KARADENIZ TECHNICAL UNIVERSITY

THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES • COMPUTER ENGINEERING GRADUATE PROGRAM

Analysis of Smart Antenna Based Scheduling Algorithms for IoT Networks

IoT Ağlar İçin Akıllı Anten Tabanlı Çizelgeleme Algoritmalarının İncelenmesi

PHD DEFENSE

Sercan KÜLCÜ
PhD Candidate

Supervisor
Assoc. Prof. Sedat GÖRMÜŞ

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AGENDA

What We'll Cover Today

01 — **Introduction, Motivation and Problem Statement**

Resource constraints in IoT networks

02 — **Smart and Directional Antennas**

Conceptual background and the 6TiSCH protocol stack

03 — **Switchable Antenna with Distributed Scheduling**

Chapter 4

04 — **Steerable Antenna with Distributed Scheduling**

Chapter 5

05 — **Steerable Antenna with Centralized Scheduling**

Chapter 6

06 — **Overall Evaluation, Conclusion and Future Work**

Summary of contributions

The Internet of Things and Resource Scarcity

The IETF 6TiSCH protocol stack uses time-slot and frequency-channel resources in a planned way to create **reliable, deterministic, low-power** wireless IoT networks.

- The 2.4 GHz ISM band is shared with Wi-Fi, Bluetooth and other IEEE 802.15.4 networks → frequency resources are limited
- Dense, high-traffic networks also face limited time-slot resources
- Omni-directional antennas share resources without exploiting the spatial dimension

THE IDEA

Spatial Reuse

If antennas with adjustable coverage are used, a third dimension — space — is added to scheduling, in addition to time and frequency.

Time × **Frequency** × **Space**

→ Higher packet delivery ratio
→ Lower end-to-end latency
→ Lower energy consumption

Types of Smart and Directional Antennas

Omni-directional antennas are exposed to signals (and interference) from every direction. Smart/directional antennas focus energy toward one direction, raising SINR, and can apply "nulling" toward interference sources.

