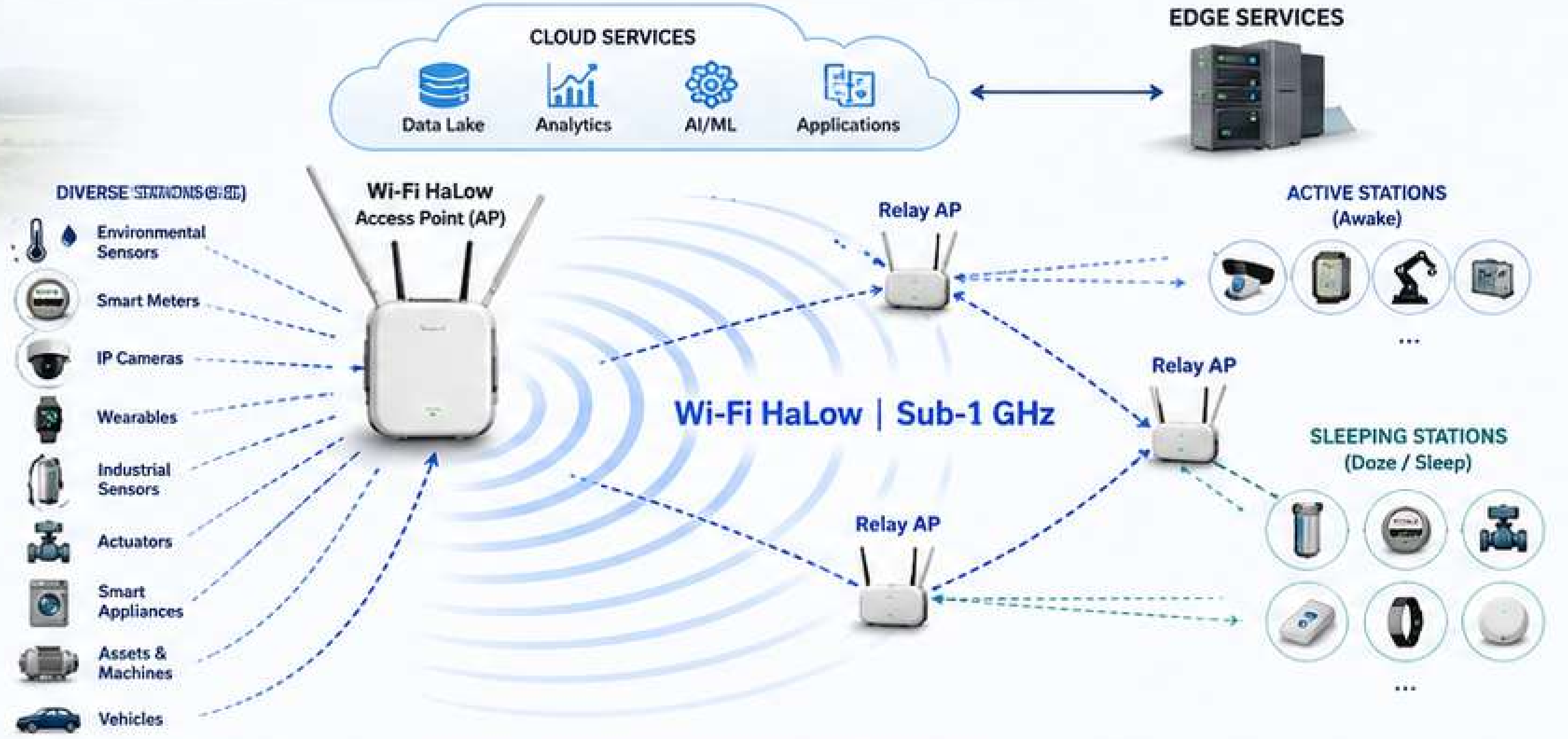
Wi-Fi HaLow for Next-Generation IoT

Can IEEE 802.11ah connect large, diverse and energy-constrained IoT networks?

MAIN RESEARCH QUESTION:
Can one wireless standard balance range, scale, data rate and power efficiency?



RAW TIMELINE (Example)

Group	RAW Slot	Wake Time
G1		T_1
G2		T_2
G3		T_3
...	...	...

Long sleep, scheduled wake.

HIERARCHICAL AID STRUCTURE

Page → Block → Sub-block → Station

- Page: Large address space
- Block: Device grouping for scale
- Sub-block: Further grouping for efficiency
- Station: Individual STA identification

Scalable grouping with AID.

