Thesis Defence for the Degree of **Doctor of Philosophy**, PhD

Designing IEEE 802.11ah-based scalable network for Internet of Things

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Outline

- Things in IoT are not only connected computers, and mobiles phones, but also sensors/actuators, and day to day objects such as books, medicines, vehicles, TVs, and refrigerators ([22] and [32]).
  1. Tiny devices powered by battery- any objects,....
  2. Heterogeneous- size, vendor, capacity,...
  3. Very large-scale deployment- thousands,...

- Human population by 2025 will be 8.1 billions[1], What about devices?

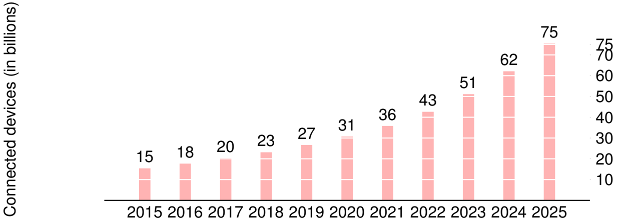


Figure 1: Connected devices wolrdwide ©Statista 2019[2]

[1] https://www.usatoday.com/story/news/world/world-population/2025/

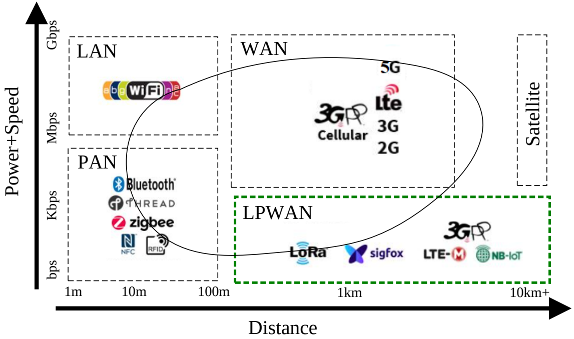
[2] https://www.statista.com/statistics/471264/iot-number-of-connected-devices-worldwide/

Introduction- Communication in IoT

- Wireless communication (license free) technologies seem to be the best option [36], need to
  - Support large coverage area
  - Improve energy efficiency
  - Support scalability
  - Support heterogeneity
  - Control huge contention and collisions
  - Minimize the protocol overhead for short frames
  - Adapt itself along with the changing nature
  - Deal with the unusual but mission-critical application
  - Reduce interference when multiple networks coexist

Background- Existing Solutions

- The existing wireless communication technologies are not suitable as
  1. These are not designed to enable channel access for such a number of devices (creating a massive collisions)
  2. Not efficient in energy and small packet Tx
  3. To cover longer distances, short-range and long-range technologies (different) are combined (creating a gap in properly connecting such devices to the Internet)
- The new PHY and MAC layer support in 802.11ah allows to construct a network with more than 8000 devices covering more than 1km of range [2]



IEEE 802.11ah-based Networking

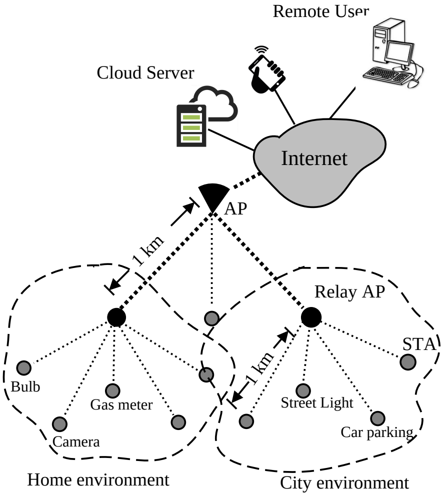
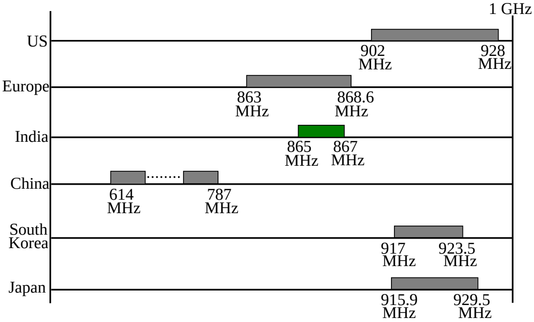


Figure 2: An example of IEEE 802.11ah-based multi-hop IoT network structure combining smart city and smart home application

Background- IEEE 802.11ah (PHY)

- Sub-1 GHz:
  1. 1 Km coverage in 1-hop
  2. Good propagation and penetration, less congested, and high sensitive
- Channelization:
  1. Configurable bandwidth of: 1, 2, 4, 8 and 16 MHz
  2. MCS(0-10) gives data-rate 150 Kbps -78Mbps



Background- IEEE 802.11ah (MAC)

1. Hierarchical Association IDentification (AID): allows up to 8,191 devices to be associated with an AP
2. Null Data Packet (NDP) MAC frames, short MAC header, and management frames: reduces Tx/Rx time and overhead
3. Target Wake-up Times (TWT), Traffic Indication Map (TIM) and Segmentation: supports very low energy consumption
4. Restricted Access Window (RAW) and Bidirectional Transmission opportunity (BDT): reduce collisions due to contention
5. Relay and sectorization operation: allows the network to extend and organize accurately

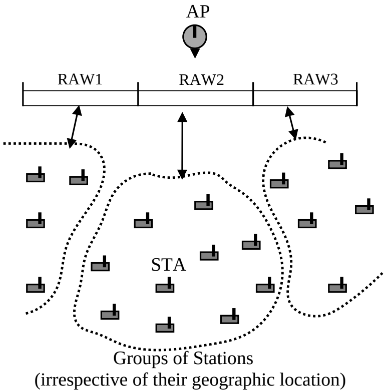


Figure 3: RAW Mechanism

Problem Space & Objectives

- Although IEEE 802.11ah with its innovative concepts solves many of these, but it does not consider many interesting issues which provide motivation and necessity for smart scalable system focusing on the MAC layer aspects.
- (Objectives)
  1. Estimation of RAW size for large, dynamic, and heterogeneous IoT environment
  2. Managing event-driven and critical traffic in RAW-based channel access mechanism employed large-scale IoT
  3. Generation of dynamic Tx/Rx time schedule for relay node in supporting scalability over multi-hop networks
  4. Unnecessary wake-ups and contentions for supporting periodic IoT traffic

Tools for Analysis

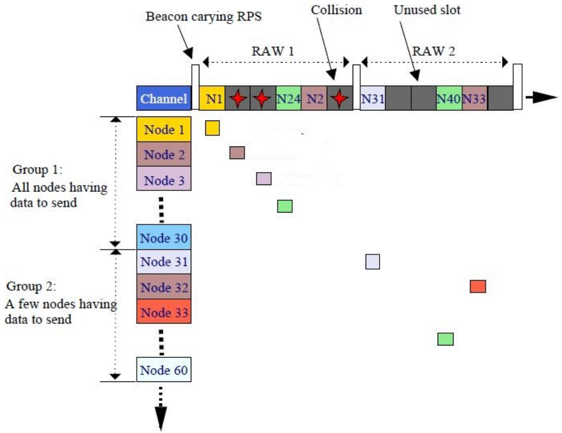
- A Relay and Multiple channel-based 802.11ah module was developed for NS-3 at the beginning
- Thereafter, IEEE 802.11ah-NS-3 [30] is combined with previous implementations
- For performance prediction, Markov-chain [7] model is used, which takes stochastic behaviours of contention mechanism during channel access
- 2D Markov chain with backoff stage and backoff counter

Contribution 1:

HL-MAC: Dynamic RAW Configuration for Heterogeneous and Multi-hop Networks

Problem Formulation

- The real-world IoT networks are being characterized by heterogeneous traffic patterns and dynamic nodes [29].
- The centralized channel access and unconfirmed RAW figure in 802.11ah are not fully suitable for such network scenarios.