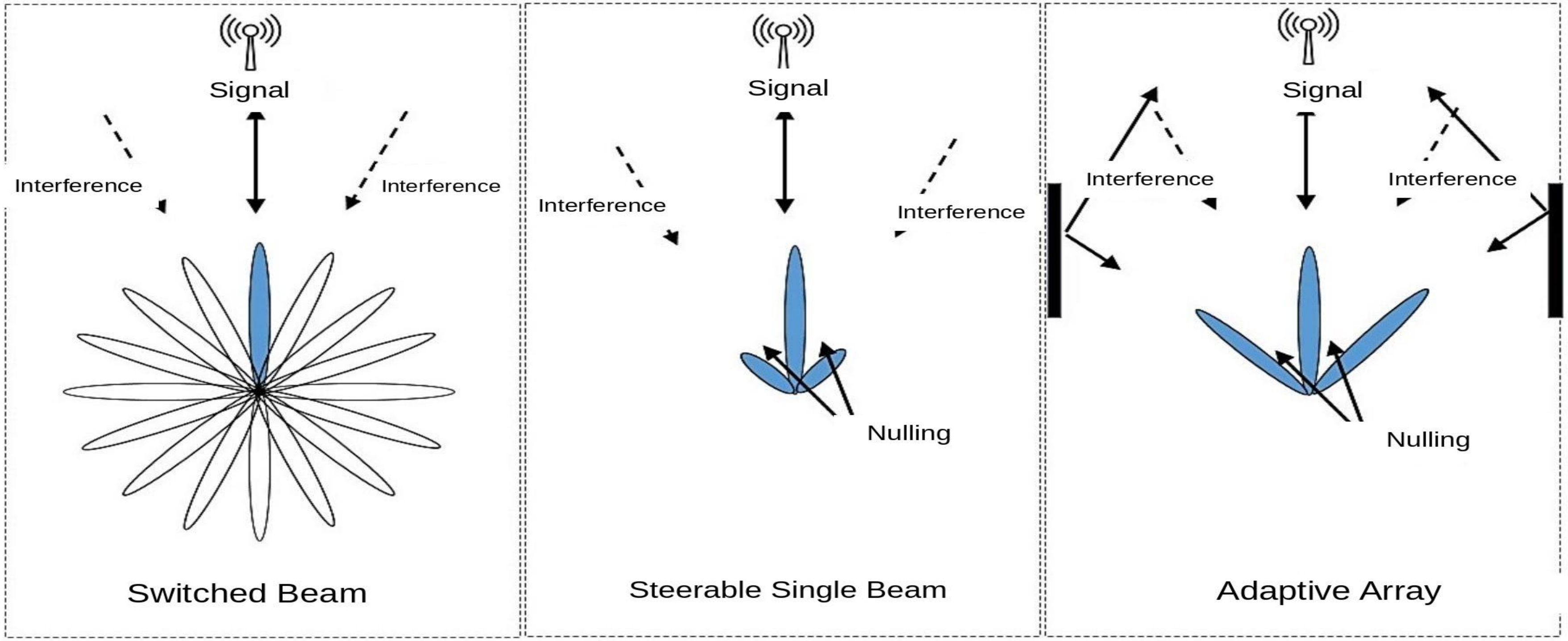


Figure: Switched Beam · Steerable Single Beam (Steerable Directional) · Adaptive Array (adapted from thesis Fig. 8)

Thesis Aim and Contributions to the Literature

Aim: To develop a low-complexity, smart/directional-antenna-based resource scheduling mechanism for IETF 6TiSCH networks that also exploits the spatial dimension.

1

Neighbor Discovery Mechanism

A novel method that lets nodes discover each other before they are synchronized to the network.

2

Best Antenna Direction Detection

A new method for finding the antenna direction that yields the maximum signal strength between neighboring nodes.

3

Two Hybrid Scheduling Algorithms

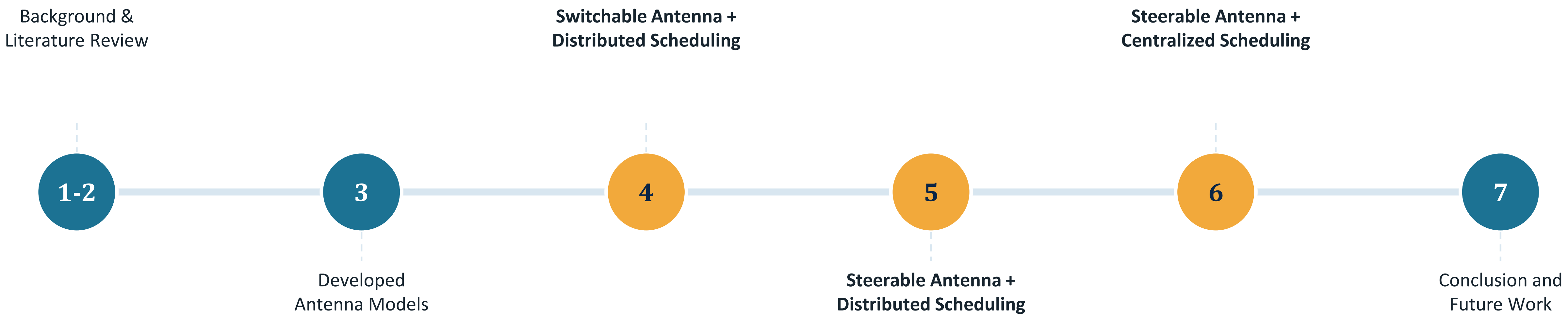
For healthy delivery of control and data packets: (i) distributed + autonomous, (ii) centralized + autonomous scheduling.

4

Antenna Models Added to COOJA

Integration of the switchable-beam and steerable-directional antenna models into the open-source COOJA simulator.

Structure of the Thesis



The rest of this talk focuses directly on the thesis's original contributions in Chapters 4, 5 and 6 (shown in gold).

The 6TiSCH Protocol Stack

On top of the IEEE 802.15.4 TSCH MAC layer sit routing (RPL), compression (6LoWPAN) and the 6top (6P) sublayer, which integrates the Scheduling Function with the upper layers.

CoAP	6LoWPAN ND	RPL
UDP	ICMPv6	
IPv6		
6LoWPAN HC	Scheduling Function	
6top (6P)		
IEEE 802.15.4 TSCH		

This thesis adds a spatial dimension to the Scheduling Function

Scheduling Approaches in 6TiSCH

A

Autonomous

Autonomous

Each node independently determines its own cells via a hash function of its ID/address. No signaling required; scalable.

D

Distributed

Distributed

Neighboring nodes negotiate cell allocation on the fly using the 6P protocol. Traffic-aware.