ADAPTIVE MCS PATH (Examples)

MCS0 → MCS2 → MCS5 → MCS10

Robust to high efficiency.

HETEROGENEOUS IOT TECHNOLOGIES → **HIGH COMPLEXITY** → **WI-FI HALOW ACCESS AND RELAYS** → **GROUPED, SCHEDULED AND ENERGY-AWARE CONNECTIVITY**

HETEROGENEOUS IOT TECHNOLOGIES: LoRa ...

HIGH COMPLEXITY
- Different bands
- Different MAC/PHY
- Varying ranges
- Varying data rates
- Energy constraints
- Interoperability issues

GROUPED, SCHEDULED AND ENERGY-AWARE CONNECTIVITY: Wide-area coverage · Massive device scale · Efficient scheduling · Long battery life

HIGHLIGHTS OF THE PAPER

01 COMPARATIVE TECHNOLOGY STUDY
The paper compares IEEE 802.11ah with Wi-Fi, BLE, IEEE 802.15.4, LPWAN, cellular and emerging wireless technologies.

02 PHY AND MAC FEATURE ANALYSIS
Sub-1 GHz operation, adaptive MCS, RAW, TIM, AID, TWT and relay support are mapped to NGI requirements.

03 PROPOSED NGI ARCHITECTURE
An IEEE 802.11ah-based architecture combines wide-area connectivity, device grouping, edge computing, programmability and energy efficiency.

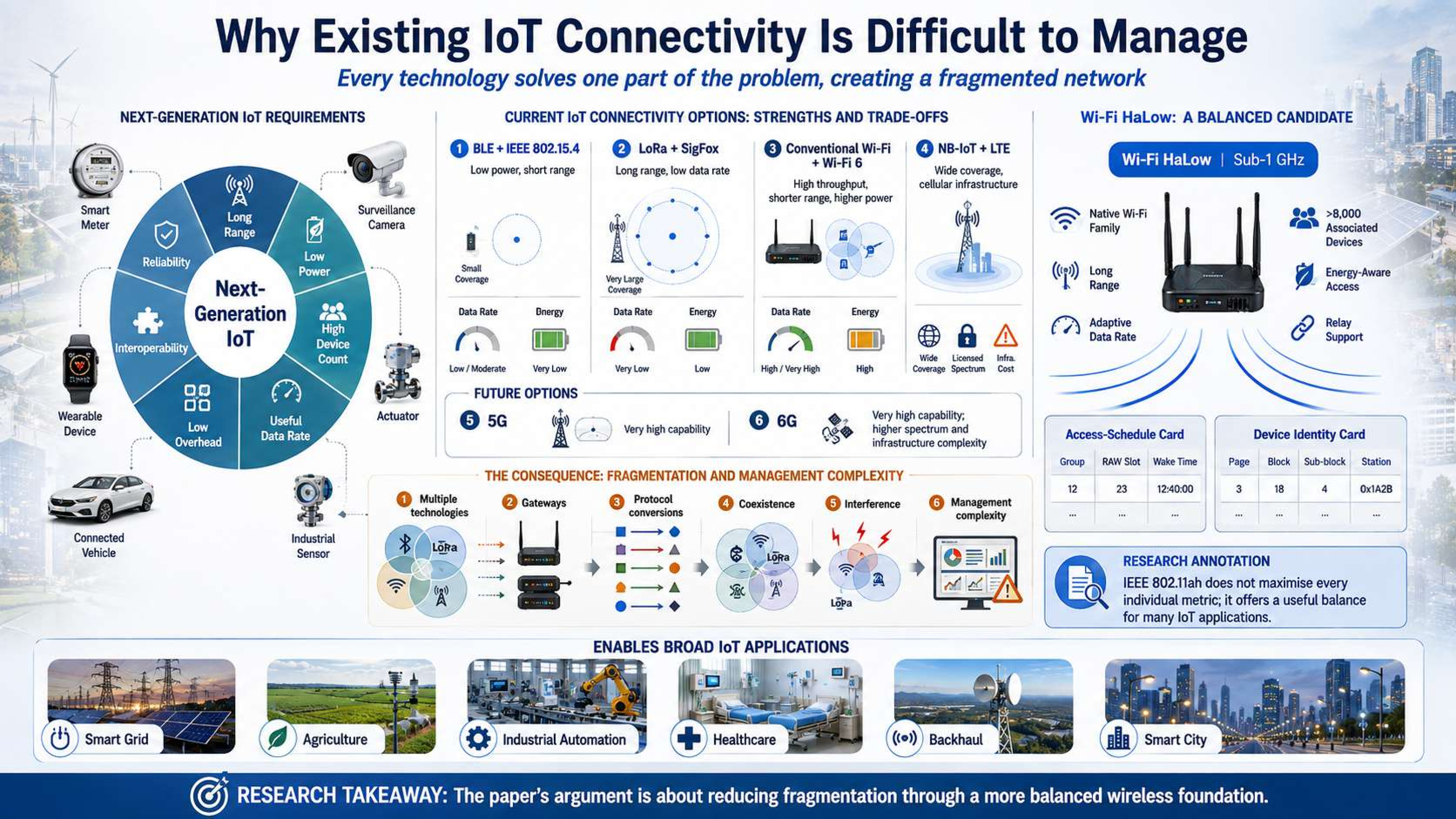
04 PERFORMANCE AND RESEARCH FINDINGS
Simulations study networks with thousands of stations and show how **RAW** size, grouping, relays, dynamic MCS and edge processing affect PRR, throughput, energy and delay.

