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Enabling space time division multiple access in IETF 6TiSCH protocol

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Abstract: IETF 6TiSCH standard aims to create reliable, deterministic, and low-power networks by scheduling bandwidth resources in time and frequency domains. The main emphasis of 6TiSCH protocol is that it creates Internet of things (IoT) networks with a deterministic and controllable delay. However, many of its benefits are tied to the ability of the 6TiSCH scheduler to optimally distribute radio resources among wireless nodes which may not be possible when the number of frequency resources are limited and several other wireless technologies share the same frequency band (e.g., WiFi, Bluetooth and IEEE 802.15.4). Here the integration of a low-complexity directional antenna system with IETF 6TiSCH protocol is investigated with the aim of creating a 6TiSCH solution with higher spatial reuse. 6TiSCH nodes equipped with such smart directional antennas can schedule bandwidth resources not only in time and frequency domain but also in spatial (space) domain.

Key words: IETF 6TiSCH, smart antennas, Internet of Things, Cooja, Contiki OS, wireless sensor networks

1. Introduction

We are witnessing an unprecedented interest towards small device communication from both industry and academia with the introduction of new application areas such as smart grid, smart health, and smart cities. As a result, it becomes a priority for research and standardization bodies to enable a ubiquitous connected network of small devices. This goal can be achieved only if such small devices are Internet-enabled and can be accessible from anywhere in the world using global IPv6 addresses assigned to them. This idea of connecting small devices to Internet utilizing IPv6 technology is coined as Internet of Things (IoT). Such networks are expected to become a major part of the future Internet. And there is a significant momentum in standardization efforts to enable such a global network of things [1, 2]. Therefore, new and novel methods need to be created by the research community to address the unique challenges that next-generation IoT networks pose.

Future wireless networks are envisaged to encompass nodes belonging to different technology categories operating on the same or adjacent frequency channels. As the need for per-user data throughput increases, the cell sizes shrink in order to cope with this increased demand. Hence, low-power wireless IoT networks will have to cope with challenges posed by such high density deployment scenarios to enable their seamless integration with heterogeneous 5G networks [3]. Increased cochannel and adjacent-channel interference will necessitate new approaches to radio interface design. The straight forward solution to address such challenges is to utilize sectorized and directional antennas instead of antennas with omnidirectional radiation patterns. Hence, low-cost radio interfaces enabling space division multiple access (SDMA) may be necessary for a successful deployment of next-generation wireless IoT networks.

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Omnidirectional antennas limit the spatial reuse of the shared wireless medium since they transmit to and receive from all directions. Directional antennas, on the other hand, can focus their radiated energy toward a particular direction extending the wireless range for the same transmit power. This can improve spatial reuse in the network and reduce the number of collisions in a contention-based access scheme. This, in turn, increases the network capacity by minimizing the cochannel interference [4]. Such a solution can also extend the lifetime of a wireless IoT network due to reduced re-transmissions caused by cochannel interference [5]. Therefore, network capacity, lifetime, and end-to-end delay of wireless IoT networks can be improved by designing new protocols and applications around directional antennas [6].

In 2012, the IEEE 802.15.4e Time slotted channel hopping (TSCH) MAC was proposed to meet the stringent reliability requirements of wireless industrial applications. IETF has recently started a working group for bringing the high reliability aspects of TSCH to IPv6 enabled low-power and lossy networks (LLNs). This new protocol is named as "IPv6 over the TSCH mode of IEEE 802.15.4e" (6TiSCH)[7]. Wireless IoT networks, utilizing 2.4 GHz ISM band, share this band with other technologies such as WiFi and Bluetooth. As highlighted in [8], only four channels (15, 20, 25, 26) of IEEE 802.15.4 do not overlap with WiFi channels. Hence, it is critical for 6TiSCH resource allocation mechanisms to take advantage of these nonoverlapping channels as often as possible to create a reliable 6TiSCH network with minimal interference from WiFi stations, but this significantly limits the frequency diversity benefits of 6TiSCH protocol. In this case, MAC layer resource scheduling mechanisms making use of advanced directional radio interfaces can be utilized to introduce an extra dimension of freedom to the 6TiSCH networks [9].

The main contribution of this study is the directional antenna aware resource scheduling mechanism for IETF 6TiSCH networks. The solution makes use of a low complexity switchable directional antenna solution to enable a hybrid medium access scheme. In this new approach, the communication resources are allocated in time, frequency and spatial (space) domains where the ultimate goal is to create a 6TiSCH network with a better throughput, a lower energy consumption and link latency as compared to the existing 6TiSCH solutions. To this end, a novel switchable directional antenna model is incorporated into Cooja simulator of Contiki OS[1] with the aim of evaluating the performance of the proposed solution against the existing 6TiSCH protocol stack. Furthermore, the performance results of several existing 6TiSCH resource scheduling mechanisms are analyzed using the proposed antenna model and their performances are compared to that of the proposed solution.

This paper presents the relevant background work in directional smart antennas and scheduling algorithms in Section 2. Section 3 briefly introduces IETF 6TiSCH protocol components. The proposed scheduling mechanism for 6TiSCH protocol and the directional antenna model for Cooja are outlined in Section 4. The evaluation of the directional antenna enabled scheduling mechanism is given in Section 5. Finally, Section 6 outlines the concluding remarks and possible future directions.

2. Related work

Neighbor nodes interfere each other when they broadcast simultaneously, so concurrent transmissions limits the capacity of wireless networks. Gupta and Kumar showed that the performance of a wireless network is inversely proportional to the node density when using omnidirectional antennas. It was shown that the per-node achievable throughput is upper-bounded by $\Theta(1/\sqrt{n \log n})$ in random networks and $\Theta(1/\sqrt{n})$ in arbitrary networks where n shows the number of nodes in the network [10]. According to [11], the capacity of a wireless

[1]Contiki: The Open Source OS for the Internet of Things [online]. Website http://www.contiki-os.org [accessed March 2019]

network can be improved by a factor of $2\pi/\sqrt{\alpha\beta}$ where α and β are the beam widths of the transmitter and receiver antennas, respectively.