C

Centralized

Centralized

A node with full network topology knowledge (PCE) computes and distributes the entire schedule. Optimal, but limited scalability.

This thesis combines all three approaches in a hybrid fashion across chapters — with autonomous scheduling as the common foundation.

Two Developed Antenna Models

Switchable Beam Antenna

Anahtarlanabilir Huzme Anten

- One of several pre-defined fixed radiation patterns is selected
- Low hardware complexity
- Used together with distributed scheduling in Chapter 4

Steerable Directional Antenna

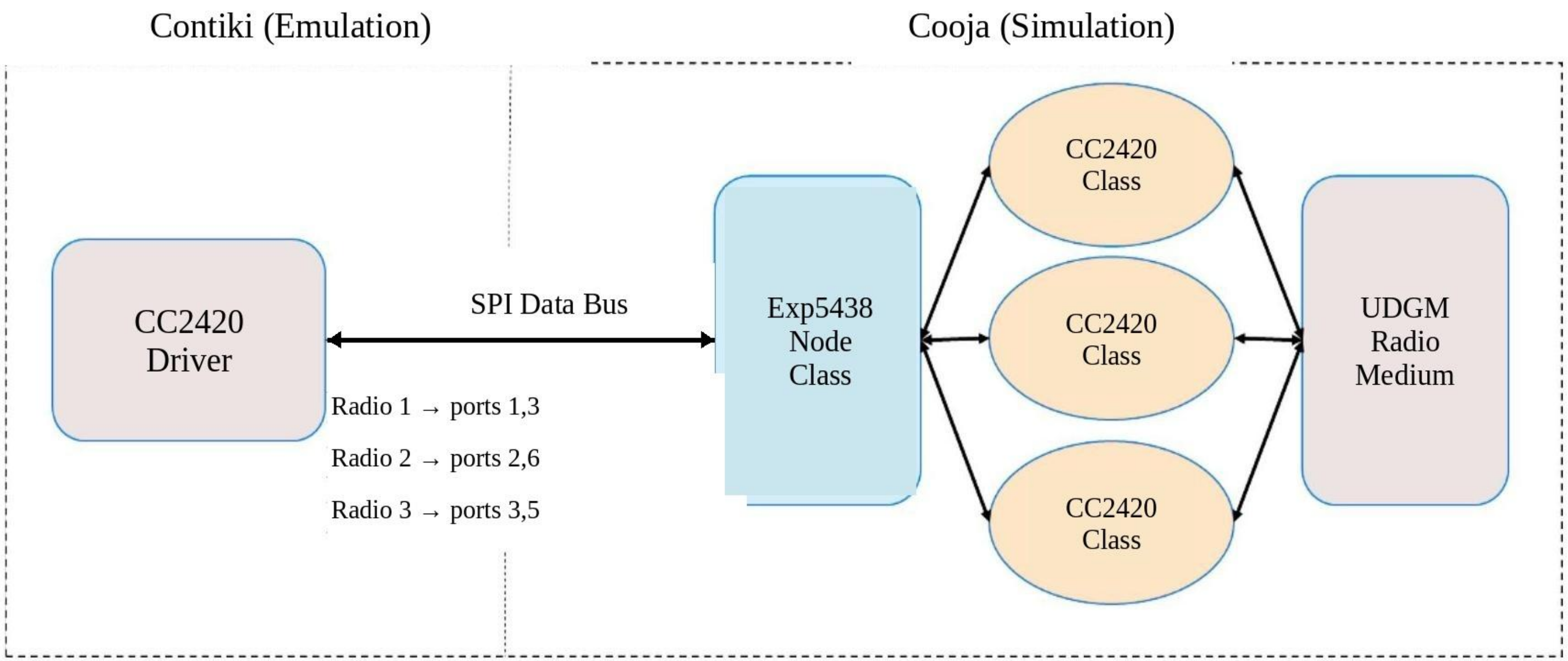
Döner Yönlü Anten

- The beam is steered toward the target, with "nulling" applied toward interference sources
- Higher SINR and range
- Used with both distributed and centralized scheduling in Chapters 5 and 6

Both models were added to the open-source COOJA network simulator and tested on Contiki OS.

Simulation Infrastructure: COOJA + Contiki

Platform: TI EXP430F5438 (MSP430F5437 MCU + CC2420 radio). COOJA's radio module was extended to manage multiple virtual antenna interfaces over SPI ports.



