System Modeling of the RBT-based Trigger-RAW Channel-Access Method for IEEE 802.11ah IOT Network

Chung-Ming Huang
Dept. of Computer Science and Information Engineering
National Cheng Kung University,
Tainan, Taiwan
PRESENTER: Prof. Chung-Ming Huang
huangcm@locust.csie.ncku.edu.tw

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PRESENTER

Chung-Ming Huang received the B.S. degree in electrical engineering from National Taiwan University on 1984/6, and the M.S. and Ph.D. degrees in computer and information science from The Ohio State University on 1988/12 and 1991/6 respectively. He is currently a Distinguished Professor of Dept. of Computer Science and Information Engineering, National Cheng Kung University, Tainan, Taiwan, R.O.C. He (i) was Chair of Dept. of Computer Science and Information Engineering and Director of Institute of Medical Informatics, National Cheng Kung University, Taiwan, R.O.C. and (ii) served as the Chair of IEEE Vehicular Technology Society Tainan Chapter. He has published more than 300 referred journal and conference papers in wireless and mobile communication protocols, vehicular network, audio and video streaming and formal modeling of communication protocols. His research interests include wireless and mobile network protocol design and analysis, vehicular network, media processing and video streaming, and innovative network applications and services. He a senior member of IEEE (SM'07) and ACM (SM'12).

Outline

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2. System Architecture and the functional scenario.
3. System Modeling of the Proposed Method.
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5. Conclusion

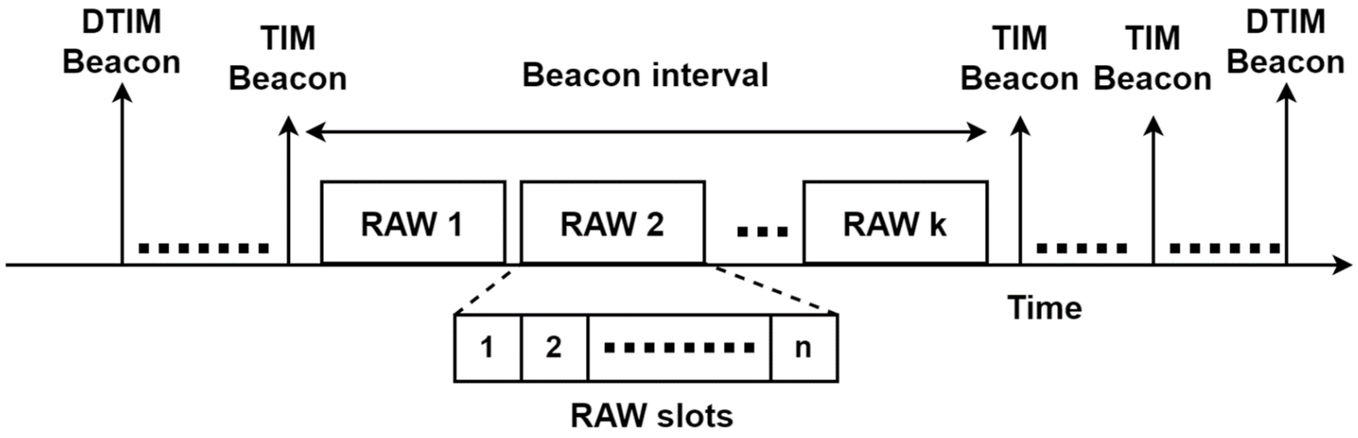
Introduction

802.11ah (Wi-Fi Halow)

- Internet of Things (IoTs), which try to connect a large number of devices such as thermometer, sensors, smart TV, etc., has become one of the most important technologies.
- IEEE 802.11ah can support up to 20Mbps data transmission rate at the PHY layer; the transmission range can be up to 1 kilometer.
- A single IEEE 802.11ah's AP can manage up to 8191 wireless stations (STAs) at the same time, for which the time-division approach is adopted for STAs' channel access.

Traffic Indication Map (TIM) Segmentation

- IEEE 802.11ah adopts the Traffic Indication Map (TIM) Segmentation mechanism to divide STAs into several TIM groups.
- STAs in each group only wakes up on specific time to access channel.
- Two types of control beacons sent from AP are Traffic Indication Map (TIM) and Delivery TIM (DTIM)
- DTIM beacon: DTIM beacon indicates which TIM segments have the buffered data on the AP side.
- TIM beacon: The TIM beacon contains the grouping information in the TIM interval.