The rapid development of radio communications and fabrication techniques led to the development of smaller and smarter antennas. Smart antennas can be roughly classified under the umbrella of switched beam, phased array, and digital beam-forming groups [5]. Mottola et al. studied the electronically-switched directional antennas in wireless sensor network by developing a prototype. It was shown that directional antenna brings significant performance gains as compared to an omnidirectional-antenna-based solution [12]. Voigt et al. proposed an efficient mechanism that selects the best antenna for communication with the neighbor node based on the received signal strength indicator (RSSI) value of the received packets for each antenna [13]. While using RSSI for selecting the correct antenna direction can create a high performance solution in a wireless network with line of sight communication paths, this observation may not hold when the propagation medium is not line of sight as discussed in [14].

Designing protocols around directional antennas have several challenges such as hidden terminal, deafness, and synchronization problems between the nodes. In particular, authors in [15] provide quantitative evidence that directional antennas can have severe limitations in networks having tree-based topology, which is the case for 6TiSCH networks using RPL routing protocol. Authors point out that the core challenge in such topology arise from the hidden terminal problem. Of course, 6TiSCH have a unique advantage in the sense that it aims to create a collision-free topology. Furthermore, the protocol capabilities of 6TiSCH is extended in this study to make an informed decision about the direction of the traffic to avoid the hidden terminal problem. Nur et al. addressed the aforementioned problems and developed a directional MAC, that benefits from spatial reusability and increased coverage of the antenna. Directional MAC achieves better throughput and increased network lifetime compared to existing protocols that has no directional awareness [16]. There exists many studies about directional antennas in the literature. However, the integration of switched-beam antennas with energy-efficient, multichannel, and synchronized MAC protocols for IoT networks has not been adequately explored yet [17].

Several centralized and distributed scheduling algorithms have been proposed recently for 6TiSCH [18]. 6TiSCH minimal configuration relies on shared cells common to all nodes in the network and the radio traffic of the entire network is carried over the cells using the same frequency channel [19]. Orchestra is an autonomous scheduling mechanism where each node builds its own schedule without any negotiation with their neighbors or a central entity. Neighbor nodes schedule cells between one another according to a hash function depending on the MAC address of the nodes. Main drawback of Orchestra is that it does not consider the need that each node may have different bandwidth requirements [20]. Minimal scheduling function (MSF)[2] is another distributed mechanism proposed by IETF 6TiSCH working group. It defines a bandwidth estimation algorithm that decides how many cells should be allocated for each neighbor node. In MSF, cells are selected randomly among the ones not used by the neighbors. Therefore, collisions may happen due to the fact that nonneighbor nodes may schedule the same cell with the same channel offset [7]. In this case, the colliding cells can be detected and relocated if an appropriate cell relocation mechanism is defined. Collisions due to incorrect frequency offset selection can become a challenging problem especially in networks with a limited pool of frequency resources. On the other hand, using directional antennas to create another dimension of freedom can greatly reduce such collisions and improve network performance as highlighted in this study.

Energy efficiency is a fundamental design goal for every IoT protocol solution. 6TiSCH is, by design, an

[2]IETF, 6TiSCH Minimal scheduling function (MSF) [online]. Website https://tools.ietf.org/html/draft-chang-6tisch-msf-02 [accessed March 2019]

energy-efficient protocol and a promising candidate for the future IoT networks requiring high reliability and low-power consumption [21]. All the nodes in 6TiSCH network must be synchronized in order to communicate with each other. This approach enables the nodes to keep their radios on for a short time minimizing the energy consumption during the idle listening. Packets are sent over different channels for successive transmissions mitigating the negative impact of external interference and multipath fading on the communicating pairs enabling highly reliable links [22].

Using a simulation tool which can accurately emulate an IoT hardware comes with several advantages such as ease of development and debug, and setting up different network topologies containing different number of nodes and assessing the performance of such a system for different propagation environments. While the directional antenna research is a mature research area, there are not many studies on bringing a directional antenna model to a platform such as Cooja simulator. Only, Rege showed that a directional antenna model can be integrated to Cooja; however, in that study, motes were equipped with only one antenna interface and tests were run by setting the orientation of the interface manually [23].

3. A brief introduction to 6TiSCH protocol

This section briefly introduces IETF 6TiSCH protocol stack and describes the protocol components that are used for enabling slot-based communications. The main goal of IETF 6TiSCH protocol is to enable IPv6 routing over IEEE 802.15.4e TSCH mode[3]. 6TiSCH develops on 6LowPAN protocol which enables IPv6 routing over 802.15.4 physical layer [24]. 6LowPAN protocol stack can run on top of a TSCH MAC with a few modifications. The most obvious difference between traditional low-power MACs and a TSCH MAC is that TSCH requires scheduled access to the wireless medium. While TSCH defines the mechanisms to execute a communication schedule, it is the responsibility of a scheduling entity to allocate resources between communicating pairs of nodes and establish routes within the network.

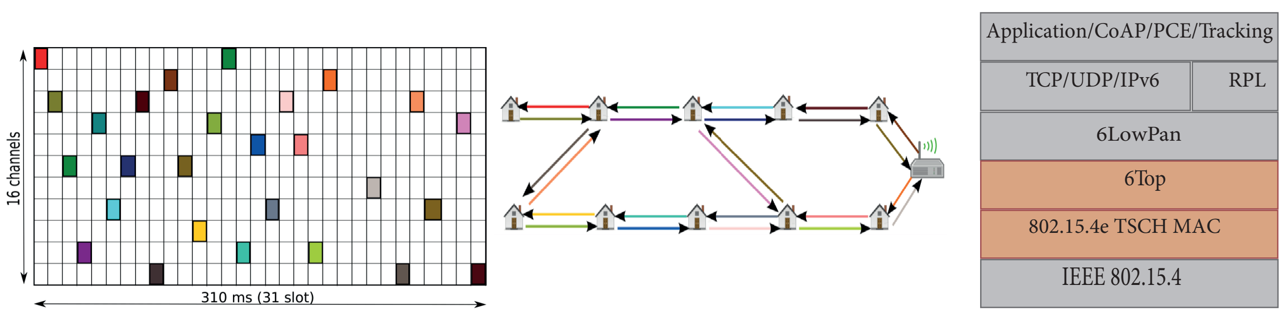


Figure 1. a) An example 6TISCH schedule using 16 802.15.4 channel at 2.4 GHz ISM band. b) An example of 6TISCH schedule and 6TISCH protocol stack.

