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Integration of Steerable Smart Antennas to IETF 6TiSCH Protocol for High Reliability Wireless IoT Networks

A smart antenna solution that helps 6TiSCH networks stay reliable as they grow

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SUMMARY

What Problem Does This Paper Solve?

1 The Problem

Steerable smart antennas need complex algorithms, which are hard to use in low-power, low-cost IoT devices.

2 The Approach

The paper adds a low-complexity steerable antenna solution to the IETF 6TiSCH protocol, called SAA6.

3 What's New

New MAC-layer and scheduling mechanisms let nodes find and track the best antenna direction on their own.

4 The Finding

In Cooja/Contiki simulations, SAA6 beats the standard omnidirectional 6TiSCH stack, especially in dense networks.

Why Combine Steerable Antennas with 6TiSCH?

The challenge

- IoT networks often use many low-cost nodes that send data at the same time, which causes interference and dropped packets.
- This problem gets worse in dense networks, where bandwidth is limited and channels are shared with WiFi and other technologies.
- Directional antennas can reduce interference, but using them well requires new, carefully designed protocols.
- This paper builds those mechanisms directly into 6TiSCH, the leading protocol for reliable industrial IoT.

8

Maximum number of neighbours stored per node

5 dBi

Maximum gain of the modelled steerable antenna

81

Nodes in the largest test network

Source: Section I (Kulcu et al. 2021)

Smart Antennas: Two Main Types

Switched Beam

- Has several fixed beam patterns
- Can act like an omnidirectional antenna when broadcasting
- Simple to control, but less flexible

Adaptive Array

- Can steer its beam toward any direction
- Can cancel signals coming from unwanted directions
- Cannot transmit omnidirectionally

ESPAR Antenna

An Electronically Steerable Parasitic Array Radiator (ESPAR) is a popular, easy-to-build option: one active element surrounded by passive elements. Changing the passive elements' values steers the beam electronically — with a full 360° scan, in steps as small as 30°, and gains of 7.5–9 dBi depending on the design.

Source: Section II-A (Kulcu et al. 2021)

6TiSCH in Brief: Two Cell Types

Shared Cell

Uses slotted-ALOHA with contention. Nodes use it to send control frames (EB, RPL, DIS) and to negotiate new cells with neighbours.

Dedicated Cell

Reserved for one pair of nodes. Gives interference-free, collision-free communication for high reliability.

How a node joins the network

1. Get synchronized — listen for Enhanced Beacon (EB) frames and learn the minimal schedule.
2. Join the routing tree — exchange RPL DIO frames to attach to a parent, forming a tree rooted at the sink.
3. Start communicating — the node now has what it needs to talk to the rest of the network.

Source: Section II-B (Kulcu et al. 2021)

CONTRIBUTION

SAA6: Steerable Antenna Agnostic 6TiSCH Solution

Faster neighbour discovery

A new, fully autonomous scheduling mechanism that finds neighbours faster, using a steerable antenna.

RSSI-based direction finding

An algorithm that uses signal strength (RSSI) to work out the best transmit and receive direction, cutting interference.

Fewer shared-cell collisions

A method that uses directional communication to reduce collisions in shared cells — key for scaling up 6TiSCH networks.

Modelling a Steerable Antenna

How the model works

- Maximum antenna gain is set to 5 dBi, matching real ESPAR designs from the literature.
- The receiver's gain depends on the angle θ between the transmitter's and receiver's antenna directions.
- This gain is added directly into the standard path-loss (signal strength) formula.
- Receiver sensitivity is set to −95 dBm, matching the CC2420 radio used in the test hardware.

$$G(\theta)\ [\mathrm{dB}] = 10(1 + \cos\theta) - 15$$

Antenna gain as a function of angle ϑ

+30 m

extra range at 0°
(main beam direction)

−40 m

shorter range at 180°
(opposite direction)

Reference distance: 1 m · Reference path loss: −52 dBm · Path-loss exponent: 2.5

Source: Section III, Eq. (1)–(2), Fig. 1 (Kulcu et al. 2021)

Finding the Best Direction to Each Neighbour

How each node learns the best direction

- Every node keeps a list of neighbours, storing each one's ID, best known direction, and the highest RSSI seen so far.
- Each time a frame arrives successfully, the node compares the new RSSI with the stored value — if it's better, it updates the direction.
- No extra "probing" frames are needed — normal control traffic (EB, RPL, DATA) is enough to learn the best direction.
- Because antennas start out pointing randomly, this discovery process naturally takes longer than with omnidirectional antennas.

Result: RSSI improves over time

In a 40 m grid test network, RSSI values **converge toward −82 dBm** as node pairs gradually find their best antenna orientation.