Related Works

Schemes (Ref.)	Details	Optimize RAW	Support Hetero-geneity	Multi-hop Support
[27, 24, 23, 31, 26, 25, 19]	Find RAW size for homogeneous network conditions	✓	✗	✗
[34, 35]	Optimize RAW based on energy consumption	✓	✗	✗
[24, 23, 10, 25]	Adjusts RAW over traffic reporting	✓	✗	✗

- Although, above enhancements improve success rate of transmission, but not good enough for scalability over a heterogeneous and large network

Dynamic RAW Configuration for Heterogeneous and Multi-hop Networks

- Although the efficiency of RAW is found to be apparent, the confirmatory size of it is still open issues
- The contribution of this work is threefold:
  1. A distributed channel access for relay based multi-hop IoT
  2. An enhancement to the RAW mechanism of 802.11ah are proposed in order to support heterogeneous loads
  3. An analytical model is developed to optimize the RAW performance over dynamic load condition

Proposed Scheme: Distributed Channel Access

Traditional Channel Access

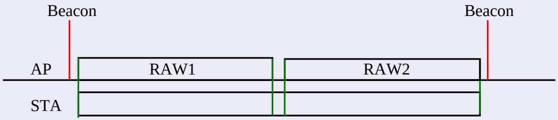


Figure 4: Example scenario of traditional RAW scheme

Proposed Channel Access

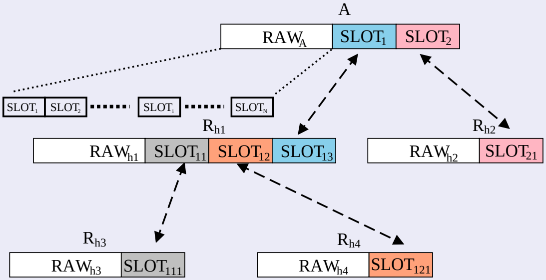


Figure 5: Example scenario of the proposed distributed channel access

- However, we optimize the size of RAW and SLOT, according the current requirements of traffic load.

The Proposed Scheme: Optimizing RAW size (1)

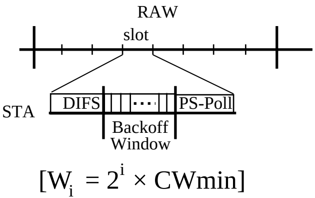


Figure 6: Contention resolution in 802.11ah

- For any fail, PS-Poll is re-transmitted again with doubling the W size on each attempt until it reaches to maximum size
- We use Markov chain model [8] to find the W_{opt}, an optimal RAW, ρ_{opt} can be calculated from W_{opt}

The Proposed Scheme: Optimizing RAW size (2)

- The value below τ_{opt} means channel is under-utilized due to idle slots and above which performance is reduced due to high collision probability
  1. $\tau < \tau_{opt}$: under-utilized due to high idle slot probability
  2. $\tau > \tau_{opt}$: performance is reduced due to high collision probability

The Proposed Scheme: Optimizing RAW size

- From W_{opt}, AP calculates optimal RAW size as

$$\rho_{\mathrm{opt}} = \frac{\mathrm{W}_{\mathrm{opt}}(\rho_{\mathrm{max}} - \rho_{\mathrm{min}})}{\mathrm{W}_{\mathrm{max}} - \mathrm{W}_{\mathrm{min}}} \quad (1)$$

  where, ρ_{max} and ρ_{min} are the maximum and minimum size of RAW respectively
- RAW is used by STA to communicate with AP and Relay, whereas Relay AP uses TDMA to communicate

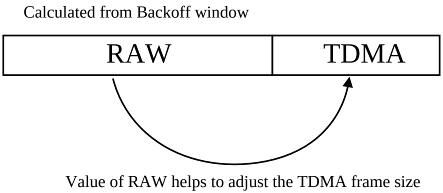


Figure 7: The complete time frame used by an AP or Relay

- The Relay can further allow STAs to use different MCSs

Performance Evaluation

Table 1: System and other parameters used in simulation analysis

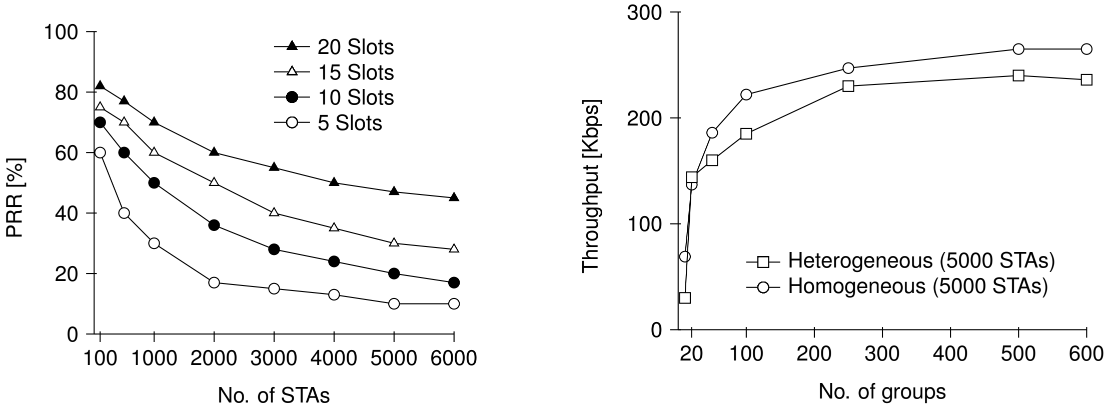
Parameter	Value
Bandwidth	2 MHz
Modulation and Coding Schemes	MCS0, MCS1, and MCS2
Data rate	650, 1300, and 1950 Kbps
Payload size	256 bytes
Radio propagation model	Outdoor (macro [5])
Backoff window size (W)	15 (Min.), and 1023 (Max.)
Orthogonal Frequency Division Multiplexing (OFDM) symbols time (T_{sym})	40 μs
MAC header	14 bytes
PHY header	6 x T_{sym}
SIFS	16 μs
DIFS	120 μs
Backoff slot size	52 μs
Initial backoff window	64
Types of traffic	UDP
Beacon size	25 bytes
ACK size	14 bytes
Simulation area	2000m $\times$ 2000m Flat-grid
No. of nodes (Max.)	6000
TIM	200 *ms*
DTIM	1000 *ms*
RAW size	5 (Min.), and 20 (Max.)
Default RAW size	10
RAW slot duration	3 *ms*
TDMA slot duration	5 *ms*
No. of Relay nodes	3

Performance Evaluation

1. Homogeneous Traffic (HM-T)- Considers a fixed traffic interval values as 0.1 Sec. to generate traffic
2. Homogeneous MCS (HM-MCS)- All STAs use MCS0 as modulation and coding scheme
   - For 256 bytes (MCS0, 2MHz) , T_{col}=0.00492 Sec.,$\gamma = 1.012$, $\mathrm{T_{DATA}}$:

- Heterogeneous Traffic (HT-T)-Traffic are generated with interval values $(0.1, 0.2, 0.07, 0.03,$ and $0.1)$ Sec.
- Heterogeneous MCS (HT-MCS) MCS0, MCS1 and MCS2 are used by the Relays and STAs

$$\mathrm{T_{DATA}} = \left\lceil \frac{8 \times (\mathrm{L_{payload}} + \mathrm{MAC})}{\frac{\mathrm{R}}{\mathrm{basic\_data\_rate}} \times \mathrm{L^{basic\_data\_rate\_sym}}} \right\rceil \times \mathrm{T_{sym}} + \mathrm{PHY} = 4.56\mathrm{ms} \quad (2)$$



(a) Packet Received Ratio (PRR)

(b) Throughput

Figure 8: Packet Received Ratio (PRR) and throughput results in traditional 802.11ah-MAC protocol

Dynamic RAW adjustment

- As HL-MAC finds the best RAW size over different traffic load conditions, it enhances with increasing loads
- In the traditional scheme, irrespective of the varying traffic loads, the size of RAW remains constant (static) over time
- Theoretical results show almost similar trends as compared to the simulation results