(adapted from thesis Fig. 13)

CHAPTER 4

Switchable Antenna with Distributed Scheduling

SF-DA: Directional-Antenna-Based Scheduling Function

- All antennas active on shared cells; only the correct antenna active on dedicated cells
- Compared against 6TiSCH Minimal Configuration and Orchestra

Space-Time Based Distributed Scheduling

On shared cells: all antenna directions are activated → guarantees communication with every neighbor

On dedicated cells: only the correct-direction antenna is activated → reduces interference and collisions

Result: collision rate on shared cells drops significantly, and network stability improves

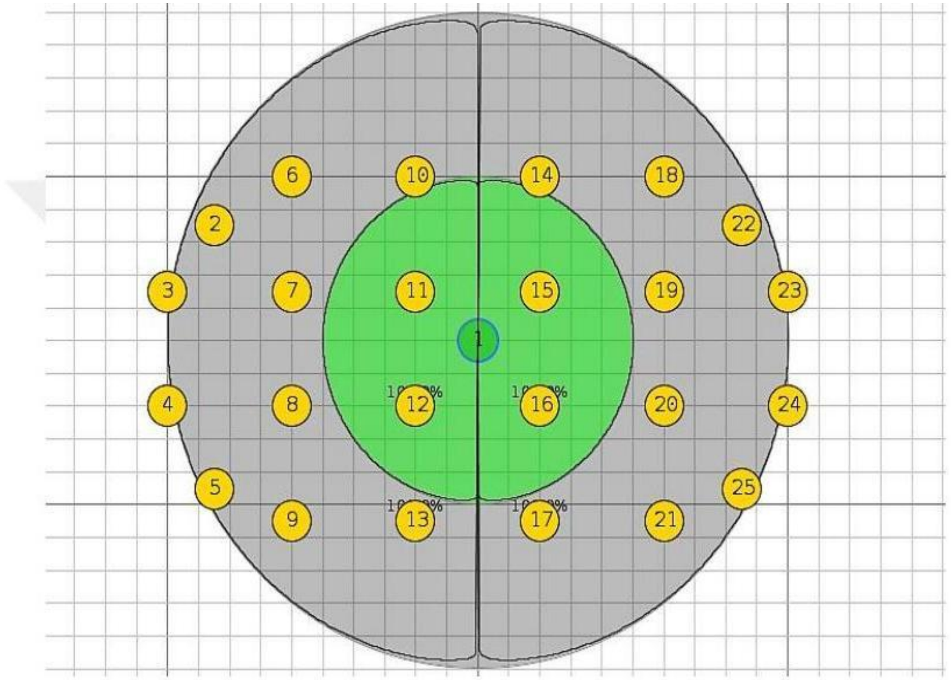
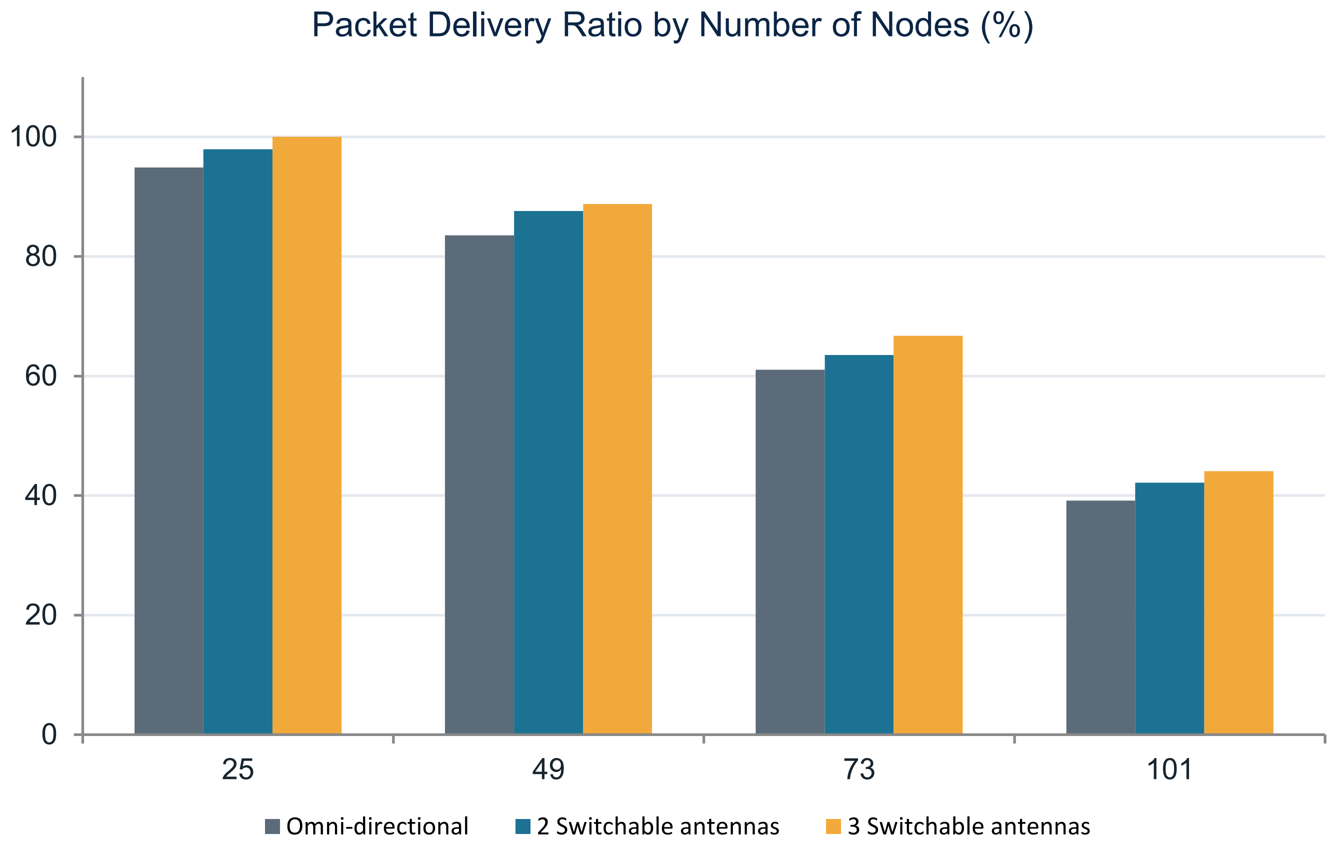