- More than **8,000** devices per AP
- Approximately **1** km single-hop coverage
- About **150** Kbps to **78** Mbps
- Sub-1 GHz license-exempt operation

⚠ configuration-dependent.

Wi-Fi HaLow aims to bridge the gap between short-range Wi-Fi and low-data-rate LPWAN.

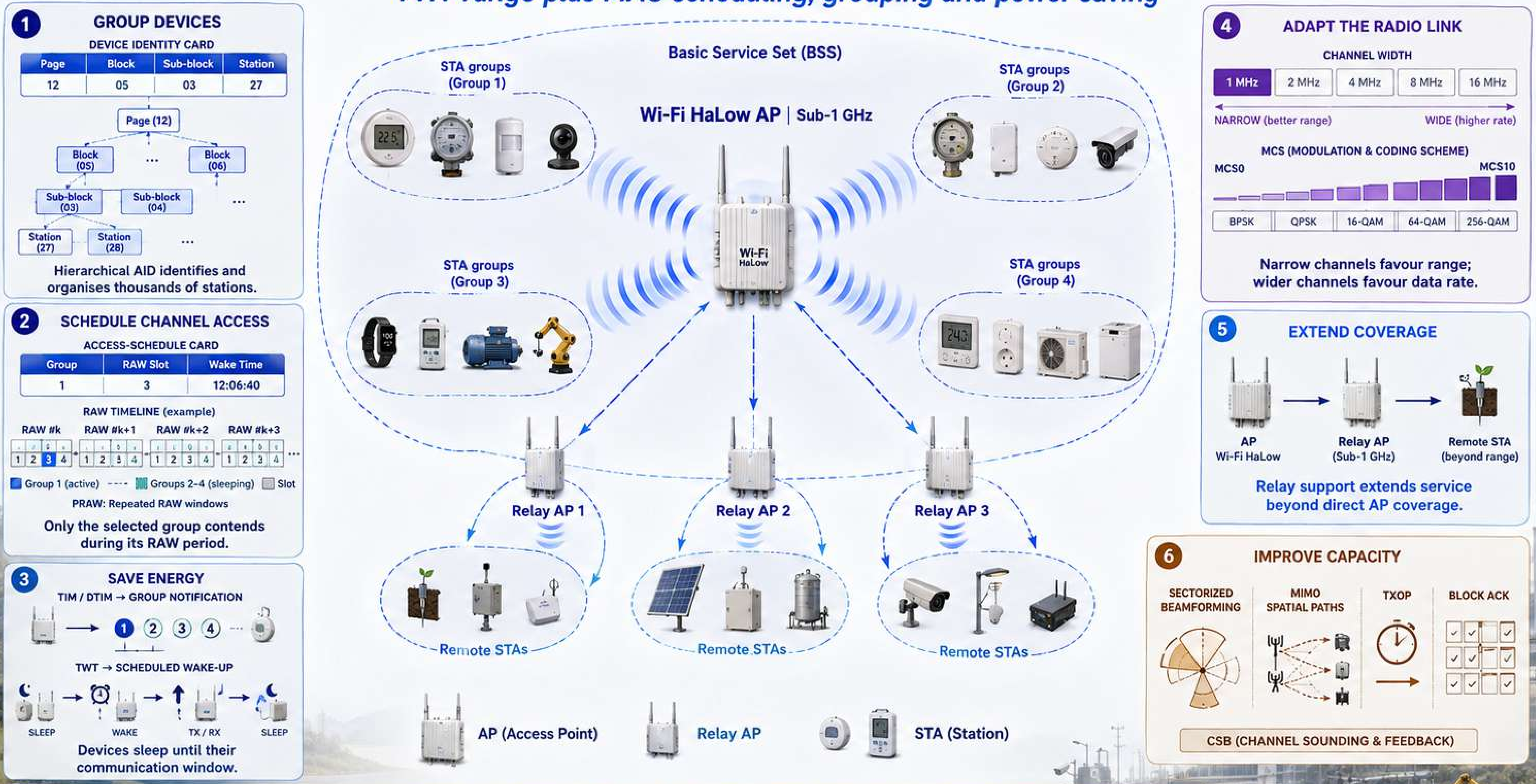
Ad Hoc Networks, 2024 | DOI: 10.1016/j.adhoc.2024.103437



