thus, when node $n2$ is transmitting on channel 1 and time slot 0, neighbor nodes $n1, n3$ need to be silent in time slot 0. Transmissions between n4−>n1 and n10−>n3 need to be scheduled in different time slots, in order to prevent interference with node $n2$.

5.3. Single channel directional case

With the use of directional transmission, as shown in Figure 8, nodes that are in interference range of each other, that is, $n0, n1, n2, n3$, can be scheduled to operate in a single channel, in different directions.

Figure 4
Directional TiSCH transmission from node A to node B and node C to node D

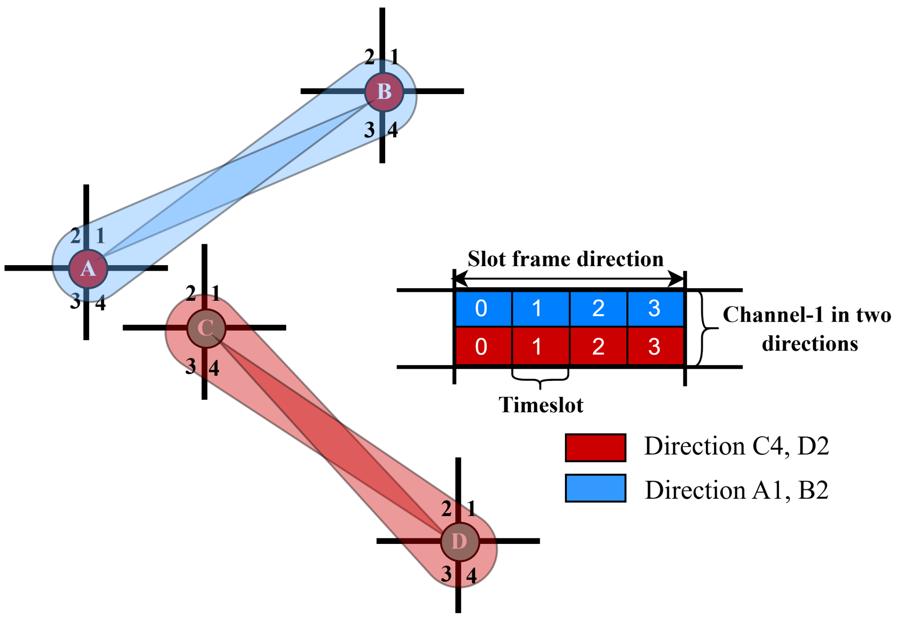


Figure 5
Level-based scheduling

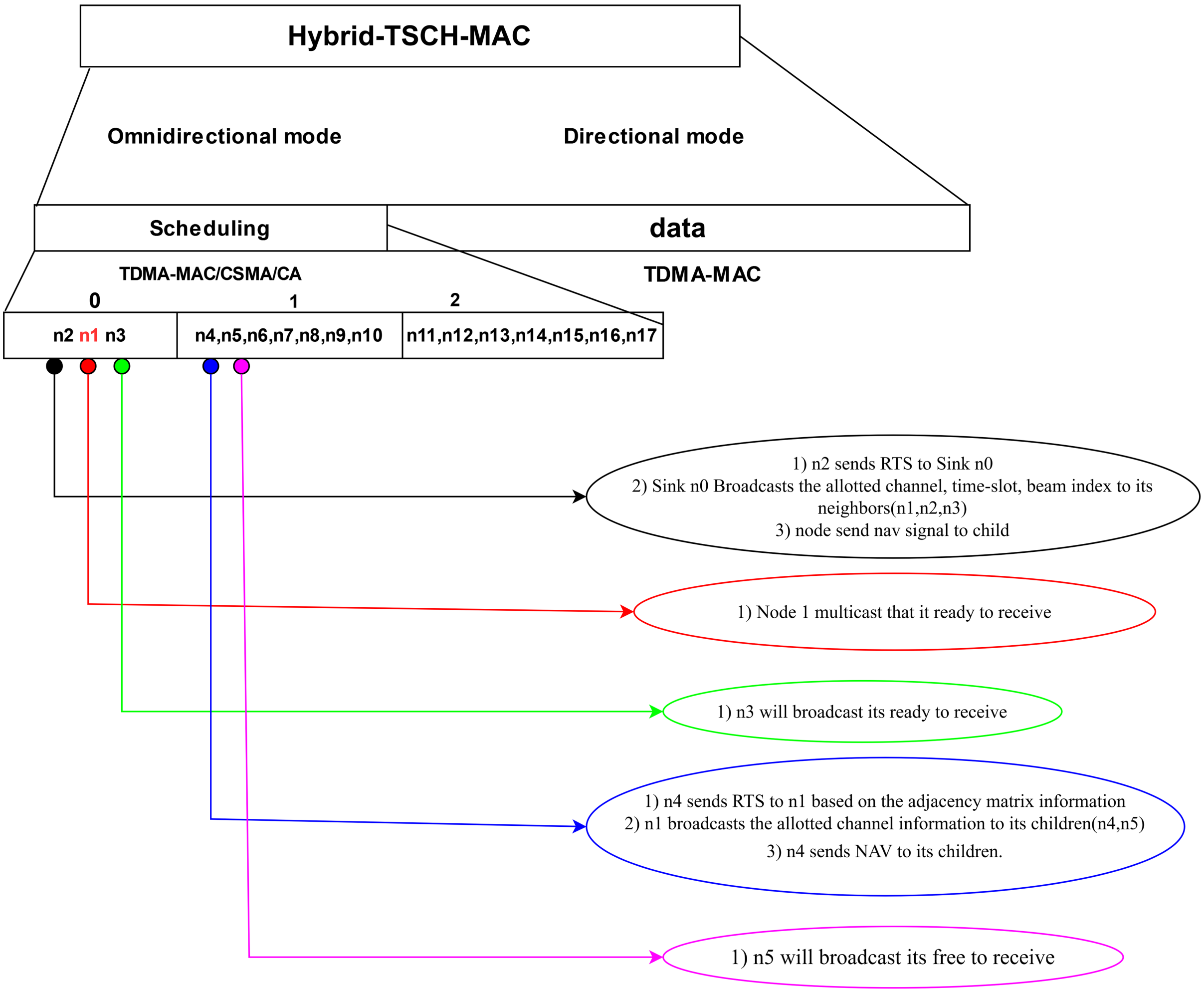
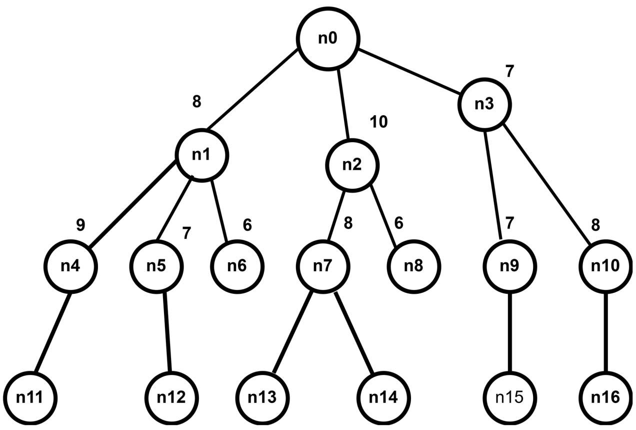


Figure 6
Top subtrees with varying loads



Transmission between $n2->n0$ uses (1,3) beam to communicate, $n4->n1$ uses (1,3) and $n10->n3$ uses (2,4) beams, respectively. All three transmissions are scheduled on channel 0, time slot 0 simultaneously. Thus, spatial reuse is achieved, thereby improving throughput and reducing delay and energy consumption. Hence, the proposed model helps to realize the minimal schedule length and minimal energy consumption, as can be seen in Figure 5.

Algorithm 1 Distributed Scheduling

Require: Every node knows its level in the tree and is fed with timer values when it needs to start its timers.

1. Nodes start their timer when the scheduling slot for their level begins.
2. Initially, one-hop neighbors from the sink start a timer (based on the number of packets remaining).
3. Node whose timer expires is assigned a slot-channel pair (toward sink) in the schedule and is updated in the schedule.
4. Parent node shares the scheduled link information with the child node (i.e., sink will broadcast the scheduled link information to node 1 and node 3.
5. When n1 timer expires, node 1 will broadcast to its child nodes and, similarly, node 3.
6. All the nodes update the information in their adjacency tables.
7. At the beginning of the second time slot, all two-hop neighbors start their timers.
8. Node 4 will check its adjacency table and send a request to n1, which is in receiving mode. n1 will multicast confirmation request. n5 and n6 will update their table.
9. Nodes not violating the adjacency constraint can be scheduled in parallel.
10. Child nodes reserve links based on the information received from the parent node.