Fig. 18. Example network of 25 nodes (green: coverage area)

Packet Delivery Ratio vs. Number of Antennas



~10% PDR improvement (with directional antenna)

~50% Reduction in latency

~60% Reduction in energy consumption (25 nodes)

CHAPTER 5

Steerable Antenna with Distributed Scheduling

Solving the new challenges created by a narrow coverage area

- Problem: narrow beam → long synchronization time, delayed network formation
- Problem: broadcast control packets cannot reach all neighbors at once

A Hybrid Approach Supported by Autonomous Scheduling

Fake Beacon Packet

A new mechanism that lets nodes discover their neighbors before synchronizing to the network.

Broadcasting via Autonomous Cells

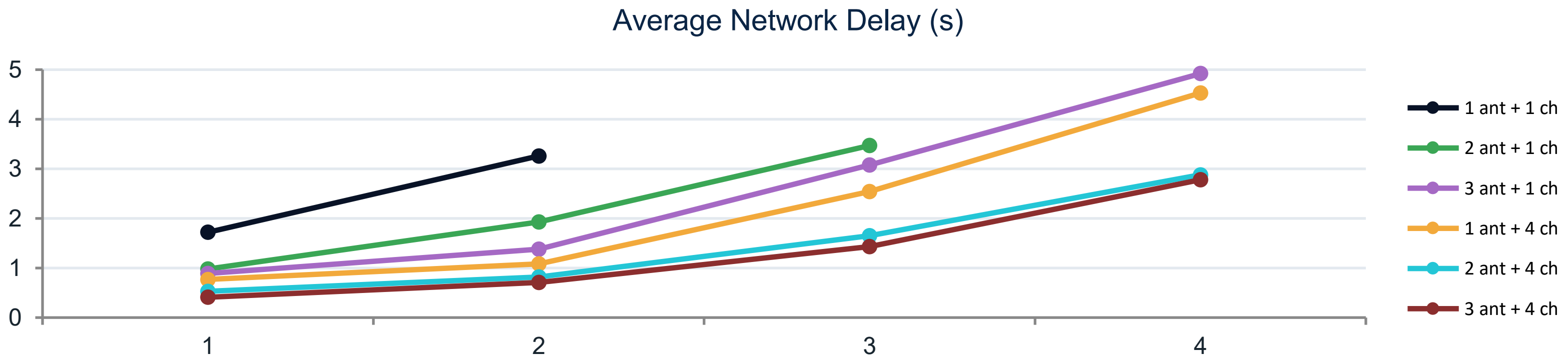
Broadcast packets are sent repeatedly over autonomously scheduled cells so they reach all neighbors.