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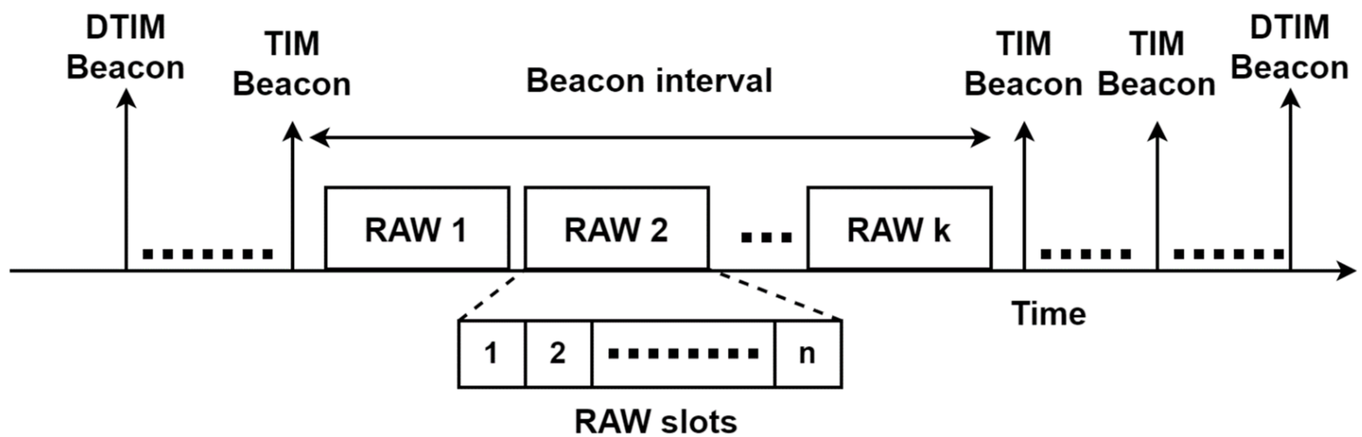
Restricted Access Window (RAW)

- Restricted Access Window (RAW) mechanism limits the number of STAs to access channel at the same time and reduces the collision probability.
- A DTIM period is divided into several TIM periods; a TIM time period is divided into several RAWs and the duration of each RAW is assigned by AP.
- Each RAW's duration is divided into several time slots.
- In a time slot, only part of the STAs, which are also called a "subgroup", in the RAW group are included.



The Collision Problem

- Although the TIM and RAW mechanism can reduce the collision, the collision still can happen when there are two or more stations, which belong to the same slot of a RAW, have data to send, having the same backoff value.

- Thus, the Registered Backoff Time (RBT) channel access approach was adopted in this work to avoid collision and make the communications between STAs and AP be more efficient.

The Claim-based Channel Access (CCA) Method

- The CCA method is one of the RBT channel access approach which is proposed for scheduling the channel access's sequence of the STAs [1][2].
- The RBT concept is that each STA randomly generates a backoff value for its next channel access, which is called RBT, to AP.
- A STA X's RBT value, which is randomly chosen from the contention window, can be (i) delivered to AP when X is associating with AP on the first time, (ii) piggybacked on its uplinked data frame that is sent to AP or (iii) piggybacked on the ACK frame that is sent to AP.
- Based on the RBT values of STAs, AP can assign the STA with the lowest RBT value among those STAs that need to access channel to get the privilege of channel access while the medium is free

The Claim-based Channel Access (CCA) Method

- The key idea of the CCA method is that the AP would know the existence of STAs having uplinked data frames through the use of the claiming RAW.
- The STAs that have uplinked data to send in RAW *i* send their Claiming frames to AP in Claiming slot *i* of the Claiming RAW.
- Then, AP can know and schedule a STA to uplink its data frame(s) on its corresponding RAW's slot if its Claim frame is successfully received by AP.