Figure 7
Single channel omnidirectional scheduling

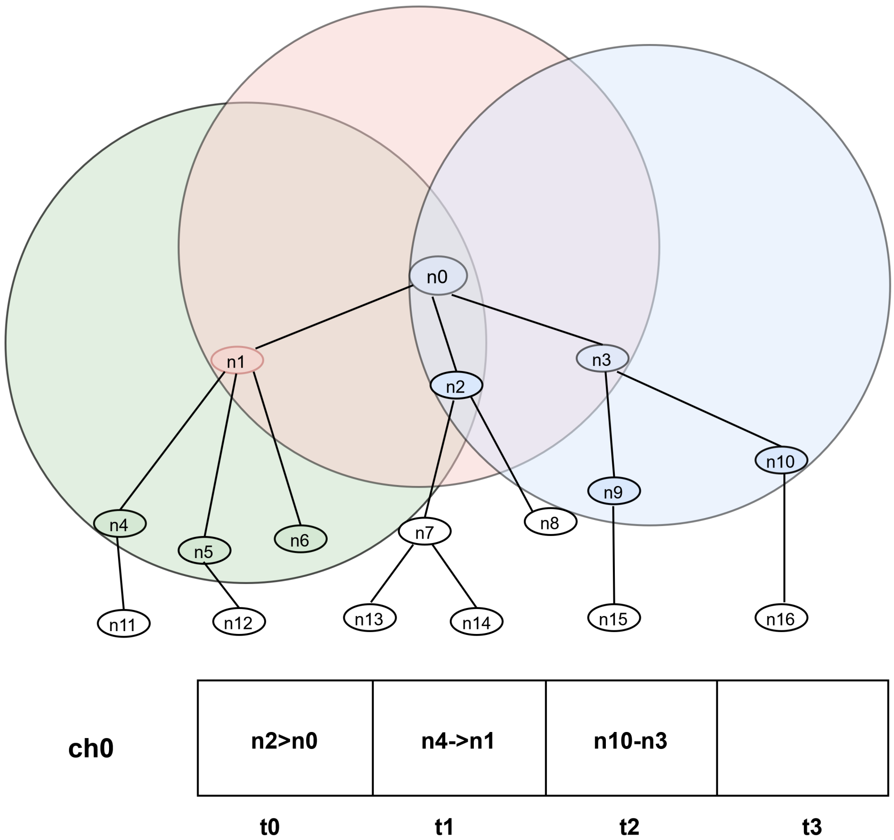
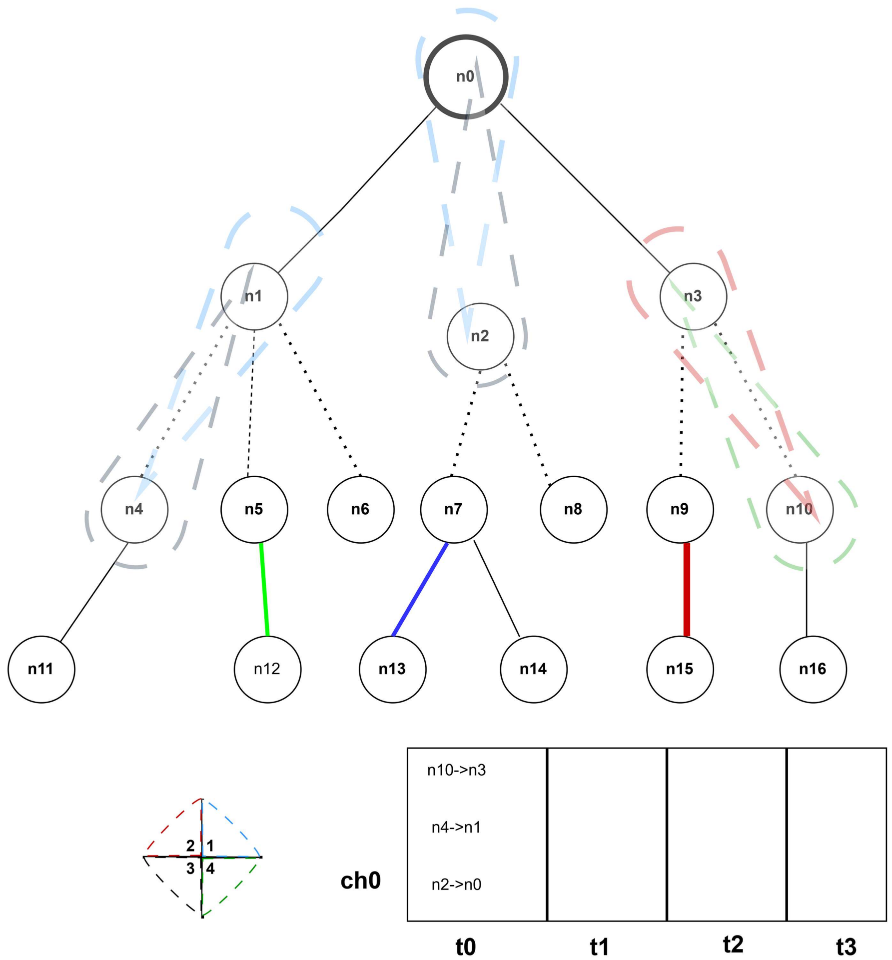