An example communication schedule is given in Figure 1a. As it can be seen from the figure, the schedule is designed to have 31 cells[4]. In this instance, the 310-ms period is called slot frame (SF) where each cell is 10 ms. The schedule repeats itself over each SF. The node pairs use a scheduling entity to allocate resources for communicating with each other. The local cells should be allocated in a way that neighboring nodes do not cause interference to each other during the communication. On the other hand, the nodes sufficiently far apart can reuse the same cell with the same channel offset for communicating simultaneously.

[3]IEEE 802.15 WPAN 4e Task Group [online]. Website http://www.ieee802.org/15/pub/TG4e.html [accessed March 2019]
[4]A cell can be defined as the unit entity that can be scheduled between communicating node pairs.

The scheduling mechanism of a 6TiSCH network can be implemented using a centralized approach where all the nodes request cells from a central entity upon joining. While creating a centralized scheduler may ascertain an optimum allocation of the resources to the entire network, it may not scale well due to messaging overhead. On the other hand, a distributed scheduler can be used to alleviate the scalability challenge where pairs of nodes negotiate resources between each other taking their neighbor's resource allocation information into account. This approach guarantees a scalable network, but may suffer from cochannel interference due to locally optimal scheduling decisions.

6TiSCH makes use of a distributed scheduling entity named as 6Top. 6Top entity is located in between the 6LowPAN and 802.15.4e TSCH MAC layer as shown in Figure 1b. 6Top layer is responsible for allocating resource to communicating node pairs. 6Top entity makes use of different scheduling algorithms optimized for a given scenario. Hence, the standard does not impose a scheduling mechanism. 6Top also can differentiate between traffic types paving the way for service quality of service (QoS) mechanisms. Furthermore, the 6Top layer can forward traffic between pairs without the help of routing layer since the schedule between the nodes explicitly creates a flow from the source to destination node named tracks.

The network-wide synchronization is achieved by the 802.15.4e TSCH MAC via enhanced beacon (EB) frames. EB frames are transmitted in predefined slots (i.e. hard slots). Each EB contains necessary information for the joining node to learn the hard slots, SF size, slot duration, and channel hopping pattern. The 6TiSCH protocol specification does not impose a limit on the SF duration. Longer SF duration reduces the energy consumption, while smaller SF duration reduces the network delay. EB also contains a 5-B counter shared by the entire network to keep track of the current slot which is used for calculating the channel of the current slot.

4. System model

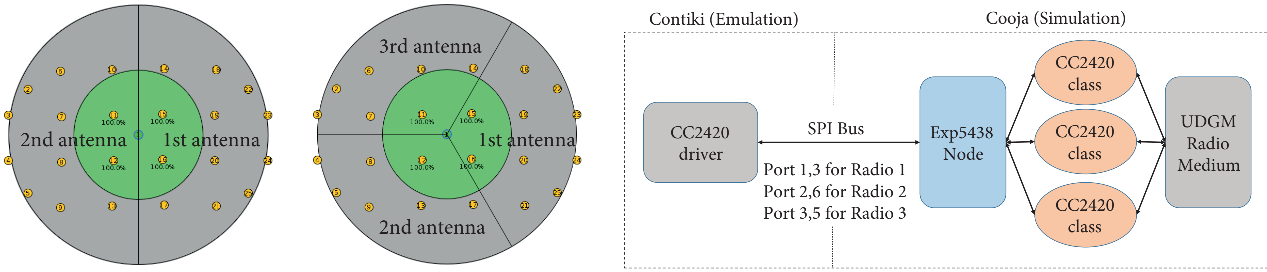
Cooja simulator of Contiki OS has been modified extensively to enable the implementation and testing of the proposed space time 6TiSCH scheduling mechanism. In addition to Cooja simulator modifications, physical, MAC, and scheduling layers of the protocol stack have been modified. These modifications enabled us to incorporate necessary functions for transmitting and receiving data frames in a desired direction using the Cooja directional antenna model. Here, the proposed antenna model is described and the space time scheduling approach, which takes not only time and frequency but also direction information into account, is introduced.

4.1. Cooja extensions

This section introduces the switchable directional antenna model for Cooja which can emulate networks consisting of various emulated hardware. The extension enables the Texas Instruments exp5438 platform to make use of multiple antennas pointing to different nonoverlapping directions as given in Figure 2a.

During the implementation, radio, radio medium, and simulated hardware modules of Cooja are modified. An extra interface, namely direction, representing the direction and beam width of the antenna is added to the simulation model. Cooja does not normally support having multiple radios on a single hardware platform. This feature is implemented by extending the EXP430F5438 platform class. Three new radio interfaces are added to EXP430F5438 platform by extending Cooja radio module. The extension allows integrating multiple interfaces into the same platform and all of them can be simulated in the same radio medium as shown in Figure 2b. Of course, in a real-life scenario each directional antenna will be connected to a single radio via an RF switch.

Unit disk graph medium (UDGM) with distance loss is used for the channel model where nodes communicate and interfere in fixed radius circles. This model reduces the received power at the destination according



(a) Simulated network topology and radiation patterns

(b) Architecture of multi-antenna modeling

Figure 2. Cooja modifications.

to free space path loss model [25]. The radio medium assumes that each device is equipped with only one antenna by default, so the UDGM module of Cooja is modified to support multiple directional antennas. The existing UDGM implementation of Cooja makes use of two distance parameters. Transmit range parameter is used to decide whether two nodes are within the communication range, and interference range parameter is used for defining area in which a node interferes with others. The newly introduced radio medium not only makes use of the transmit and interference ranges but also the direction of the transmission which also affects the successful reception of the transmitted packet. Direction of the transmission is calculated using the relative coordinates between the two nodes. In Figure 2a, the green circle represents the transmission range of node 1 and gray circle represents the interference zone of the same node for all of the antennas. Naturally, during a scheduled unicast transmission, only one of these antennas will be active limiting the interference zone. This enables two communicating pairs of nodes to schedule the same time slot with the same frequency channel by taking advantage of space time separation brought forward by the use of directional antennas.