Best Transmit Power / Direction Update

Tracking and updating over time the antenna direction giving maximum signal strength between node pairs.

Scalable Synchronization

Autonomous scheduling provides a synchronization time that is scalable and independent of network density.



Values read from thesis Fig. 26

Result

Clear improvement in network performance metrics over omni-directional antennas; autonomous scheduling solves the synchronization problem in a scalable way.

CHAPTER 6

Steerable Antenna with Centralized Scheduling

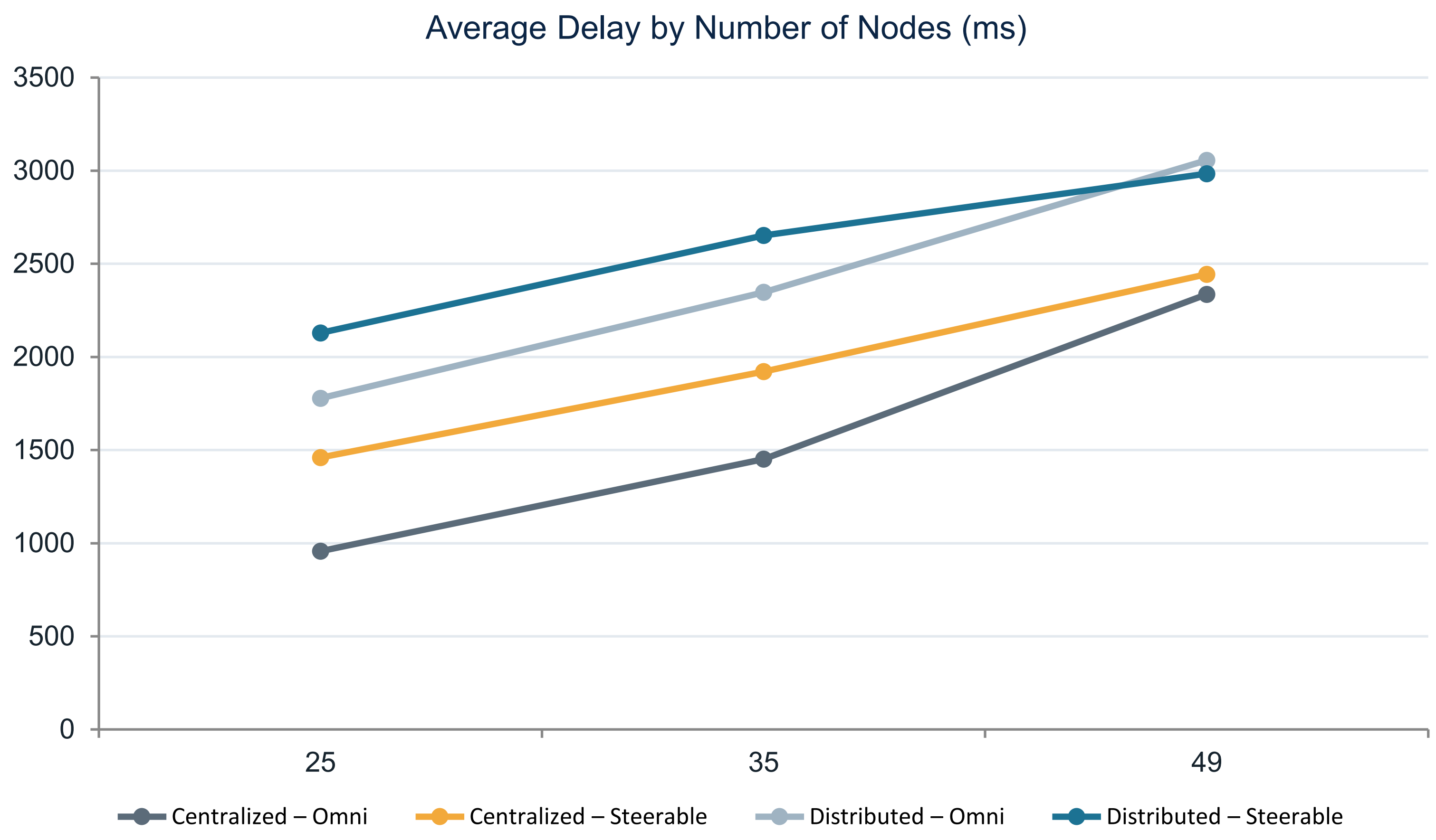
Adapting the TASA algorithm and bidirectional scheduling