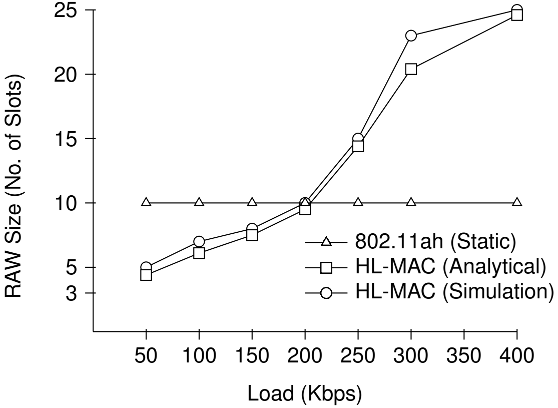
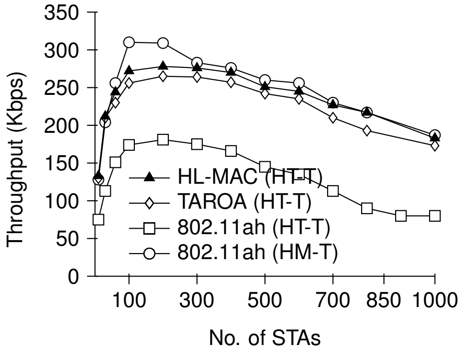
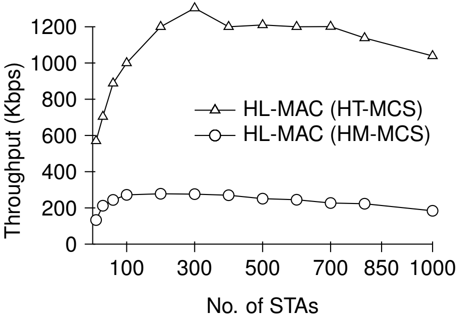


Figure 9: Dynamic RAW adjustment with varying load conditions

Dynamic RAW Configuration- Throughput



(a) HL-MAC Vs. TAROA Vs. 802.11ah-RAW



(b) HL-MAC

Figure 10: Average throughput achieved at AP node over heterogeneous traffic and MCSs

- HL-MAC improves throughput performance up to 44% and 14% as compared to the traditional and TAROA [31], respectively.

Average Delay

- Delay is significantly reduced in the proposed protocol

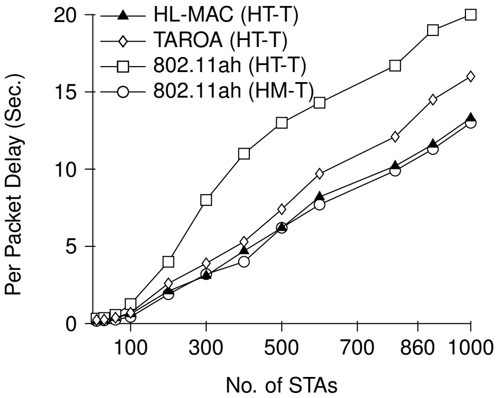
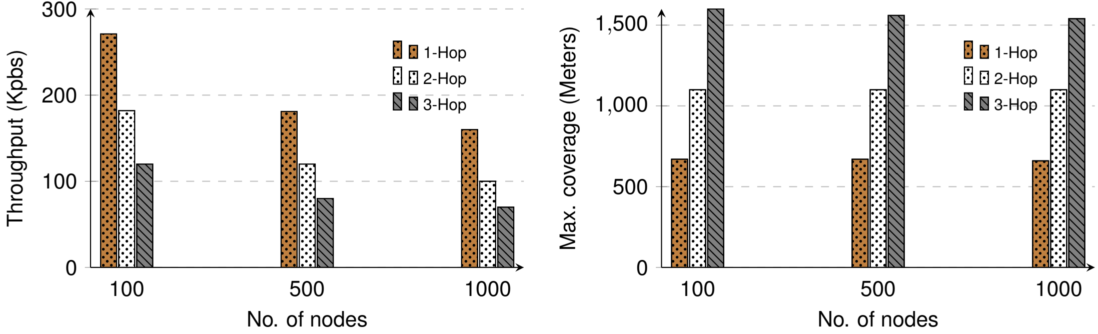


Figure 11: Average end-to-end delay incurred using MCS0

Multi-hop results



(a) Average throughput

(b) Average network coverage

Figure 12: Throughput achieved and distance covered using multiple hops

- Multi-hop support with proper channel access mechanism shows better end-to-end results in terms of coverage range (i.e., up to 1500 m) and throughput (i.e., up to 280 Kbps) in a large scale IoT network.

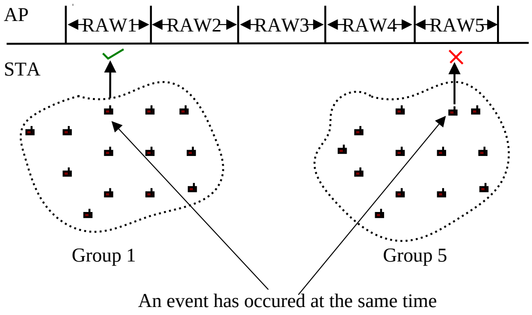
Summary

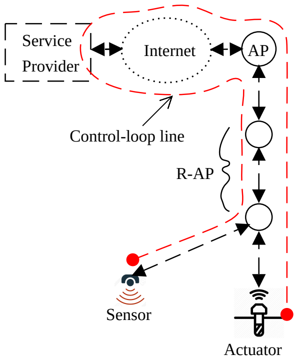
- In dynamic and saturation environment, the proposed protocol shows performance close to network with homogeneous nodes
- With the support of heterogeneous MCSs, the proposed protocol improves scalability over IoT to a great extent
- While supporting the requirements of different IoT applications, QoS is another important parameter that needed to be consider.

Contribution 2:

QS-MAC: QoS-aware Scheduling and Node-grouping Scheme for IoT

- Critical and rare traffic demand special processing over continuous data flows to meet different requirements
- RAW mechanism may differ a possible event-driven transmission





Related Works

Protocols (Ref.)	Details	Provide QoS	Dynamic Grouping	Priority Scheduling
[31, 20]	Provide QoS for priority traffic	✓	✗	✓
[14, 11, 17, 33]	Re-group STAs to solve hidden node problems	✗	✓	✗
[16, 18]	Enhance DCF backoff scheme	✗	✗	✗

- However, provisioning QoS considering important requirements of application is till challenging

QoS-aware Scheduling and Node-grouping Scheme for IoT

- Existing solutions do not consider traffic types, QoS, and distribution of traffic loads among the groups
- Contributions of the work can be summarized as:
  1. A QoS-aware RAW slot assignment and fairness method to handle the traffic flow of critical applications
  2. We propose a load balancing scheme among different RAW groups using dynamic AID allocation to improve network reliability

The Proposed Scheme: Traffic Classification- An Exampe

- **Latency:** There are many critical applications (e-Health, Face Recognition, and Vehicular Communications) which need to process within a time bound [3]
- **Reliability:** There may be a huge amount of on-demand reporting type of traffic from thousands of smart-grid stations [24], also many traffic are very rare
- {L← **Latency**, R←**Reliability**}:
  1. **QoS Traffic:** $C_1 \in \{L, R\}, C_2 \in \{L, -\}, C_3 \in \{-, R\}$
  2. **Non-QoS Traffic:** $C_4 \in \{-, -\}$

Class	LR	Value
1	11	3
2	10	2
3	01	1
4	00	0

Table 2: Binary and Decimal Representation of Traffic Classes

The Proposed Scheme: Priority Scheduling

- A smaller backoff window is assigned to a higher priority station so that it can win an earlier slot
- Instead of uniform random backoff time selection, we use a non-uniform random backoff time selection using a truncated distribution defined in $[0, W_i-1]$ where i is the actual backoff stage
- In truncated distribution, ceiling is set with backoff stages: i=4, 6, 8, & 10 for C=1,2,3, & 4 respectively.