In this study, TI EXP430F5438[5] platform is chosen for the evaluation of the proposed algorithms. This platform comes with a TI MSP430f5437 MCU with a low-power cc2420[6] radio transceiver. Existing cc2420 physical layer module is extended in Contiki OS to handle extra radio interfaces. These radio interfaces are used to emulate the behavior of switchable directional antennas. The communication between the emulated hardware and the Cooja radio modules is established via I/O ports using Serial Peripheral Interface (SPI) communication protocol. Additional SPI ports are allocated for the secondary and tertiary radio interfaces in Cooja as given in Figure 2b. These new interfaces support two-way data transfer and handling interrupts when the mote receives the signal over any directional interface. The direction information is added to cc2420 driver module to enable MAC protocol to listen to a given direction at the given time. The direction information of the received packet is passed to the upper layers so that 6TiSCH protocol can make an informed decision on scheduling resources in a nonconflicting manner. In the protocol stack, the direction information is stored in the neighbor table of the MAC layer so that nodes can send a unicast message in a predefined direction over the correct antenna. Of course, the space time resource scheduling algorithms also make use of this information to allocate resources between communicating pairs.

[5]MSP430F5438 experimenter board [online]. Website http://www.ti.com/tool/MSP-EXP430F5438 [accessed March 2019]
[6]CC2420 radio [online]. Website http://www.ti.com/product/cc2420 [accessed March 2019]

4.2. Distributed 6TiSCH scheduling

A node running a distributed 6TiSCH scheduler collects the schedule information of its neighbors during the cell allocation process. This step aims to improve the network performance by finding nonoverlapping cells in neighboring nodes. This enables orthogonal resource allocation in time and frequency domain. Distributed scheduling functions generally perform the following resource management functions:

(1) Add a transmit/receive cell to neighbor depending on a trigger function that uses statistical information about the data traffic (buffer occupancy). (2) Delete a transmit/receive cell to neighbor. Delete operation can make use of statistical information such as the queue size to a particular destination. (3) Relocate a cell to another channel offset. Trigger for relocation can be configured as the expected transmission count for the cell. The goal of any 6TiSCH scheduling function is to utilize bandwidth resources for a predefined objective toward a particular destination.

For each content added to the MAC buffer of a source node, the traffic event of the scheduling functions which calculates statistics for the scheduled cells is triggered. A new cell allocation is triggered when the traffic demand for a destination cannot be served by the existing resource blocks. To allocate a cell, the node requiring extra resource makes a request from the destination node with a list of free cells and the number of required cells, and then destination node sends a positive response if it has enough available resources. If there is an underutilized cell, it is removed from the schedule by invoking the relevant 6P command [7]. When a particular cell scheduled toward a destination performs poorly, the relocation event of 6Top protocol is triggered to change the channel offset of the underperforming cell.

4.3. Space time distributed 6TiSCH scheduling

4.3.1. Prerequisites

In this study, each low-power node is equipped with either two or three RF switchable directional antenna front-ends. The communication between the nodes is half-duplex, that is, nodes cannot transmit and receive simultaneously. A message can be transmitted over all antenna interfaces to all directions at the same time representing a multicast traffic pattern. The scheduler allocates resources in time, frequency and space domains taking neighbor statistics stored at TSCH MAC layer neighbor table into account.

Two example 6TiSCH schedules representing the schedules created by the traditional and proposed scheduling mechanisms separately where 9 nodes form a mesh network with Node 1 as the root node are given in Figure 3. Here the number of available frequency channels are assumed to be 2. The node pairs with sufficient space time distance can communicate simultaneously when the schedule resources consist of time slot, frequency channel, and antenna offset values. The extra dimension created by directional antennas can be utilized to allocate resources with minimal collisions when the number of frequency channels available for communication is limited (e.g., 868 MHz band has a limited number of channels that can be utilized in Europe). It can be seen from the figure that the nodes in the network can transmit 1 data packet to the root node with a minimum schedule size of 10 slots when they are equipped with omnidirectional antennas. On the other hand, the second schedule takes advantage of directional antenna communications and can deliver the same number of packets to the root node using only 8 time slots. The reason for this is the fact that a significant number of parallel transmissions can be utilized with space time scheduling as compared to a network with omnidirectional antennas.

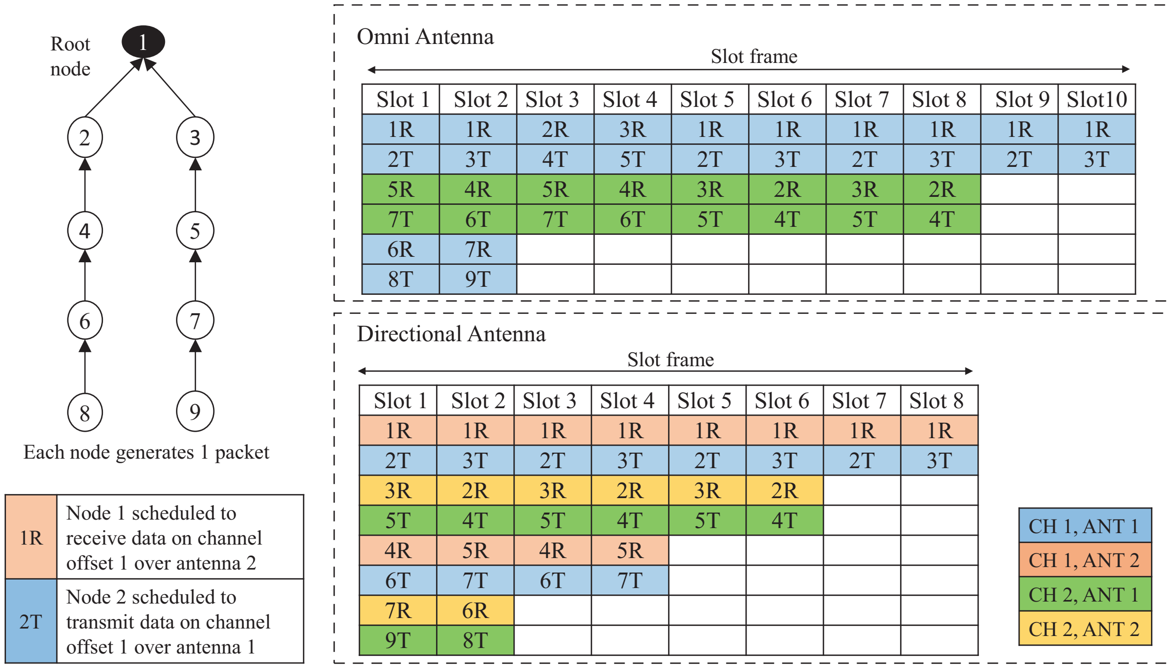


Figure 3. Omni vs directional antenna aware scheduling.