Why Existing IoT Connectivity Is Difficult to Manage
Every technology solves one part of the problem, creating a fragmented network
NEXT-GENERATION IoT REQUIREMENTS
Smart Meter
Surveillance Camera
Long Range
Reliability
Low Power
Next-Generation IoT
Interoperability
High Device Count
Low Overhead
Useful Data Rate
Wearable Device
Actuator
Connected Vehicle
Industrial Sensor
CURRENT IoT CONNECTIVITY OPTIONS: STRENGTHS AND TRADE-OFFS
1 BLE + IEEE 802.15.4
Low power, short range
Small Coverage
Data Rate
Bnergy
Low / Moderate
Very Low
2 LoRa + SigFox
Long range, low data rate
Very Large Coverage
Data Rate
Energy
Very Low
Low
3 Conventional Wi-Fi + Wi-Fi 6
High throughput, shorter range, higher power
Data Rate
Energy
High / Very High
High
4 NB-IoT + LTE
Wide coverage, cellular infrastructure
Wide Coverage
Licensed Spectrum
Infra. Cost
FUTURE OPTIONS
5 5G
Very high capability
6 6G
Very high capability; higher spectrum and infrastructure complexity
THE CONSEQUENCE: FRAGMENTATION AND MANAGEMENT COMPLEXITY
1 Multiple technologies
LoRa
2 Gateways
3 Protocol conversions
4 Coexistence
LoRa
5 Interference
LoPa
6 Management complexity
Wi-Fi HaLow: A BALANCED CANDIDATE
Wi-Fi HaLow | Sub-1 GHz
Native Wi-Fi Family
Long Range
Adaptive Data Rate
>8,000 Associated Devices
Energy-Aware Access
Relay Support
Access-Schedule Card
Group | RAW Slot | Wake Time
12 | 23 | 12:40:00
... | ... | ...
Device Identity Card
Page | Block | Sub-block | Station
3 | 18 | 4 | 0x1A2B
... | ... | ... | ...
RESEARCH ANNOTATION
IEEE 802.11ah does not maximise every individual metric; it offers a useful balance for many IoT applications.
ENABLES BROAD IoT APPLICATIONS
Smart Grid
Agriculture
Industrial Automation
Healthcare
Backhaul
Smart City
RESEARCH TAKEAWAY: The paper's argument is about reducing fragmentation through a more balanced wireless foundation.