Class	Ceiling	Backoff range
1	4	$[0, 2^4 x W_{min} - 1]$
2	6	$[0, 2^6 x W_{min} - 1]$
3	8	$[0, 2^8 x W_{min} - 1]$
4	10	$[0, 2^{10} x W_{min} - 1]$

Table 3: Truncated Ceiling value and Backoff counter range for different classes

- For maximum permissible window sizes $W_m = \{W_1, W_2, W_3, W_4\}$, AP finds a set of X, where X_m is the number of counts for same entries
- Enhancing PigWin [12], the ease of transmission (θ) which is the reciprocal of the average *W* size is used in the recent past is calculated as:

$$\theta_{G_i} = \frac{\sum_{m=1}^{4} X_m}{\sum_{m=1}^{4} W_m X_m} \tag{3}$$

Large θ values imply that stations are using small *W* sizes, and the amount of transmission failures taking place is low

The Proposed Scheme: Adaptive Grouping (2)

- A threshold value ($\theta^{t}_{G_i}$) is calculated considering $X = \{1, 1, 1, 1\}$
- An example:
  1. $C = \{1, 2, 3, 4\}, W_m = \{16, 64, 256, 1024\}$
  2. For threshold, $X = \{1, 1, 1, 1\}$

$$\theta^{t}_{G_i} = \frac{1 + 1 + 1 + 1}{16x1 + 64x1 + 256x1 + 1024x1} = \frac{4}{560} = 0.00294 \quad (4)$$

  3. Case 1: $X = \{1, 1, 2, 3\}$, $\theta^{1}_{G_i} = 0.00191$; $\theta^{1}_{G_i} < \theta^{t}_{G_i}$ hence, group is heavily loaded
  4. Case 2: $X = \{1, 1, 0, 0\}$, $\theta^{2}_{G_i} = 0.025$; $\vartheta^{2}_{G_i} > \theta^{t}_{G_i}$ hence, group is lightly loaded

The Proposed Scheme: Adaptive Grouping (3)

- Re-grouping using Dynamic AID allocation:
  1. In general, dynamic AID allocation is initiated by a non-AP node by sending AID switch request
  2. In our scheme, an AID switch frame is sent to a particular STA of heavy loaded group with a new or unused or AID from lesser loaded group

The Proposed Scheme: Fairness Method

- Fairness for critical traffic
  1. Along with average W_a of a class C, AP node periodically monitors the failure count (T_c) of an STA (S) from QoS class C (i.e., $S \in C_i$).
  2. On every failure, (T_c) is updated as:
     $T_c = T_c + 1$
  3. QoS class promotion: **Loop:** If $(W_a(C_{i-1}) < W_m^{i-1})$ then promote $S \rightarrow C_{i-1}$ with highest T_c

Performance Evaluation

Parameters	Value
Bandwidth	2MHz (MCS0)
Data rate (basic_data_rate)	650Kbps
Payload size ($L_{payload}$)	256Bytes
CWmin	15
CWmax	1023
Slot time	52 μs
SIFS	160 μs
DIFS	SIFS+2 *Slot time (μs)
RTS/CTS	Not enabled
Station distribution	Random
Beacon Interval	0.1s
Number of station	1000
No. of data bits in one OFDM ($L^{basic\_data\_rate\_sym}$)	26 bits
Symbol duration (T_{sym})	40 μs
Coding rate for BPSK-MCS0 (R)	0.5
PHY header	6 * symbol duration (μs)
MAC header (MAC_h)	14 B
Number of slot in each RAW	10
RAW slot duration	15 ms
Queue size	100 packets
No. of QoS stations	50%
No. of groups	2-10
Simulation area	$1000 \times 1000\ m^2$
Simulation time	5 min

Analytic- Throughput

Table 4: Saturation throughput: analytical vs. simulation

Traffic Class	Protocol	A/S	N_{C_1}=100 N_{C_2}=100 (Kbps)	N_{C_1}=100 N_{C_2}=150 (Kbps)	N_{C_1}=150 N_{C_2}=200 (Kbps)	N_{C_1}=250 N_{C_2}=300 (Kbps)
C1	QS-MAC	A	104.9	111.7	116.3	121.4
		S	101.4	107.2	113.4	120.5
C2	QS-MAC	A	102.3	100.1	97.1	100.7
		S	91.0	93.2	94.9	92.7
Default	802.11ah	A	60.3	63.9	66.1	70.9
		S	56.0	58.2	59.8	61.8

- Throughput achieved by the QoS scheme is much higher than the conventional DCF used in 802.11ah
- The required bandwidth is optimally utilized for more reliability and low latency in priority traffic

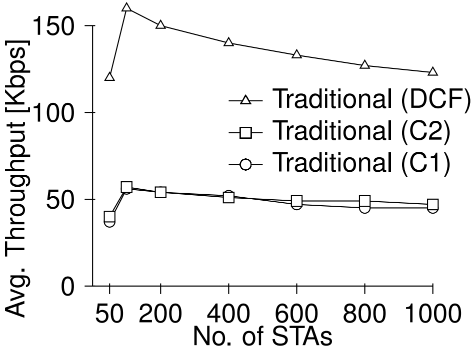
Analytic- Delay

Table 5: Saturation delay: analytical vs. simulation

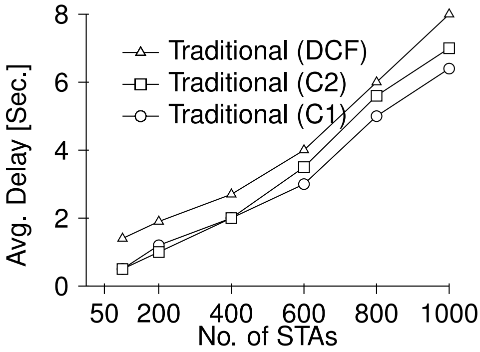
Traffic Class	Protocol	A/S	N_{C_1}=100 N_{C_2}=100 (Sec.)	N_{C_1}=100 N_{C_2}=150 (Sec.)	N_{C_1}=150 N_{C_2}=200 (Sec.)	N_{C_1}=250 N_{C_2}=300 (Sec.)
C1	QS-MAC	A	1.902	1.954	2.077	2.167
		S	1.941	2.105	2.167	2.311
C2	QS-MAC	A	3.101	3.201	3.658	3.814
		S	3.112	3.402	3.756	3.987
Default	802.11ah	A	9.081	11.102	12.982	14.088
		S	9.120	11.201	13.321	14.568

- The saturation delay is greatly improved in the proposed protocol.
- About 700% and 500% (on average) lesser latency can be noticed in C1 and C2 respectively as compared to the default DCF scheme.

Traditional- Throughput and delay



(a) Throughput

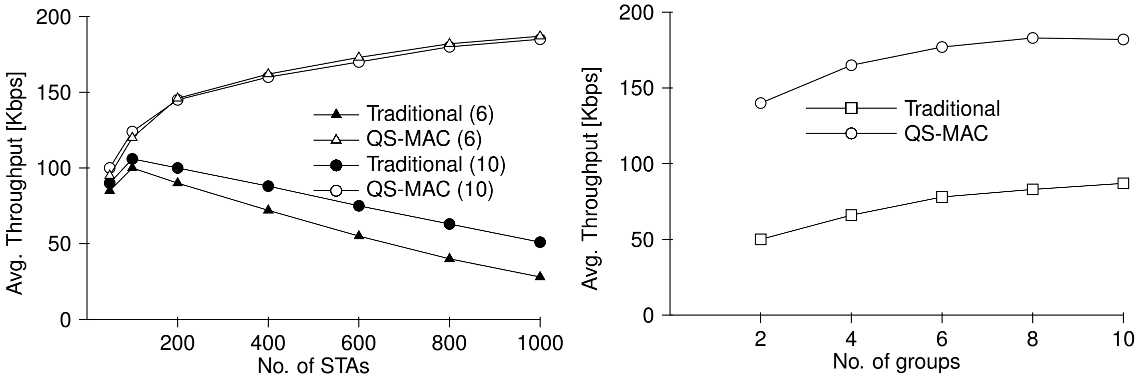


(b) Delay

Figure 13: Throughput and delay characteristics with increasing number of STAs in traditional scheme

- For the single group in the DCF mechanism, throughput decreases drastically (even if we apply QoS traffic)