4.3.2. Protocol stack extensions

In order to enable the proposed space time scheduling mechanism, 6Top, MAC, and PHY layers of the 6TiSCH protocol stack are modified. In the proposed system, the multicast messages need to be sent over all of the antennas to enable efficient distribution of control information within the network. The unicast messages, on the other hand, can be sent via the antenna facing the destination node reducing interference within the network. To select the correct antenna toward the intended receiver, EB frames carry extra information about the arrival angle of the received frame. Upon receiving the EB frame, the receiving node updates The 6TiSCH neighbor table and registers the direction information[7]. Following this step, the scheduler allocates the resource cells represented by time slot, channel offset, and antenna direction triple. This process can be visualized with the help of the resource blocks given in Figure 3. When there is a scheduled packet in the MAC Layer's queue, the direction information is retrieved and passed to the Radio layer which, in turn, activates the correct antenna interface for the transmission of the frame.

In the standard 6TiSCH solution, cell statistics are regularly updated to make accurate resource allocation, deallocation, and relocation decisions. On the other hand, for the directional antenna solution presented here, the cell statistics should be calculated on per-antenna basis rather than per-cell basis to accurately estimate different channel characteristics experienced by each antenna. The reason for this is the fact that antennas facing different directions may experience different channel characteristics depending on external factors such as cochannel and adjacent channel interference. As a result, nodes at the center of the network can benefit from an extra dimension of freedom when scheduling their bandwidth resources. With the help of this extra dimension, the resource allocation can be made by looking at the best combination provided by antenna, time,

[7]Here, it is assumed that the arrival angle of the frame can be accurately estimated.

and frequency channel set.

In a realistic setup, a low-cost antenna solution similar to the one presented in [26] can be utilized. Algorithm 1 outlines the selection of the antenna tuple when space time distributed scheduling function is used. In this case, the selection of the antenna depends on the neighbor direction, transmit slot type, and packet destination (unicast or multicast). Algorithm 2 gives the overall slot allocation process for proposed solution.

Algorithm 1 SF-DA behavior

```
for each slot ∈ slotframe do
    ret ← get scheduled packet(slot)
    if ret = UNSCHEDULED then
        wait for the next slot
    else if ret = SCHEDULED then
        if slot_type = SHARED then
            if content_buffer = ∅ then
                pkt ← listen from all antennas
                if pkt ≠ ∅ then
                    process pkt
                    update neighbour list(dst, ant)
            else
                transmit pkt over all antennas
        if slot_type = TRANSMIT then
            if content_buffer = ∅ then
                wait for the next slot
            else
                if pkt.dst = BROADCAST then
                    transmit pkt over all antennas
                else
                    offset ← get antenna(pkt.dst)
                    transmit pkt over antenna[offset]
        if slot_type = RECEIVE then
            offset ← get antenna(pkt.dst)
            pkt ← listen from antenna[offset]
    update cell statistics
```

Algorithm 2 SF-DA Cell Allocation

```
Input: dst                                    ▷ keeps destination node
Input: cell_type                              ▷ cell can be Receive or Transmit
Output: available_cell                        ▷ cell contains slot, channel and antenna offsets
cell ← ∅                                      ▷ initialize available cell
p_cell_list ← Set of scheduled cells of parent
n_cell_list ← Set of scheduled cells of 1-hop neighbors
while threshold not reached do                ▷ until a cell found or a threshold value reached
    cell.slot ← random() % SLOTFRAME_LENGTH   ▷ find a random slot offset
    if cell.slot ≠ ∀p_cell_list.slot then     ▷ parent does not use this slot
        while threshold not reached do
            cell.channel ← random() % MAX_AVAILABLE_CHANNEL   ▷ find a random channel
            if cell.channel ∉ failed_channel_list then        ▷ channel statistics are good
                found_a_cell ← true
                for each c ∈ n_cell_list do
                    if cell.slot = c.slot then                ▷ a cell with the same slot offset
                        if cell.channel = c.channel then      ▷ a cell with the same channel offset
                            if dst.antenna = c.antenna & cell_type ≠ c.type then   ▷ if two antennas face each other, when one is in receive mode the other can not be in transmit mode
                                found_a_cell ← false
                            else if cell_type = c.type & dst.antenna ≠ c.antenna then   ▷ if two cells are scheduled for the same mode, antennas should not face each other
                                found_a_cell ← false
                if found_a_cell then
                    return available_cell
return null
```

5. Results and discussion

The developed smart antenna model is initially tested with 6TiSCH Minimal Configuration[8] and Orchestra resource scheduling implementations of Contiki OS for having omnidirectional and two and three directional antennas, respectively. Following these initial tests, the proposed directional antenna aware 6TiSCH scheduling mechanisms (SF-DA) are tested for both omnidirectional and smart switchable antenna models. To enable a meaningful comparison of the 6TiSCH scheduling mechanisms, a grid network topology is created to evaluate the developed mechanisms. The network setup is given in Figure 2a. The network consists of 25 nodes within a 200 $\times$ 150 m area, one of which (node 1) is configured as RPL[27] root located at the center of the evaluated network and the rest of the nodes are located horizontally and vertically at equal distances from each other. The nodes are configured to have either two directional antennas with the beam width of 180° or three directional antennas with the beam-width of 120°.

The physical layer is based on the IEEE 802.15.4 PHY, MAC and 6Top layers are implemented by us following IEEE 802.15.4-e TSCH and IETF 6TiSCH standards, respectively. Packet receive ratio (PRR), energy consumption, and end-to-end latency metrics are used for the evaluation. PRR is calculated as the ratio of the successfully received packets to total transmitted packets during the test duration, and end-to-end latency is measured as the time elapsed between the transmission of a packet from the source node and its reception at the root node. Detailed configuration settings for all tests are given in Table 1.