How Wi-Fi HaLow Connects Thousands of Devices

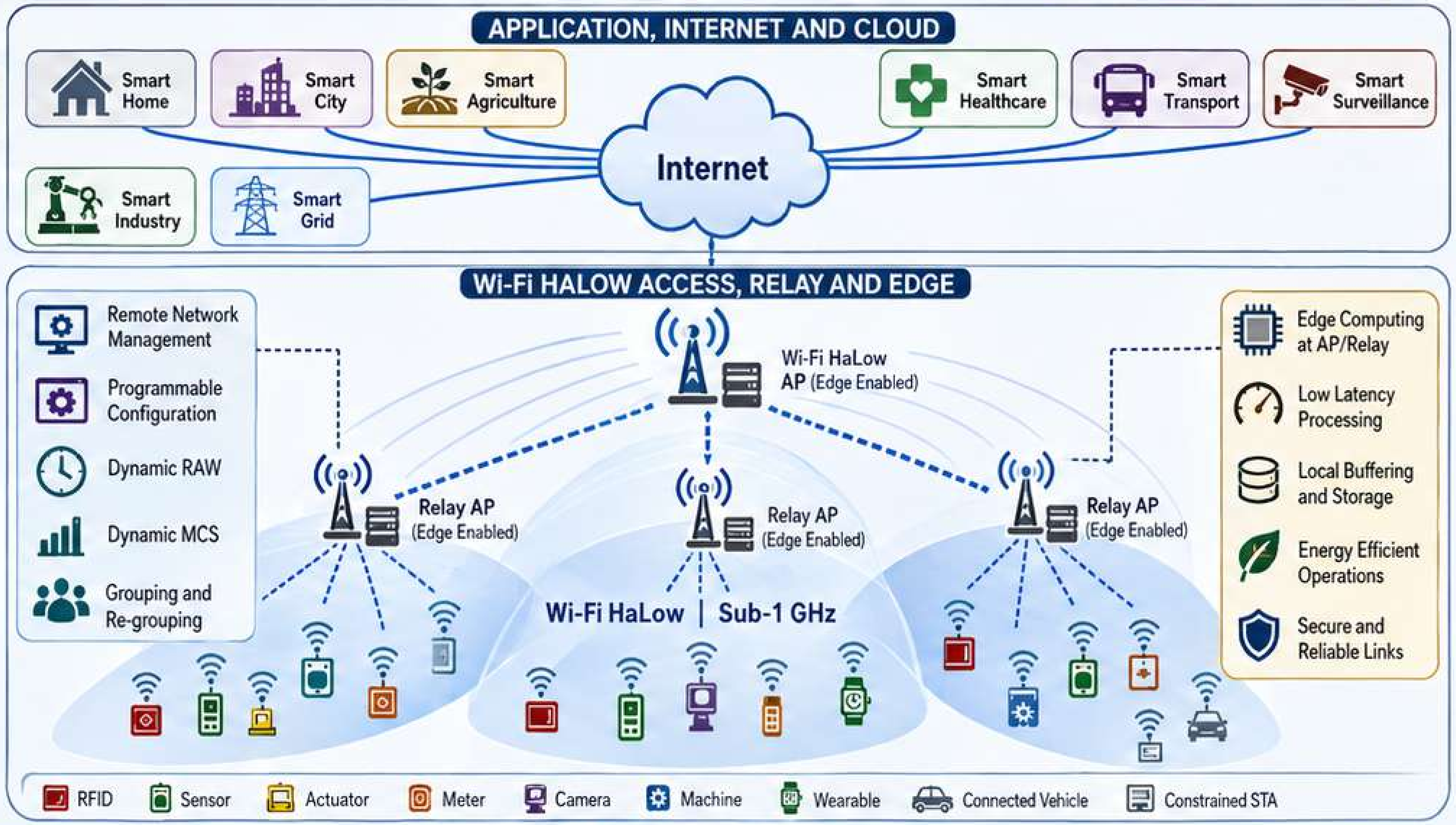
PHY range plus MAC scheduling, grouping and power saving



RESEARCH TAKEAWAY: Group the devices, schedule their access, let them sleep and adapt the link.

An IEEE 802.11ah-Based Architecture for Next-Generation IoT

Wide-area connectivity, edge intelligence and lightweight Internet protocols



NGI Components

- Programmable
- Reconfigurable
- Scalable
- Network Management
- Wide-Area Coverage
- Coexistence
- Grouping/Re-grouping
- Edge Computing
- Energy Efficient

Lightweight IoT Protocol Stack

Application	IoT Application | Device Management
Data	Binary | JSON | CBOR
Messaging	CoAP | MQTT | XMPP
Transport	UDP | DTLS
Internet	IPv6 | RPL
Adaptation	6LoWPAN
Link	IEEE 802.11ah MAC IEEE 802.11ah PHY

DATA FLOW AND NGI OPERATION

1. IoT device generates data
2. STA joins an AID-based group
3. TIM/TWT indicates communication time
4. STA transmits during RAW allocation
5. AP or Relay AP selects MCS
6. Relay extends out-of-range STAs
7. Edge processes latency-sensitive data
8. Internet/cloud provide services and storage
9. Remote management reconfigures parameters