Throughput- Stations & Groups



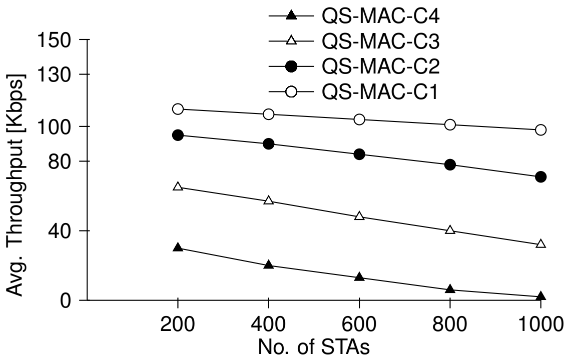
(a) With increasing number of STAs

(b) With increasing number of groups

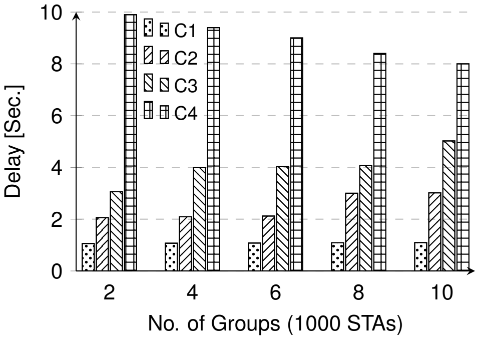
Figure 14: Throughput characteristics with increasing number of STAs and groups

- More than 50% of throughput improvement over IEEE 802.11h

Network and Groups- Throughput & Delay



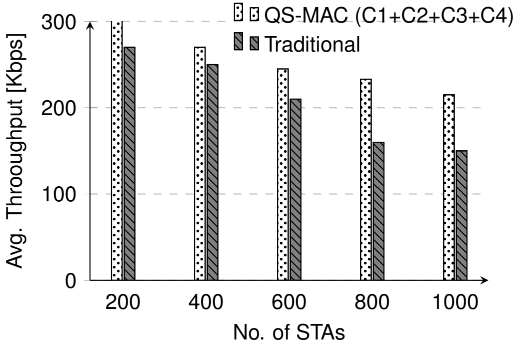
(a) Throughput



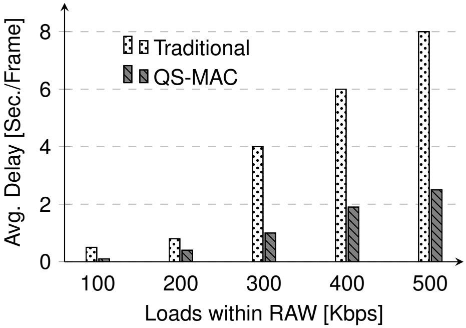
(b) Delay

Figure 15: Average throughput and delay for different network and node group sizes respectively

Effect of dynamic AID



(a) Effect of grouping in throughput



(b) Effect of dynamic AID in delay

Figure 16: Average throughput and delay performance

- Considering 50% of QoS traffic in a RAW group, overall throughput up to 32.3% and delay up to 250% are improved.

Summary

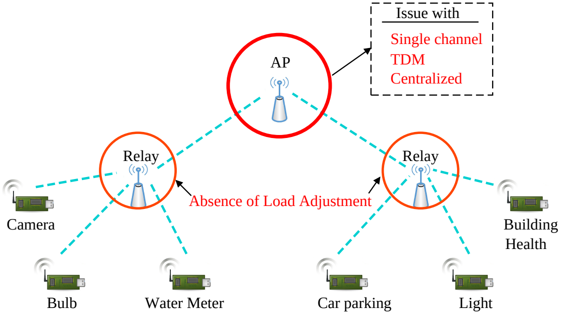
- Throughput performance improved for priority classes
- Throughput performance shows almost stable results due to the load balancing over groups
- Per packet latency also reduced for priority traffic
- Due to the dynamic grouping scheme, the proposed protocol improved throughput up to 12.7% and delay up to 300% over existing RAW schemes.
- Although the proposed QoS scheme can ensure guaranteed services for critical application upto a certain extent, with an increasing number of STAs and critical traffics, congestion will be high.

Contribution 3:

DL-MAC: Dynamic Load Balancing Scheme for Relay-based Networks

Problem Formulation

- Traffic load is not same in all parts of the network distributed by Relay
- Possibility of poor quality data reception due to long communication range and multi-hop transmission



Related works

Protocol	Details	Sectorization	Relay Support	Load Adjustment	Multi-Channel
[21, 9]	Relay node solutions for long range communication	✗	✓	✗	✗
[14, 11, 17]	Re-group STAs to solve hidden node problems	✓	✗	✗	✗
[6]	Sectorization scheme use single channel at AP	✓	✗	✗	✗

- However, absence of dynamic bandwidth adjustment at relay and congestion at AP are the issues that still need to solve

Dynamic Load Balancing Scheme for Relay-based Networks

- The contributions of this work:
  1. A large-scale network for IoT - distributed association, relay planning, and sectorization solution.
  2. A MAC layer protocol for RAPs or AP, to periodically check its load and adjust bandwidth using multiple MCSs dynamically.
  3. An efficient transmission scheduling scheme for RAP and AP communication.

The Proposed Scheme: Relay Node Planning

- Wireless distance between transmitter and receiver $d = 10^{(T_{xpower} - RSSI)/20}$ [15]
- Ang. Sep., $\theta = \frac{360^0 \times 2D}{2\pi d}$ and $\theta = \frac{360^0}{\pi}$ (d=2D), where D is the RAP node coverage.
- Minimum no. of relay nodes required in 1-hop, $N_n^1 = \lceil \frac{360^0}{\theta} \rceil$
- Since, d increases as 2d, 3d,..., with increasing hops, we can calculate the number of relay nodes in k^{th} hop as $N_n^k = \lceil \frac{k \times 360^0}{\theta} \rceil$

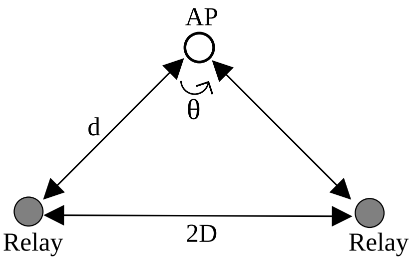


Figure 17: Position of AP and Relay nodes in the proposed network

The Proposed Scheme: Distributed Association

- Relay AP distributively takes the responsibility for node association, total association time is

$$T_{assoc} = \max\,(T_{g_a}, T_{g_i}), \forall i = 1, 2, ..., n(relays) \quad (5)$$

Where T_{g_a} and T_{g_i} is the association time required in AP and Relays respectively.

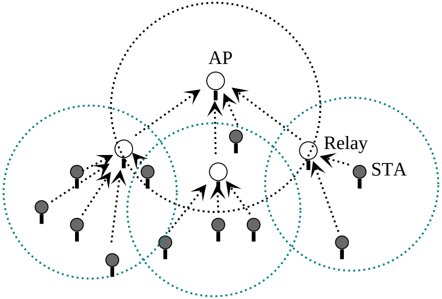


Figure 18: An example scenario of node association mechanism

The Proposed Scheme: Bandwidth Adjustment

- Allows STAs to use MCSs according to their data rate requirements
- The relay nodes monitors the current load of itself in a periodic manner
- The load is proportional to the amount of time wasted in collisions for a time duration (t) [13], which can be calculated as

$$L_t = \frac{T_{col}}{T_{col} + T_{idl} + T_{bus}} \tag{6}$$

  Where, T_{col}, T_{idl}, and T_{bus} are collision, idle, and busy time respectively. $L_t \in [0, 1]$; lower bound 0 is to say that there is no collision and upper bound, theoretical 1 means there are collisions in the complete t duration.
- Considering application's traffic requirements, number of stations, and network conditions, a Γ is chosen, switch to MCS with higher data rate when $L_t > \Gamma$ and a lower one when $L_t < \Gamma$.