Table 1. Test parameters.

Parameter	Value
Min back-off exponent	1
Max back-off exponent	7
Back-off increment	2
Retransmission count	5

Parameter	Value
Frame size	127 byte
Buffer depth	5
Timeslot duration	15 ms
Slotframe length	15

Parameter	Value
Transmit range	50 m
Interference range	100 m
Node distance	40 m
Test duration	2 h

The simulation is based on a data collection application where nodes periodically sends "Hello" messages to the root node. This scenario generates a converge-cast communication that causes congestion around the root node. The PRR results of SF-DA algorithm are analyzed by increasing the network traffic. When the packet generation frequency is increased, this creates a saturated traffic within the 6TiSCH network. In this case, it is expected that collisions due to improper selection of channel offsets by the distributed scheduling algorithms becomes dominant. On the other hand, the delay experienced in the 6TiSCH network will increase rapidly with the increased traffic in the network due to nodes having to buffer the traffic prior to transmission.

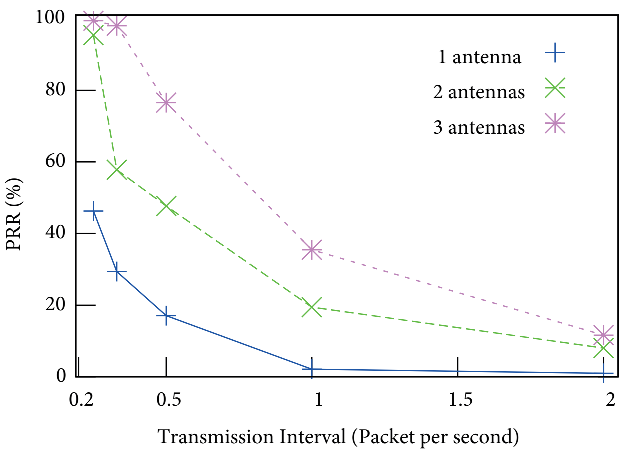
6TiSCH Minimal and Orchestra scheduling mechanisms use only shared channels to communicate; hence, the collisions within the network are expected to be high. As a result, most of the packets are dropped within the network leading to a low PRR as shown in Figures 4a and 4b. For these scheduling approaches, the MAC layer is modified to enable sending of the data towards the intended receiver by turning on the correct directional antenna. The main aim behind these tests is to highlight the impact of having directional antenna communication for shared slots. This approach is expected to significantly reduce the interference for the shared slot communications. Here, the transmitting node transmits using the correct antenna towards the destination. However, the interference suppression capabilities of these approaches are quite limited due to the fact that the receiving nodes listen to the channel omnidirectionally turning on all of the directional antennas. Directional antenna aware 6TiSCH scheduling function, on the other hand, is a distributed scheduling algorithm which can

[8]This configuration uses shared cells to enable communication in a slotted-Aloha like slot allocation approach.

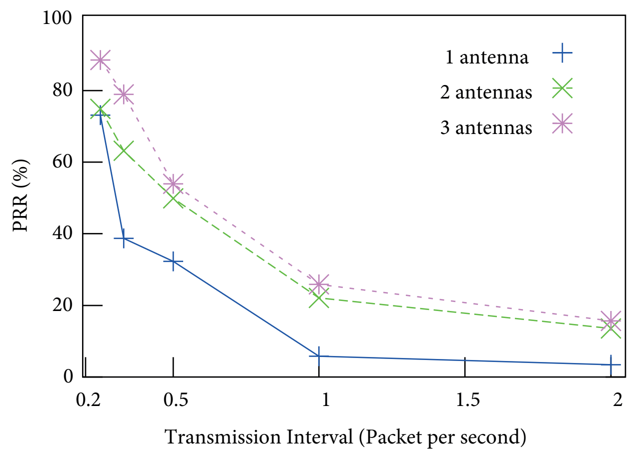
listen and transmit on the correct antenna making use of the information stored in 6TiSCH neighbor table. In this case, the receiving device will listen to the incoming traffic by turning on the correct antenna. This is achieved by retrieving schedule information stored in the nodes scheduling table. This makes the approach resilient against in-network interference.

5.1. 6TiSCH minimal configuration

In the minimal configuration tests, only one slot frame is created with three slots. The first slot is configured as a shared slot. All of the nodes communicate with each other in this time slot using the same frequency channel as specified in [23]. The results, given in Figure 4a, show that use of directional antennas increases the PRR significantly compared with scenarios using omnidirectional antennas for the same traffic requirements. As the number of the antennas increases, higher PRR values are observed. The reason for this is narrow antenna beam-width provides higher spatial separation. This, in turn, increases the average PRR by 2-3 times depending on the data transmission rate.



(a) Minimal Configuration



(b) Orchestra Scheduling

Figure 4. PRR Comparison of minimal configuration and Orchestra scheduling algorithms.

5.2. Orchestra scheduling

In the Orchestra scheduling tests, three slot frames are created. The length of the MAC slot frame to send the TSCH beacons is set to 31, the length of the routing slot frame to send RPL messages is set to 13, and the length of the application slot frame to send data packets is set to 5 that is smaller than the network size. Note that for this scheduling approach, the application slot frame length must be set to a value greater than the network size to ensure contention-free transmission. However, this parameter setup is chosen to compare the qualitative performance of the analyzed scheduling mechanisms under heavy loads with limited resources. In case slots from different slot frames overlap, the slot in the highest priority slot frame takes precedence. While MAC slot frame has the highest priority, application slot frame has the lowest priority.

The results, given in Figure 4b, are similar with the those of the minimal configuration tests, use of directional antennas significantly increases the network performance under heavy loads. Again, the results here present the relative improvements achieved by making use of directional antennas for each 6TiSCH scheduling approaches. It again proves that the 6TiSCH network performance can be improved by smart directional antennas. The performance results for each scheduling approach are given separately due to inherently different scheduling approaches. However, each scheduling function can benefit from directional antennas even if the scheduling mechanism does not explicitly make use of the smart directional antennas.