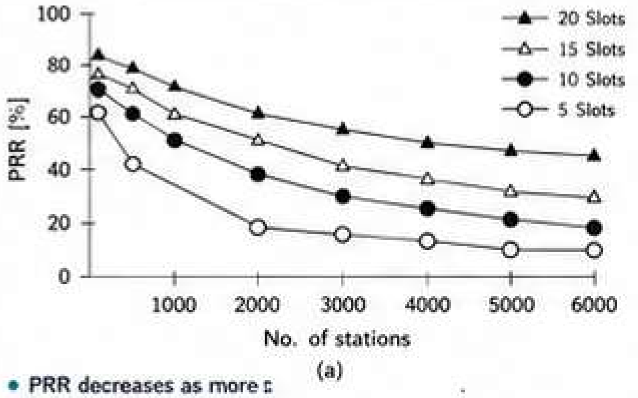
Upper-layer adaptation remains necessary because IEEE 802.11ah primarily defines PHY and MAC operation.

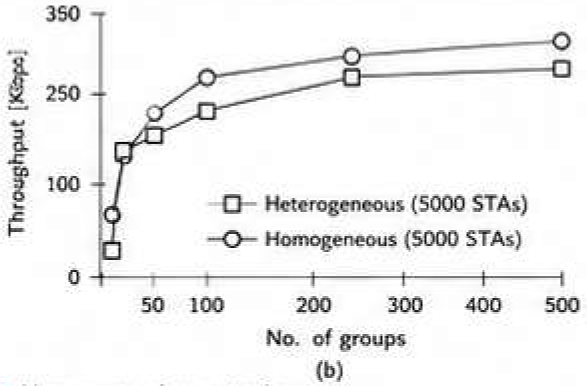
IEEE 802.11ah provides the wireless foundation; edge, management and lightweight Internet layers complete the NGI system.

What the IEEE 802.11ah Analysis Shows

Performance depends on scheduling, grouping, traffic, coverage and radio configuration

1 RAW SIZE AND DEVICE GROUPING



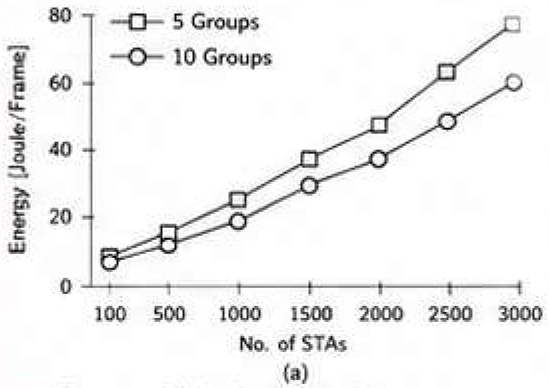


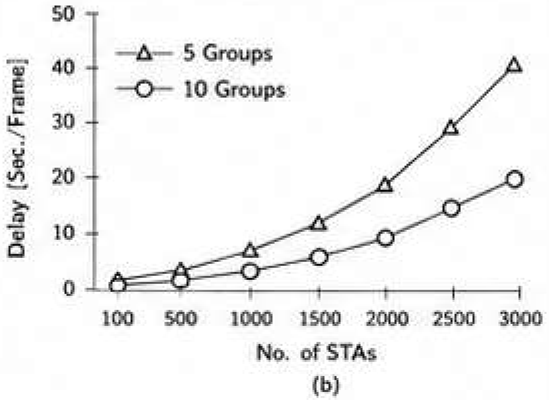
- PRR decreases as more s
- Larger RAW allocations improve
- access opportunities.

- More groups reduce contention.
- Fixed RAW performs worse under heterogeneous traffic.

TAKEAWAY: RAW must adapt to device count and traffic pattern.

2 ENERGY AND DELAY





- Energy and delay rise with station count.
- More groups reduce repeated contention in the evaluated configuration.

TAKEAWAY: Better grouping reduces repeated contention.