Figure 8
Single channel directional scheduling



6. Simulation Setup

For simulations, we consider a wireless IoT network that consists of N = 16 nodes, one of which is the sink node. An example of this network is shown in Figure 6. The $n - 1$ nodes are uniformly distributed, and the distance between node i and the sink is denoted as d_i. Every node's wireless channel follows i.i.d. Rayleigh fading with the total allowed bandwidth W_{ij} = 20 MHz, which is modeled as h_{iJ}. We have used a quasi-switched beam antenna, which can be steered at a span of 360 degrees. Parameters for the simulation are shown in Table 2.

Table 2
Parameters used in simulation

Parameters	Value
Area	1000 × 1000 m
Number of Nodes	16
Transmission Power	15 dBm
Receiving Threshold	–81.0 dBm
Sensing Threshold	–91.0 dBm
Data Rate	2 Mbps
Packet Size	127 bytes
Simulation Time	5 min

7. Result Analysis and Discussion

We have simulated IEEE 802.15e TiSCH with directional antennas [3]. The average link, network throughput, and end-to-end delay are evaluated with increasing beam width in Figures 9, 10, 11, and 12.

In Figure 9, as the data rate is increasing, the link throughput of our proposed 6TiSCH with directional antenna is much better than that of 6TiSCH with omnidirectional scheduling function. Also, the average end-to-end delay is approximately half that of 6TiSCH omnidirectional. Similarly, as you can see in Figure 10, the average network throughput of the proposed protocol is much better as the

Figure 9
Throughput comparison of 6TiSCH with directional vs. omnidirectional antennas

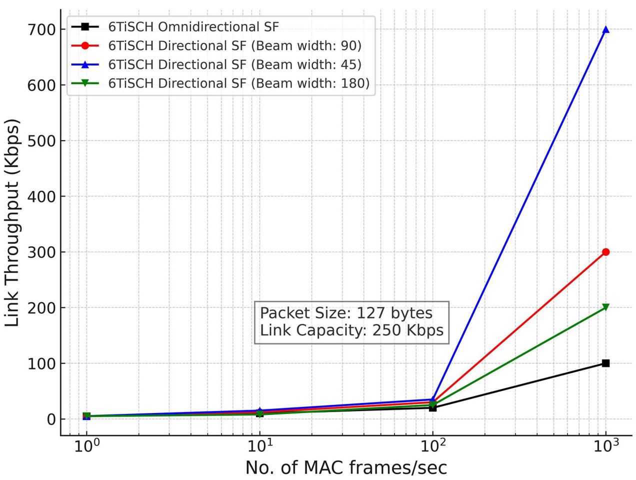
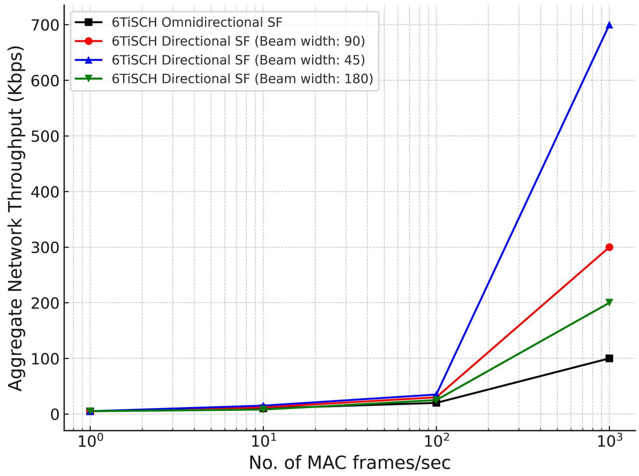


Figure 10
Energy usage—6TiSCH, directional (45°/90°) vs. omnidirectional antennas



nodes, which don't have a chance to send data to sink nodes, are not idle, but they collect information from their child nodes.