5.3. Space time scheduling for 6TiSCH

In the space time scheduling tests, only one slot frame consisting of 15 slots is created, and the first slot is configured as a shared slot. Tests are run at different data rates for different frequency hopping sequences over a subset of available IEEE 802.15.4 frequency channels. Naturally, having a large number of available frequency channels can improve the network performance. However, it is also true that most of the 802.15.4 channels suffer from WiFi interference and hence limit the number of interference-free channels for 6TiSCH. Furthermore, there can be a significant in-network interference especially for shared slot communication as highlighted in Figure 5. For the tests presented in this section, only SF-DA results for various antenna configurations are given where 1 antenna results represents the standard 6TiSCH Scheduling function (SF0) performance as a baseline.

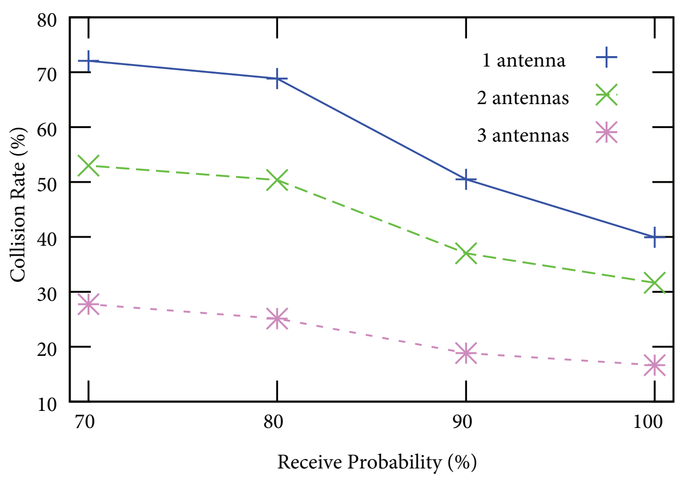


Figure 5. Shared slot collisions of SF-DA for different antenna configurations.

Figures 6a and 6b present the PRR results with 100% and 80% receive probabilities at the receiver side, respectively. The 80% receive probability only happens when the communicating pairs of nodes are at maximum distance from each other and this probability increases with decreasing inter-node distances according to Cooja simulators free space path loss model [25]. General trends in the figures show that using directional antennas in a 6TiSCH network can bring about PRR performance increases of up to 100% for the evaluated network scenario. As expected, when the number of available frequency channels are limited, the extra spatial dimension enabled by the directional antennas can provide a significant improvement in PRR results. On the other hand, when the available frequency channels are greater than 8, using directional antenna does not provide a significant performance improvement for the evaluated network topology. Therefore, directional antennas may not improve the 6TiSCH performance in low interference and sparse networks. However, it is possible to improve 6TiSCH network performance significantly using the proposed scheduling function under heavy traffic regimes with limited frequency channel resources. In the simulations, SF-DA performance improves with the increasing number of directional antennas as shown in Figure 6a. Moreover, it can be seen in 6b that as the channel quality deteriorates, the impact of the directional antennas on the network performance becomes pronounced. This is due to fact that retransmissions due to packet drops increase the network traffic resulting in elevated collisions. Our solution also achieves lower latency results as given in Figure 7a, where the mean delay of the evaluated network is given.

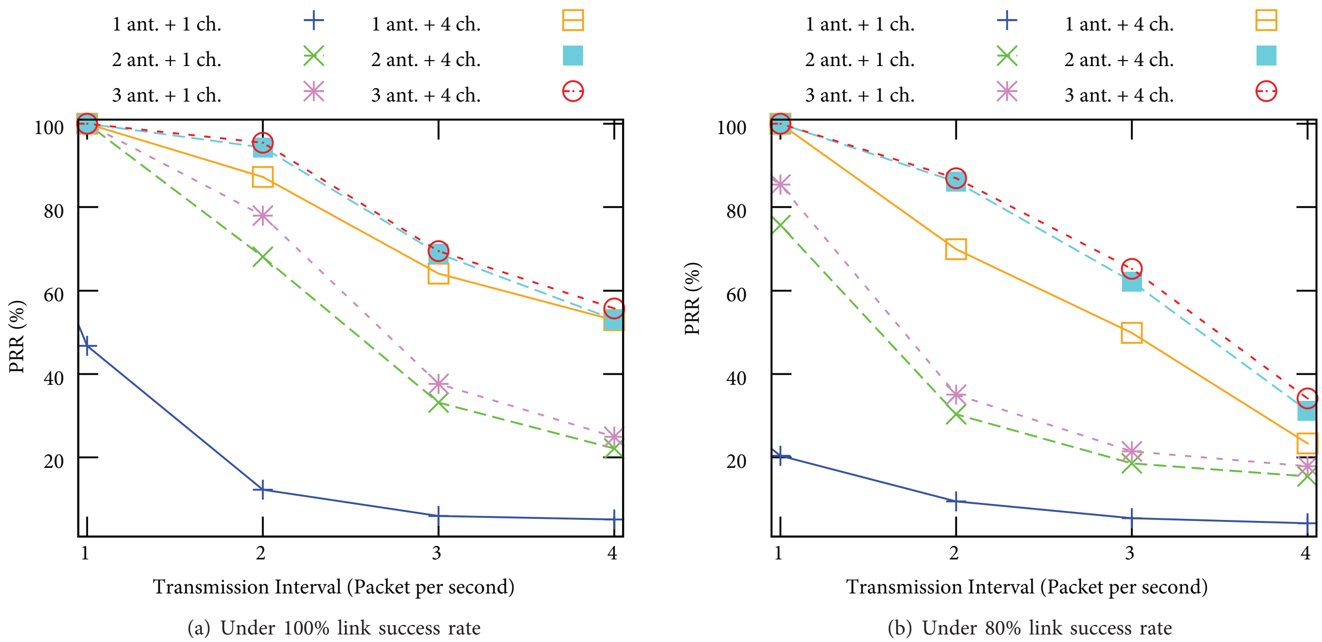


Figure 6. PRR comparison of SF-DA for different antenna configurations and count of available frequency channels

It is assumed that the energy required by a transmitter using a directional antenna is proportional to its beam-width[28]. Therefore, a directional antenna with 180° beam-width requires half of the transmit power as compared to an omnidirectional antenna to reach the same distance. The average energy consumption has been calculated by considering the energy used by the microcontroller in active and sleep modes, and the energy consumed by the radio in the receive and transmit modes. MSP430F5438 microcontroller consumes 2.5 mA in active mode and 0.5 μA in low-power mode and the cc2420 radio chip consumes 17.4 mA in TX mode and 18.8 mA in RX mode [29]. Using directional antenna provides significant savings in the average energy consumption as observed in Figure 7b. The energy saving becomes more pronounced in the poor communication channels as seen in Figure 7b. This is due to fact that collisions due to increased transmissions have a reduced impact on the network with directional antennas.