The Proposed Scheme: Multi-band Sectorization

- AP node can be coped with multiple channels and hence, stations from different sectors can transmit simultaneously using different channels
- Sectorized beaconing is carried out using sector antennas

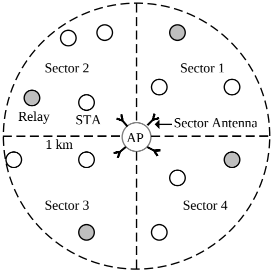


Figure 19: Sectors around the AP node

The Proposed Scheme: Channel Access (1)

- STAs associate with an AP or Relay based on the received signal strength
- AP and Relay broadcast the supported channel and MCS to the associated STAs
- There are two modes of TXOP
  1. **BlockACK-TXOP**- If the network having only Uplink Traffic (STA to AP)
  2. **BD-TXOP**- Network with bi-directional traffic, the relay switch its mode to BD-TXOP

The Proposed Scheme: Channel Access (2)

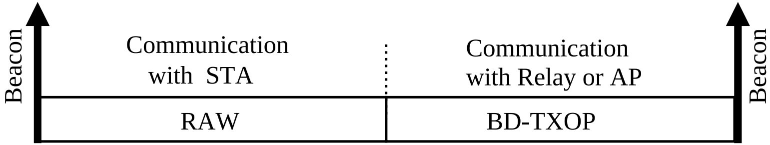


Figure 20: Channel access frame for Relay or AP

- With 2 Sectors and 2 Channels

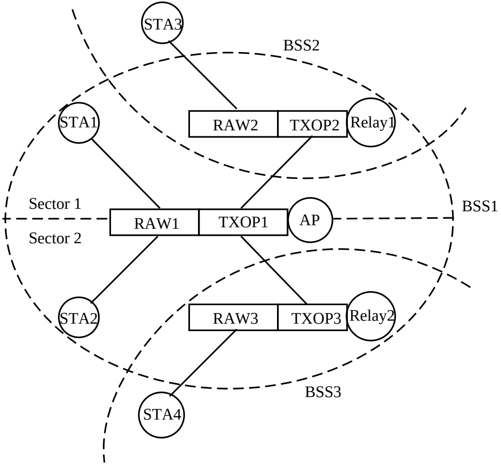


Figure 21: Schematic representation of hierarchical RAW and TXOP

The Proposed Scheme: Channel Access (4)

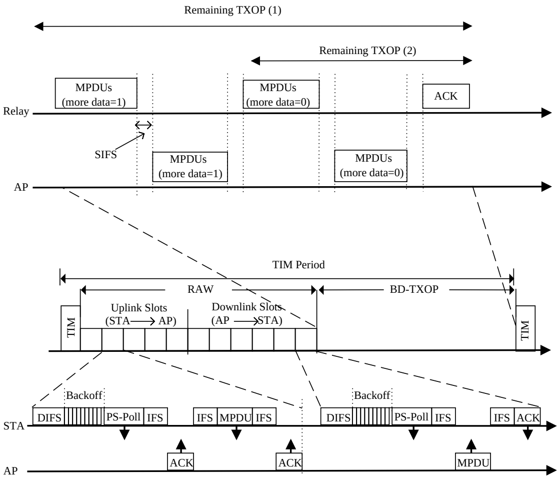


Figure 22: RAW and TXOP based access in the proposed solution

Performance Evaluation

Table 6: System and other parameters used in simulation analysis

Parameter	Value
Basic data rate	650, 300 Kbps
Payload size	256 Bytes
Radio propagation model	Outdoor (macro [4])
OFDM symbol time (T_{sym})	40 μs
MAC header	Legacy
PHY header	6 x T_{sym}
Slot time	52 μs
SIFS	16 μs
DIFS	SIFS + 2 x Slot time
Modulation and Coding	MCS0, MCS1
[CW_{min}, CW_{max}]	[15, 1023]
Backoff time	($W_{min}/2$) $\times$ Slot time
Initial backoff window	64
Types of traffic	UDP
Traffic Interval	100 *ms*
Simulation area	2000 *m* $\times$ 2000 *m* Flat-grid
Bandwidth	1, 2 MHz
TXOP	BlockACK (Uplink), Bi-Directional
No. of nodes (Max.)	3000
RAW size	15
Group size	8
Beacon interval	100 *ms*

Association Time

1. Total association time for 2000 devices in the , whereas, in traditional 802.11ah, it is 42 Seconds.
2. The RAP nodes are further supported with multiple MCSs, where it can choose an MCS with a higher or lower data-rate according to the current requirements of a BSS

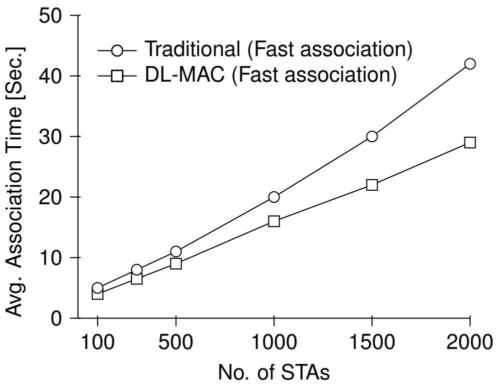
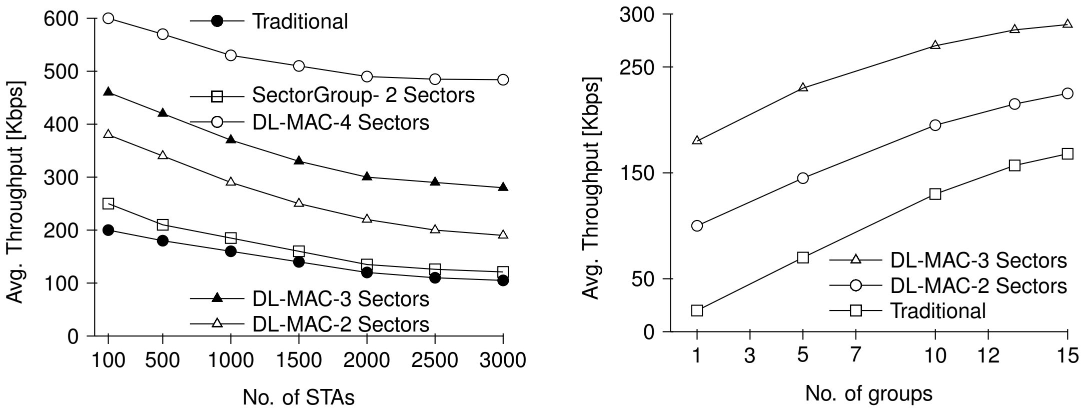


Figure 23: Average association time in proposed Vs. traditional Scheme

Throughput Performance



(a) Increasing number of STAs

(b) Increasing number of groups

Figure 24: Throughput characteristics in proposed Vs. existing schemes

Throughput at Normal Load

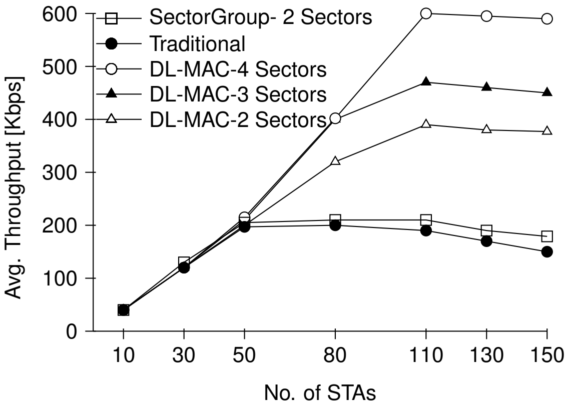


Figure 25: Throughput characteristics at normal load condition

- Once the saturation point has achieved, the performance of the proposed protocols start deteriorating

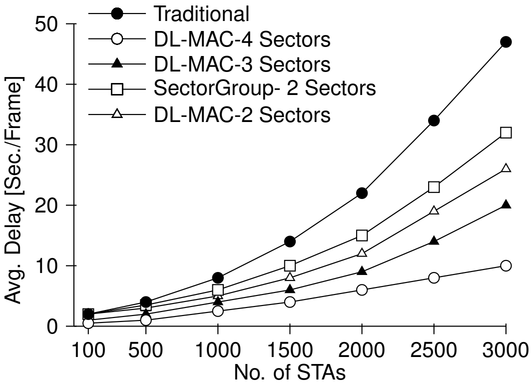


Figure 26: Average packet delay

- The proposed protocol allows simultaneous transmission indifferent sectors by using different channels

Dynamic Load Balancing

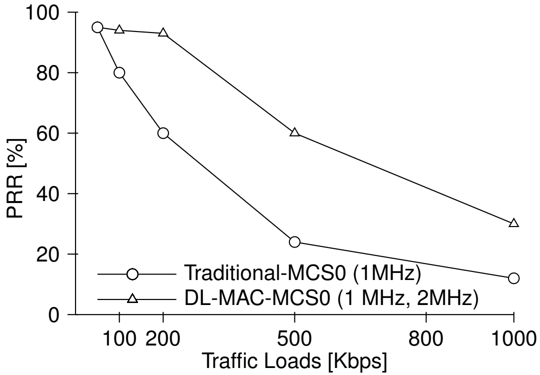


Figure 27: Average Packet Received Ratio (PRR)

- The proposed scheme performs almost 25% better than the traditional one.