- A central node (PCE) computes the entire schedule from the network topology
- The path a data packet takes from source to sink is taken into account

Adapting TASA and Bidirectional Scheduling

1	**Connectivity / Interference / Conflict Matrices**	The steerable antenna's direction information is used to derive a graph representation of the network.
2	**Adapting the TASA Algorithm**	Time, frequency and antenna direction are jointly assigned to produce a conflict-free schedule.
3	**Path-Based Schedule Generation**	Cells are allocated in sequence along the multi-hop path a packet follows from source to sink.
4	**Bidirectional Centralized Scheduling**	Upstream and downstream traffic are scheduled simultaneously, reducing end-to-end latency.

Centralized vs. Distributed Scheduling



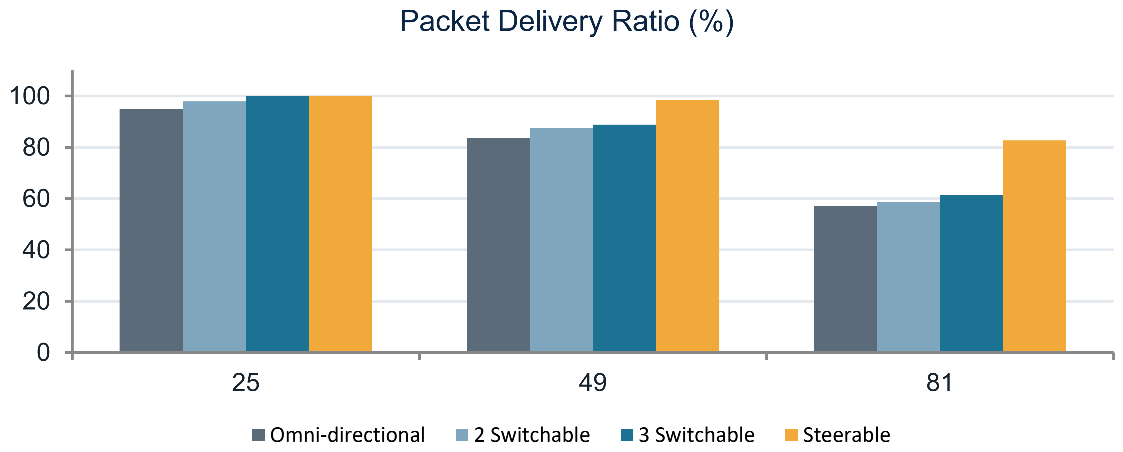
Observation

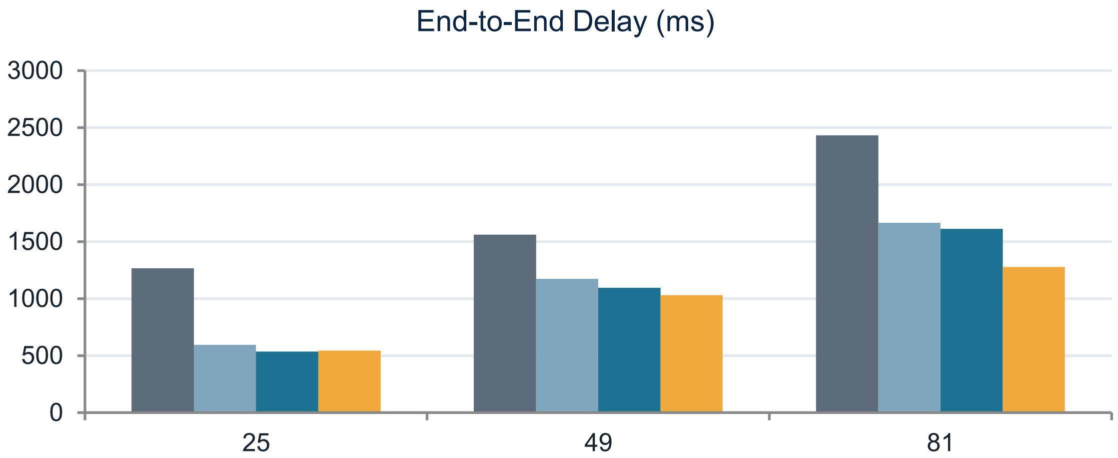
Centralized scheduling achieves lower end-to-end latency and energy consumption than distributed scheduling.