The size of the network is also an important factor impacting the performance. Hence, several tests are run for different network sizes evaluating PRR, delay, and energy consumption metrics. In these simulations, nodes are placed in a grid where internode distances are set to 40 m. In addition, the number of available frequency channels are set to 4 and the link success rate is set to 100% and it is assumed that each node generates 1 packet per second. The rest of the parameters are the same as the parameters given in Table 1.

Table 2 presents the performance results of the simulations. As the number of nodes in the network increases, the PRR value decreases due to packet having to travel longer hop distances. On the other hand, the delay in the network and the average energy consumption of the network increase with the increasing number of nodes in the network. The PRR performance of the evaluated scenarios improve around 5% to 10% with 3 directional antennas as opposed to scenarios with omnidirectional antennas. On the other hand, there is around 50% decrease in the average network delay. The same trend is observed for the energy consumption of the nodes using 3 directional antennas as given in the Table 2. These results show that many of the key performance metrics of an IoT network can be significantly improved using a low-complexity switchable antenna system in

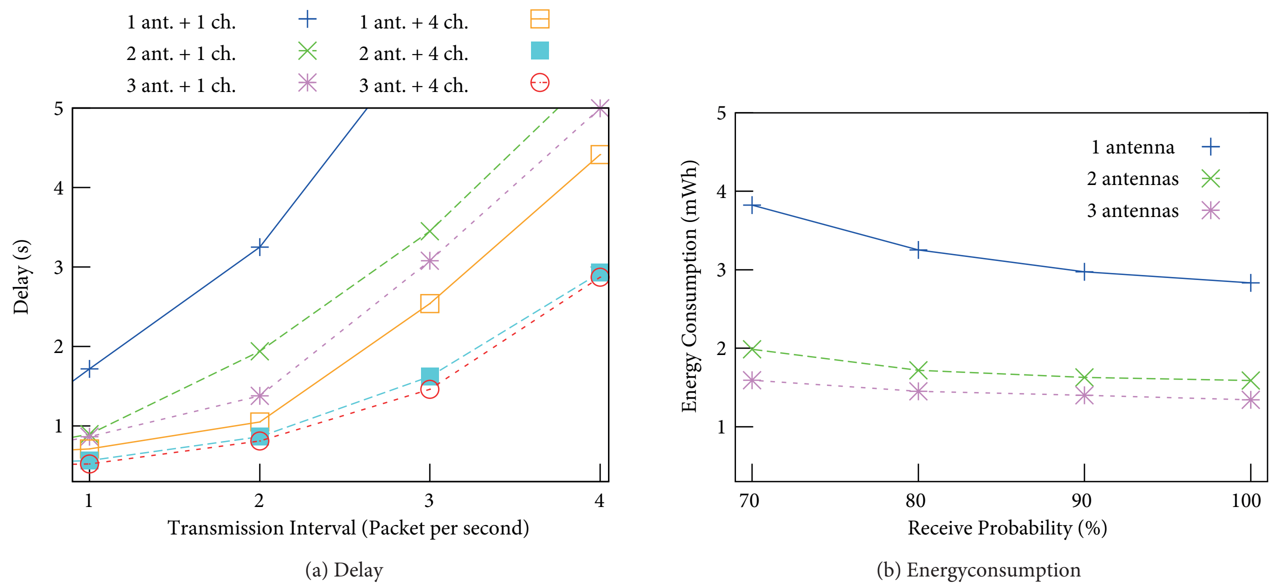


Figure 7. Delay and energy consumption of SF-DA for different antenna configurations.

IoT devices.

Table 2. The comparison of PRR, delay, and energy consumption according to network size.

Number of nodes	1 directional antenna			2 directional antennas			3 directional antennas		
	PRR (%)	Delay (ms)	Energy cons.(mWh)	PRR (%)	Delay (ms)	Energy cons.(mWh)	PRR (%)	Delay (ms)	Energy cons.(mWh)
25	94.87	1267	3.21	97.94	595	1.55	100	536	1.26
49	83.55	1560	3.65	87.61	1174	1.82	88.77	1094	1.49
73	61.04	2254	4.09	63.49	1594	1.89	66.74	1544	1.65
101	39.13	3145	5.08	42.17	2324	2.31	44.06	1793	1.77

The results in this work show that using directional antennas can significantly improve the performance of the 6TiSCH networks especially for the scenarios with limited frequency channels. Furthermore, 6TiSCH requires one or more shared slots to configure and maintain the network. The unicast control traffic transmitted over these shared slots can have a significant reliability advantage using directional antennas since they will be transmitted towards the intended destination reducing shared slot collisions.

6. Conclusions and future work

In this study, a directional antenna aware scheduling (SF-DA) mechanism for 6TiSCH networks is proposed and its performance is evaluated. The performance evaluations for 6TiSCH minimal configuration, Orchestra, and SF-DA indicate that using a simple RF-switchable smart antenna system can improve the network performance and reduce the end-to-end latency and energy consumption. Furthermore, the results show that performance of the 6TiSCH protocol can be significantly improved when the scheduling decisions are made using antenna direction information obtained from the smart antennas. The results of energy consumption and network delay experiments also show a similar trend. These promising results show that the extra dimension of freedom enabled by directional communication can pave the way forward for high performance and dependable IoT solutions.

As part of the future work, simulation results will be validated using a testbed consisting of nodes integrated with switchable and steerable smart antenna solutions. We will primarily focus on the network capacity improvement using smart 6TiSCH scheduling algorithms. Creating high-reliability and high-capacity industrial wireless IoT networks is the ultimate goal of this study.

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