Also, in Figures 11 and 12, the end-to-end delay is significantly decreased in the proposed directional protocol. This is because if every node fails to find a time slot to send data to the parent node, it announces its availability to receive data packets from its child nodes.

While the proposed Directional Scheduling protocol shows promising results in enhancing the performance of constrained deterministic 6TiSCH-IoT networks, there are still areas that can be further improved. One drawback of the proposed algorithm is that it relies on directional transmissions, which may not be feasible in certain scenarios where nodes have limited mobility or fixed locations. In addition, the protocol currently focuses on one-hop scheduling and does not address multi-hop scenarios, which may be relevant for larger IoT networks.

7.1. Practical implications of the study

We have clarified the practical implications of our research, which include:

1) **Scalability**: The proposed **Directional Scheduling protocol** enhances spatial reuse and reduces interference, making it ideal for large-scale IoT networks such as smart cities and industrial IoT applications.
2) **Energy Efficiency**: By leveraging directional antennas, our protocol significantly reduces energy consumption, which is particularly beneficial for battery-powered IoT devices in applications like healthcare monitoring and environmental sensing.
3) **Improved Throughput**: Our protocol allows multiple nodes to transmit simultaneously, increasing throughput, which is crucial for high-data-rate applications like video surveillance and real-time industrial data transmission.
4) **Practical Applications**: The protocol is suitable for IoT deployments in areas like smart agriculture, industrial automation, and smart grids, where efficient use of bandwidth and low latency are key.

These implications underscore the value of our research in developing **scalable, energy-efficient, and high-performance IoT networks**.

Figure 11
End-to-end delay—6TiSCH, directional (45°/90°) vs. omnidirectional antennas (30% reduction)

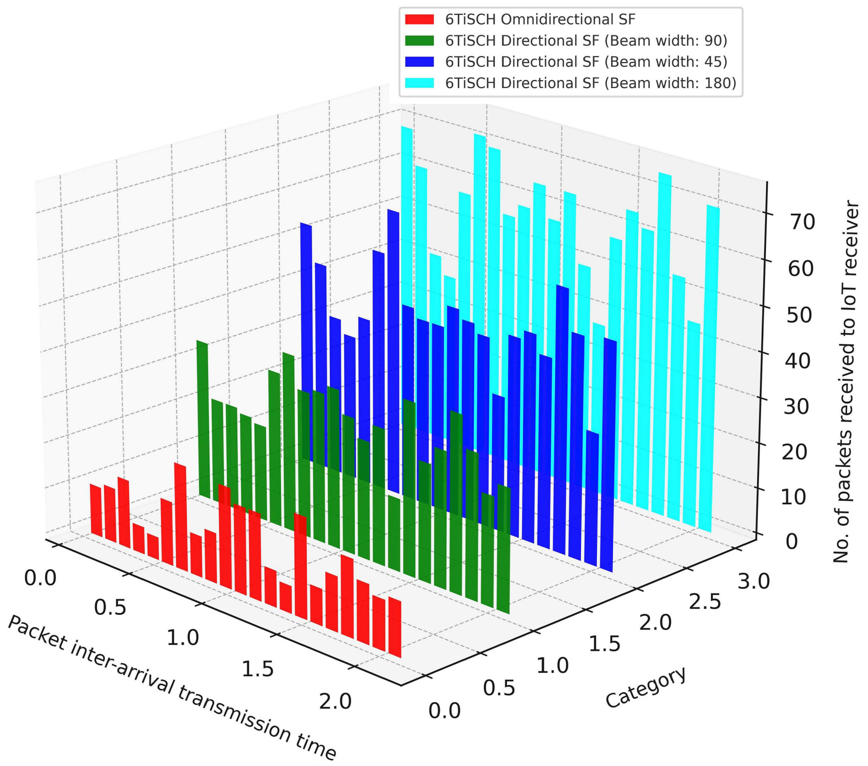
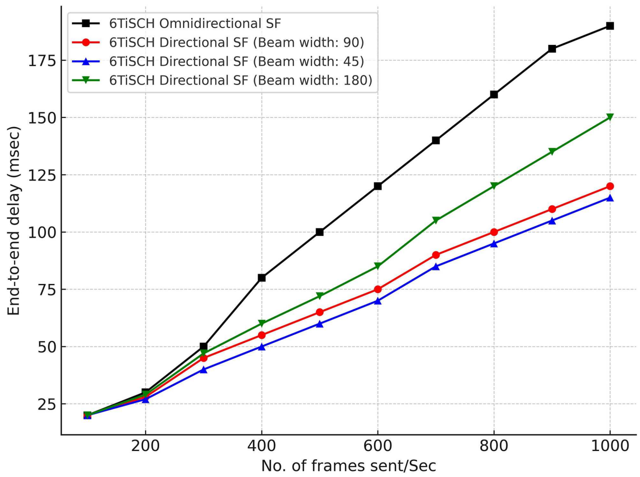