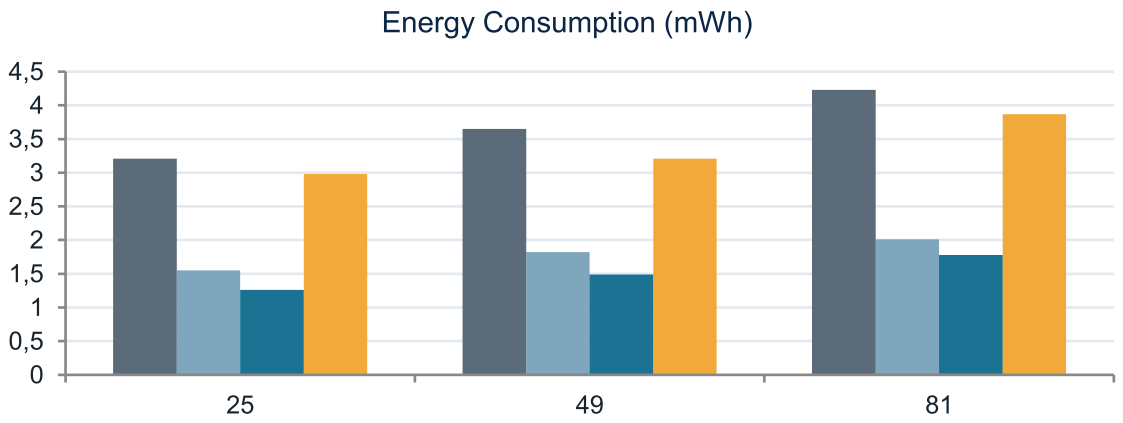
However, the centralized solution is not scalable → best suited to small, sparse, static networks.

The algorithm is validated against the TASA algorithm adapted for the steerable antenna.

Overall Comparison of Antenna Models







Overall Finding

By using the spatial dimension in addition to time and frequency, smart/directional antennas outperform omni-directional antennas on all three metrics (PDR, delay, energy). The gap is most pronounced in dense networks (81 nodes).

Conclusion and Evaluation

Switchable Antenna (Ch.4)	Reduced collisions/interference on shared cells and improved network stability; improved PDR, energy and delay under limited frequency resources.
Steerable Antenna (Ch.5)	The hybrid autonomous+distributed solution solved the synchronization-time problem in a scalable way and improved performance over omni-directional antennas.
Centralized Scheduling (Ch.6)	Path-based and bidirectional scheduling achieved lower delay/energy than the distributed solution; scalability is limited to small networks.

Overall: Nodes equipped with smart/directional antennas, scheduling bandwidth resources across the time-frequency-space dimensions, deliver superior network performance compared to the traditional omni-directional approach.

Future Work and Publications

FUTURE WORK

1. Validating the simulation results on a real hardware testbed
2. Analyzing performance in a high-interference environment shared with other technologies in the 2.4 GHz band
3. Developing machine-learning-based algorithms for best antenna direction and cell selection
4. Integrating multipath communication with steerable antenna solutions

PUBLICATIONS

IEEE Access (2021)

Kulcu, S., Gormus, S., Jin, Y. "Integration of Steerable Smart Antennas to IETF 6TiSCH Protocol for High Reliability Wireless IoT Networks", IEEE Access, 9, (2021) 147780-147790.

TJEECS (2019)

Görmüş, S. and Külcü, S. "Enabling space time division multiple access in IETF 6TiSCH protocol", Turkish Journal of Electrical Engineering and Computer Sciences, 27, 6, (2019) 4151-4166.

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Thank You

I welcome your questions

Sercan KÜLCÜ • Supervisor: Assoc. Prof. Sedat GÖRMÜŞ

Karadeniz Technical University · Graduate School of Natural and Applied Sciences · Computer Engineering