Neighbour list size is capped at **8 neighbours** per node to keep memory and processing needs low.

A frame update is skipped if a neighbour hasn't sent anything recently, saving energy.

Source: Section IV-A, Algorithm 1, Fig. 3 (Kulcu et al. 2021)

Two Slotframes: One for Data, One for Control

The proposed solution runs two independent slotframes with lengths that are mutually prime, so they rarely overlap:

📦 Data Slotframe (SF0)

Scheduled by the standard 6TiSCH Scheduling Function Zero. Carries regular data traffic between nodes.

🔁 Autonomous Slotframe

Runs without any negotiation. Each node hashes its own ID and its neighbour's ID to pick a time slot and channel automatically.

Why two slotframes?

A directional antenna cannot broadcast to every neighbour at once — so multicast control messages need their own dedicated cells, sent one direction at a time.

Each node autonomously reserves 1 transmit and 1 receive cell per neighbour, moving this traffic off the contention-based shared cell.

Source: Section IV-C–D, Eq. (3), Fig. 4 (Kulcu et al. 2021)

Is the Extra Signalling Worth It?

The autonomous cells add some overhead, but steerable antennas also need fewer hops to reach the root — so the net cost depends on the traffic rate:

Transmission Interval	Omnidirectional Cells	Steerable Cells	Ratio (Steerable / Omni)
1 s	296	240 + 80 = 320	**1.08**
0.5 s	592	480 + 80 = 560	**0.94**

+8%

more cells needed than omni, at a 1 s interval

−6%

fewer cells needed than omni, at a 0.5 s interval

~25%

fewer cells overall thanks to reduced hop count

Source: Table 1, Section IV-E, Eq. (4)–(8) (Kulcu et al. 2021)

Simulation Setup and Assumptions

Slotframe & Timing	
Slotframe length	**51**
Autonomous slotframe length	**397**
Timeslot duration	**15 ms**
Test duration	**2 hours**

Antenna Range	
Transmit range (omni)	**50 m**
Interference range (omni)	**100 m**
Transmit range (steerable)	**15–80 m**
Shared cells (omni / steerable)	**3 / 1**

Network Layout	
Inter-node distance	**40 m**
Network dimensions	**320 × 320 m**
Min / max EB period	**16 s / 50 s**
Min / max DIO interval	**4.1 s / 1048.6 s**

Key assumptions: nodes are static with one fixed-power (0 dBm) radio; each steerable node can scan the full 360°; the root node uses three switchable 120° antennas that can also emulate omnidirectional behaviour.

Source: Table 2, Section V-A (Kulcu et al. 2021)

Synchronization Time and Collision Rate

Synchronization Latency

Sync time grows with network size for every antenna type. SAA6 is much faster than a plain steerable antenna, and close to the omnidirectional baseline, thanks to autonomous cells — at the cost of slightly more energy.

Shared-Cell Collision Rate

Steerable antennas cut the collision probability by more than 20% in shared cells — with no need for extra tricks like adjusting the beacon interval.

Note: because all synchronized nodes share the same frequency channel in the shared cell, adding more channels does very little to reduce collisions — antenna direction matters far more.

Source: Fig. 6(a)–(b), Sections V-B–C (Kulcu et al. 2021)

Packet Delivery and Energy Savings

+30%

higher packet delivery ratio (PDR) than omnidirectional, across tested transmission intervals

↑ PDR

with limited channels — the antenna direction acts as a third scheduling dimension

–20%

lower energy consumption thanks to longer range and fewer retransmissions

Why does this happen?

- Shorter transmission intervals create heavier traffic, so SAA6's spatial separation matters most exactly when the network needs it.
- With few frequency channels available, nodes often reuse the same channel offset — directional antennas reduce the resulting interference.
- Fewer dropped frames means fewer retransmissions, which is the main reason energy consumption drops.

Source: Fig. 6(c)–(e), Sections V-D–E (Kulcu et al. 2021)

6TiSCH Is Ready for Smart, Directional Antennas

- SAA6 outperforms the standard omnidirectional 6TiSCH stack in every tested aspect, especially reliability and network throughput.
- The gains are largest in dense networks and in scenarios with limited frequency channels — exactly where industrial IoT networks struggle most.
- This confirms that 6TiSCH can support directional and smart antennas without losing its low-power, reliable design goals.
- Future work: validate the results on real hardware, use machine learning to find the best antenna direction, and add multi-path communication to further cut network latency.

REFERENCE

Source and Acknowledgment

Kulcu, S., Gormus, S., Jin, Y. (2021).
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Thank You