Efficiency of BD-TXOP

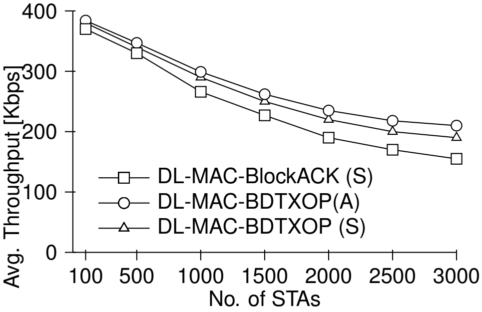


Figure 28: Throughput performance with increasing number of STAs

- The theoretical results show almost similar throughput as compared to the simulation performance considering the same configuration

Summary

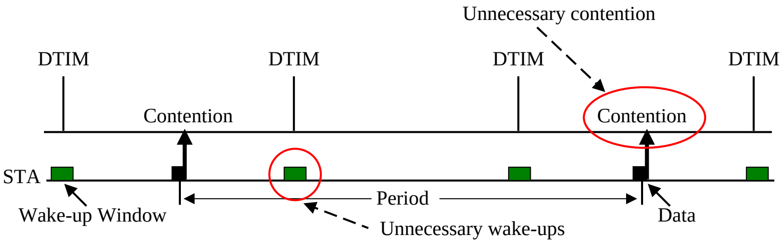
- With the support of multi-band sectorization and dynamic bandwidth allocation scheme the proposed protocol increases channel capacity upto a great extent
- The proposed solution further improves efficiency by allowing TXOP based communication between AP and Relays
- In IoT, most of the implementations deploy a huge number of periodic STAs for monitoring purposes. A channel access mechanism can be redesign to achieve better efficiency in terms of throughput and power consumption

Contribution 4:

PS-MAC: Periodic Traffic Scheduling Scheme for IoT

Problem Formulation

- The applications including smart-healthcare, smart-agriculture, etc., require a large-scale nodes to be deployed for the purpose of monitoring (Interval $\geq$ 1 Sec.)
- Repeated channel access and unnecessary wake-up of low-power devices are not suitable



Related works

Protocol	Details	Reduce Unnecessary Contention	Consider Periodicity of Traffic	Saves Energy
[27, 23, 31, 26, 25, 34, 35]	Estimate RAW size for TIM stations	✗	✗	✗
[24]	Predict alarm reporting and schedule over RAW	✗	✓	✗
[34, 35]	Optimize RAW based on energy consumption	✗	✗	✓

- However, unnecessary wake-up and high contention still exist

Periodic Traffic Scheduling Scheme for IoT

- Identifying periodic STAs is beneficial and further investigating how they negotiate over periodic RAW with a large number of STAs is a challenge
- Contributions:
  1. A hybrid MAC protocol considering contention and reservation-based scheduling for large-scale 802.11ah networks
  2. A service interval prediction algorithm is developed to appropriately adjust the next slot for transmission
  3. An efficient RAW for the periodic stations to reduce contention over the time frame

The Proposed Scheme: RAW Structure

- The new RAW is a combination of PS – PollRAW, UplinkPRAW, and NormalRAW

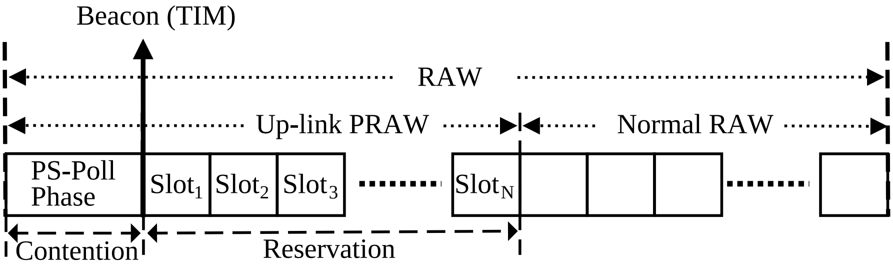


Figure 29: The RAW structure used in the proposed scheme

The Proposed Scheme: Initial contention (1)

- It helps to appropriately predict the number of periodic stations in the network which are trying to access in a RAW group
- STAs use the traditional DCF based access mechanism to grab the channel
- Initially, the size of PS-Poll is kept as large as possible so that all the stations get a chance for contention
- Let T_{CON} be the contention time for requesting the AP node for transmission, then

$$T_{CON} = T_{PS-PoLL} + T_{ACK} + 2T_{P} + T_{BO} + 2T_{IFS} \quad (7)$$

Where, $T_{PS-PoLL}$, T_{ACK}, T_{BO}, and T_{P} are the time required to send a PS-Poll, an ACK, for Backoff, and Propagation respectively

The Proposed Scheme: Initial contention (2)

- If there are N_{RAW} number of stations in a group, assuming all station are not transmitting at the same time, the maximum time kept for the first phase is

$$T_{PS-PollPhase} = N_{RAW} \times T_{CON} \quad (8)$$

- The value of $T_{PS-PollPhase}$ is reduced based on the number of stations in a group not entered yet in the PRAW phase, which is calculated as

$$N_{NCON} = N_{RAW} - N_{CON} \quad (9)$$

Where, N_{CON} are the number of already contended STAs

The Proposed Scheme: Prediction of Frame Interval

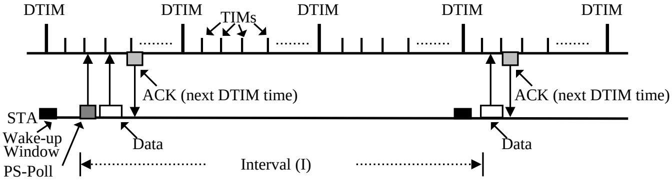
- For a RAW group, a Circular Queue (CQ) is maintained to keep track of the recent traffic interval scenarios of different stations
- The packets coming from the same stations are numbered in a sequence with increasing values
- The AP calculates packet interval (I) value for each of the STAs from the times of recently received two consecutive frames
- If $T_{P_1}, T_{P_2}, ..., T_{P_{k-1}}, T_{P_k}$ are the times at which packets are received consecutively from a STA, I-value can be calculated as:

$$I = \frac{(T_{P_2} - T_{P_1}) + ... + (T_{P_k} - T_{P_{k-1}})}{k}$$

For higher variation in the interval σ ($\sigma \leq \sigma_{max}$, where σ_{max} is the maximum value of allowed variance), we may need to set a higher value of k for better accuracy.

The Proposed Scheme: Scheduling

- Number of wake-up windows for DTIM and contention for Tx is reduced using achieved (P_I) value
- An example:



The Proposed Scheme: An Example

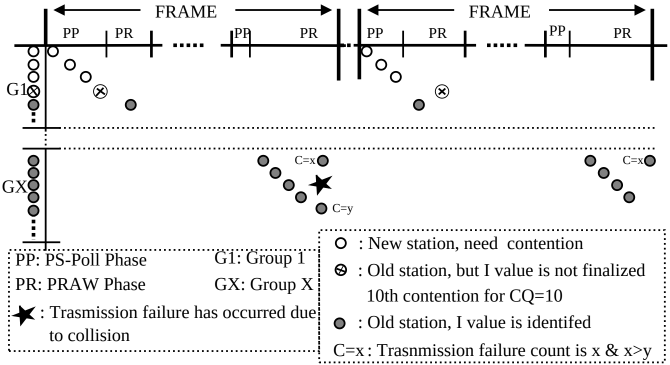


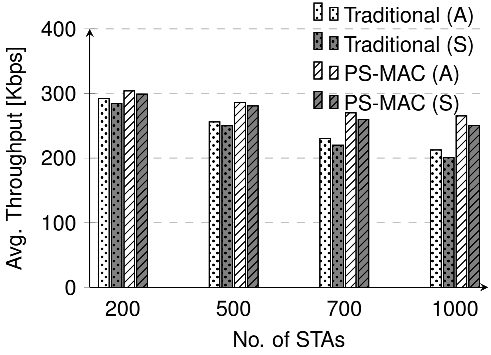
Figure 30: RAW-based hybrid access mechanism