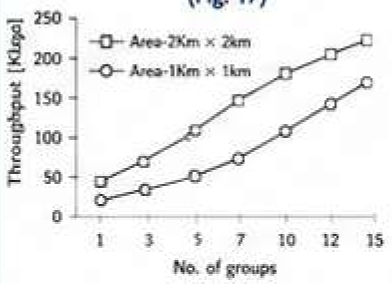
REMAINING CHALLENGES

- Coverage versus data-rate trade-off
- Coexistence with other sub-1 GHz networks
- Lightweight long-range security
- Upper-layer and TCP/IP integration
- Interoperability between vendors
- Deployment and infrastructure cost
- QoS for time-sensitive applications
- Fully programmable network control
- Network slicing
- SDN and P4 integration
- Intent-driven networking
- Edge intelligence
- Mobile IoT and augmented reality
- Fair access for thousands of stations

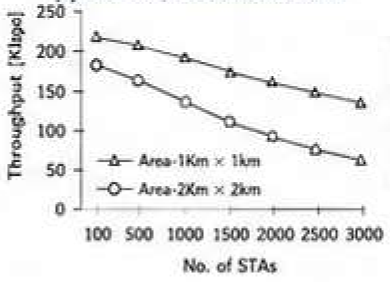
Commercial modules and prototypes exist, but full NGI integration still requires further research.

3 COVERAGE, HIDDEN NODES AND RELAYS

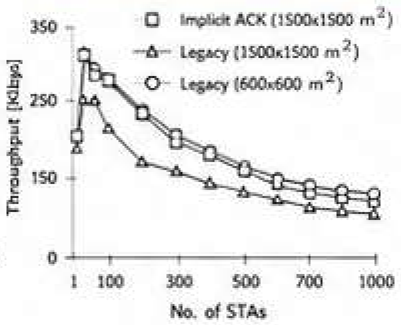
Hidden Nodes (Throughput) (Fig. 17)



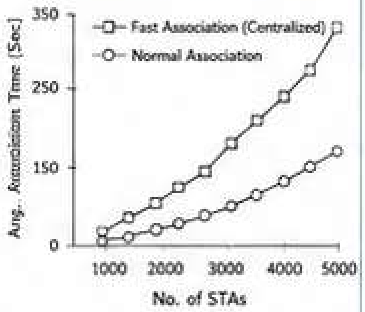
(b) non-TIM / Unscheduled STAs



Relay Network Performance (Fig. 18a)



Association Time (Fig. 18b)

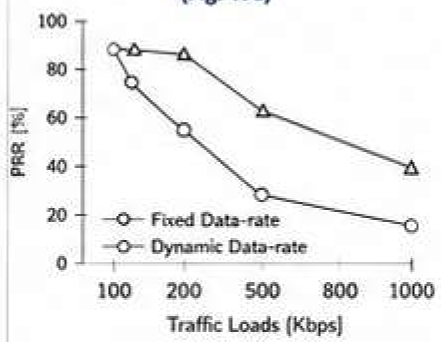


- Larger coverage increases hidden-node effects and reduces throughput.
- Relay networks, TXOP and Block ACK improve multi-hop efficiency.
- Association time rises with station count.

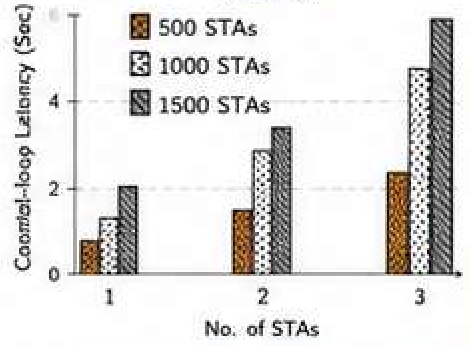
TAKEAWAY: Longer coverage needs careful relay and access design.

4 DYNAMIC MCS AND CONTROL-LOOP LATENCY

(Fig. 19a)



(Fig. 19b)



- Dynamic data-rate configuration maintains higher PRR than fixed data rate as load increases.
- Control-loop latency increases with station count and hop count.
- Nearby relay processing can reduce delay.

TAKEAWAY: Adapt the MCS and process close to the event.

SIMULATION SETUP (NS-3) | up to 6000 stations | 2000 × 2000 m² | 5 minutes | 2 MHz MCS0 | 650 Kbps | 256-byte UDP | RAW/group variation | relay and multi-hop analysis

Sub-1 GHz range → adaptive PHY → grouped MAC access → power saving → relay and edge support → scalable NGI connectivity

IEEE 802.11ah is a strong candidate for Next-Generation IoT because it balances scale, coverage, data rate and energy efficiency, but it must be integrated with management, security, interoperability and upper-layer solutions.

Long range alone is not enough: schedule, adapt, relay and manage the network intelligently.