Figure 12
Directional antenna discovery for neighbor node



7.2. Limitations

The proposed Directional Scheduling protocol provides significant performance improvements in terms of throughput, delay, and energy consumption for 6TiSCH IoT networks. However, there are some limitations that need to be addressed for broader application:

1) Directional Antenna Limitations: While the use of directional antennas significantly reduces interference and enhances throughput, it assumes that nodes can accurately align their beams. In dynamic or mobile environments, this may lead to challenges in beam alignment, causing miscommunication or degraded performance.
2) Single-Hop Focus: The current protocol is evaluated primarily in single-hop communication scenarios. In multi-hop networks, additional considerations such as routing protocols and inter-hop coordination may introduce increased delays and collisions, which are not fully captured in this study.
3) Synchronization: Achieving perfect synchronization for all nodes in large-scale or heterogeneous IoT networks remains a challenge. Although we assumed synchronized nodes for the simulation, in real-world applications, especially with larger and more dynamic networks, achieving precise synchronization across nodes can be more difficult.

7.3. Future work

The proposed Directional Scheduling protocol shows promise in improving network performance for 6TiSCH IoT networks, but there are several avenues for future research:

1) **AI-Driven Scheduling:** Future work can explore the application of **AI** techniques, such as **reinforcement learning** or **deep Q-networks**, to dynamically optimize scheduling and resource allocation. AI can enable nodes to adapt to real-time network conditions, such as *traffic patterns, mobility*, and *channel quality*, to make intelligent scheduling decisions that improve throughput and reduce energy consumption.
2) **Blockchain Integration:** Another promising direction is the integration of **blockchain technology** for enhancing **resource allocation** and ensuring **security** in decentralized IoT networks. Blockchain can facilitate *trustless communication* between nodes, where nodes can securely share data and scheduling information without requiring centralized control. This approach could improve *transparency* and ensure that nodes follow agreed-upon protocols in a scalable manner.

3) **Hybrid Antenna Systems:** Exploring the combination of **directional** and **omnidirectional antennas** in hybrid systems could further enhance throughput and reduce the complexity of hardware while maintaining high network performance.
4) **Multi-Hop Networks:** While this study focused on single-hop communication, future research could extend this protocol to **multi-hop networks**, where inter-hop coordination and routing protocols would be essential for maintaining scalability and efficiency.

Future research can explore the use of machine learning and AI techniques to optimize the scheduling and channel access at the MAC layer of IoT networks. AI can be used to learn from the network environment and make intelligent decisions on scheduling and resource allocation based on various factors such as network congestion, channel quality, and mobility patterns of the nodes. This can potentially improve the performance of IoT networks in various scenarios, including those with limited resources and mobility constraints.

Furthermore, future work can investigate the integration of the proposed Directional Scheduling protocol with other existing scheduling protocols, such as TDMA and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), to further improve the performance of IoT networks.

8. Conclusion

In this paper, we have proposed distributed scheduling for the IEEE 802.15.4e network in the TiSCH MAC mode. The use of directional antennas has helped to reduce power consumption, collisions, and delay while increasing spatial reuse and parallel transmissions. To address these limitations and further enhance the performance of IoT networks, future research could explore the use of AI and blockchain technologies. AI can be used to dynamically adjust the scheduling algorithm to account for changing network conditions, while blockchain can ensure secure and efficient communication between IoT devices. Additionally, future work could investigate the use of hybrid directional and omnidirectional antenna-based scheduling protocols to achieve higher throughput without the cost of complex hardware.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Author Contribution Statement

Anil Carie: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Abdur Rashid Sangi:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Satish Anamalamudi:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Murali Krishna Enduri:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Baha Ihnaini:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Hemn Barzan Abdalla:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration.

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