Performance Evaluation

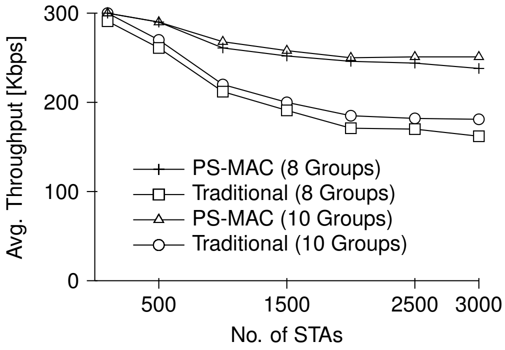
Table 7: Parameters used in Simulation and Analysis

Parameters	**Value**
Bandwidth	2MHz (MCS0)
Data rate	650Kbps
Payload size (L) /Traffic type	256Bytes/UDP
Avg. Traffic rate	$\approx$2Kbps
Traffic type	UDP
CWmin/ CWmax	15/ 1023
Backoff slot time	52 μs
SIFS time	160 μs
DIFS time	SIFS+2*slot time μs
Distribution / Path loss model	Random /Macro
T_{PHY}	6 * symbol duration (μs)
MAC (m_h) header	14Bytes
Queue	100
CQ size	10
Group size	2-10
RAW size	15
No. of STAs (Max.)	3000
$P_{tx}/P_{rx}/P_{id}/P_{sl}$	255 /135/135 /1.5mW [28]
Simulator	NS-3 [1]
Simulation area	$1000 \times 1000\ m^2$
Simulation Time	5 min

Throughput results



(a) Simulation and analytical results

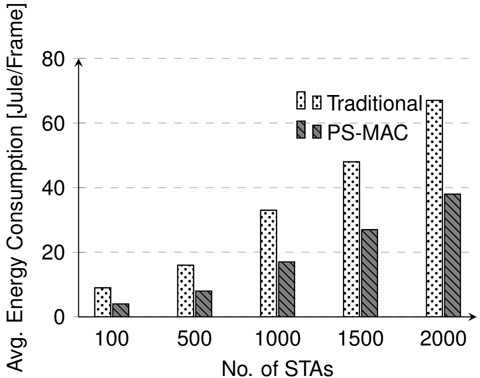


(b) Extensive simulation analysis

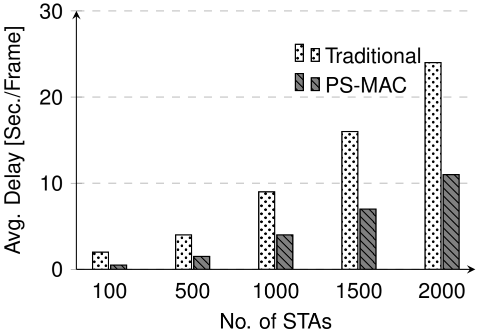
Figure 31: Throughput achieved with increasing number of STAs

- In saturated network conditions, the proposed protocol shows throughput improvement up to 25%

Energy and delay analysis



(a) Average energy consumption



(b) Average delay incurred

Figure 32: Average energy consumption and delay incurred

- For delay and energy consumption, the proposed protocol improves performance up to 55.5% and 48.4% respectively over saturated conditions

Throughput over Simulation time

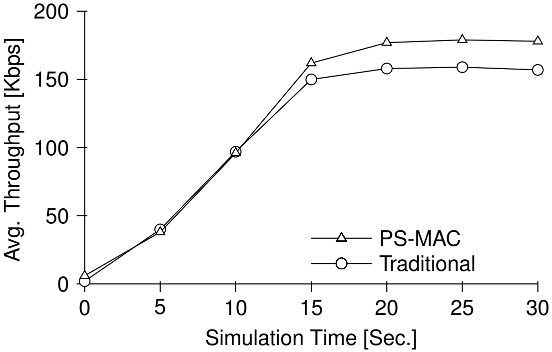


Figure 33: Average throughput achieved over simulation time

- After the association, contention continues over simulation resulting in poorer performance in the traditional scheme.

Throughput- Periodic Vs. Non-periodic Traffic

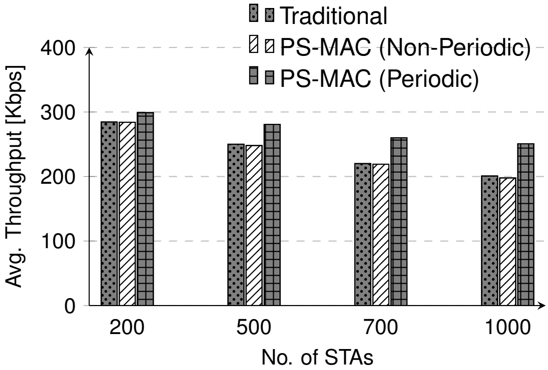


Figure 34: Throughput achieved using periodic and non-periodic traffic

- Due to the hybrid channel access, throughput results with non-periodic traffic in the proposed protocol shows almost similar results with the traditional scheme

Delay Vs. Group Size

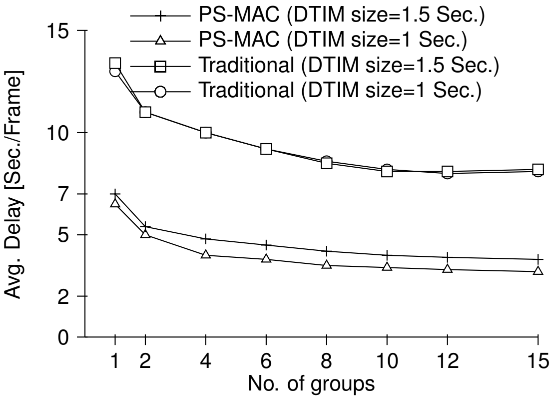


Figure 35: Average delay incurred with increasing number of RAW groups

- The proposed protocol reduces latency close to 52.3% (on average) considering 1000 STAs

Summary

- Considering the periodicity of traffic nature in IoT-based monitoring application, the proposed protocol properly predicted the traffic nature and created the transmission schedule effectively
- Power consumption due to unnecessary wake-up and channel access time is reduced upto a great extent

Overall Summary

- It can be expected that the novel IEEE 802.11ah technology will emerge more and more in the near future
- Considering the requirements of IoT applications, we have contributed the following protocol:
  1. A RAW optimization scheme for heterogeneous load conditions
     - Improved throughput performance up to 44% and 14% as compared to the traditional and TAROA protocol, respectively
     - Enabled efficient multi-hop communication
  2. A priority RAW and re-grouping scheme
     - Improved throughput up to 12.7% and delay up to 300% over existing RAW schemes.
     - Priority scheduling, fairness scheme, and adaptive grouping, use the same backoff result, consequently, reducing computation cost.
  3. The total network capacity is increased with the support of a dynamic load adjustment scheme
     - Delay performance is improved up to three as compared to traditional scheme
     - Traffic congestion issues at AP node have been resolved up to a great extent
  4. We have presented a RAW and sleep scheduling scheme for periodic stations
     - PS-MAC reduces the average latency up to 55.5%
     - Save energy consumption up to 31%
- We believe that the proposed solutions can help to achieve a scalable IEEE 802.11ah-based IoT

Limitations & Future Works

- Limitations:
  1. The proposed RAW optimization scheme considers only traffic load of the network
  2. Very less bandwidth of sub-1GHz is currently kept to use freely world-wide
- Future Works:
  1. Identification of stations to classify them into different categories is still challenging
  2. Accurately finding the service interval is still a challenge
  3. TWT time synchronization, Unnecessary wake-up, Power saving of relay node, etc.
  4. 802.11ah and 802.15.4-based networks are likely to coexist
  5. Mobility, association delay, multi-hop overhead, lightweight upper layer solution, etc.

List of publications

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Thank you