The Claim-based Channel Access (CCA) Method – Remaining time

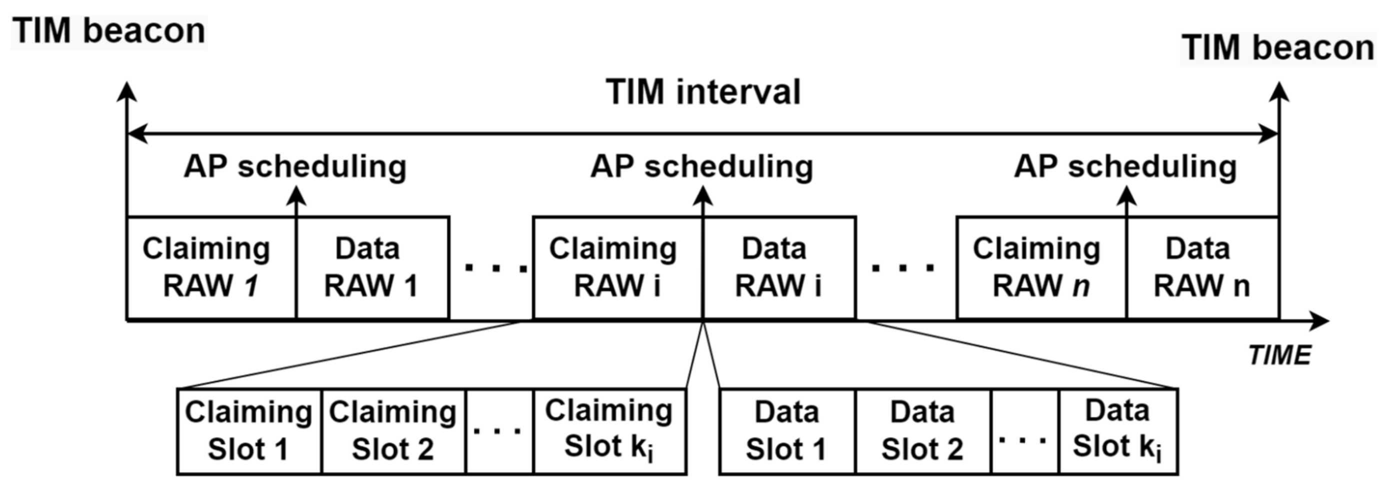
- Authors in the CCA method using the algorithmic way without the mathematical modeling and analysis.

- In this work, the CCA method is revised, for which each RAW is composed of one Claiming RAW and one Data RAW, and the mathematical modeling and analysis are presented.

System Architecture and the Functional scenario

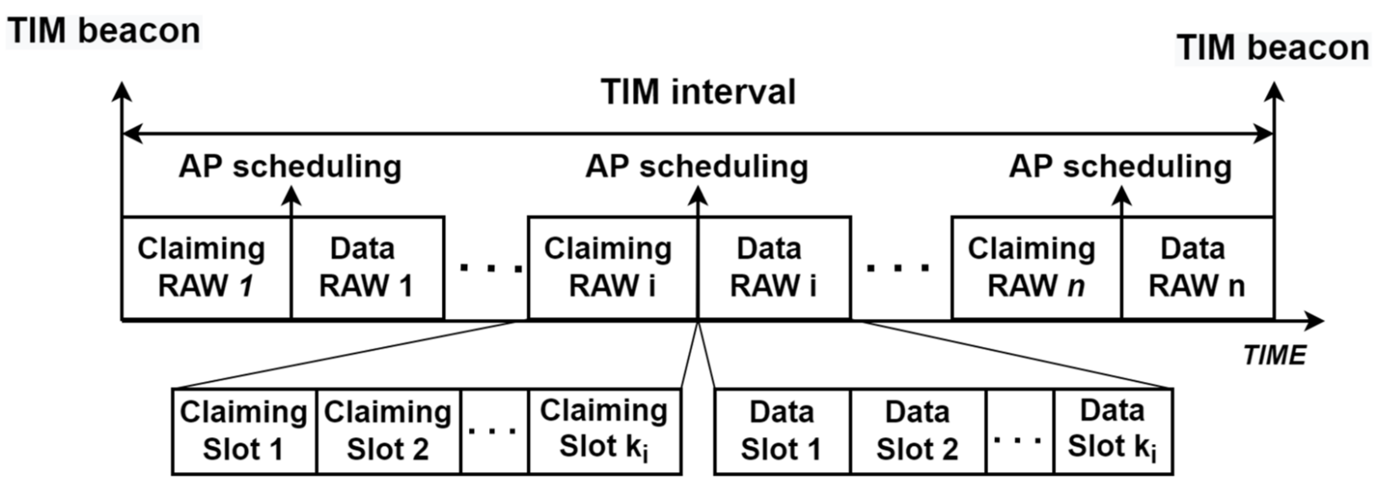
System Architecture

- Referring to the Figure, let one TIM interval have *n* groups. Each group is associated with two RAWs, in which one is Claiming RAW and the other one is Data RAW.
- The Claiming RAW is for STAs to contend their claims of the intension for delivering uplinked data frame(s) to AP by sending their claiming control frames



System Architecture

- The Data RAW is for STAs to send uplinked data to AP or/and receive downlinked data from AP.
- Each RAW is divided into k slots and each slot is for the channel access of a subgroup of STAs belonging to the RAW's group.



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Functional scenario

In the proposed method, the functional scenario is divided into three phases:

1. The claiming phase.
2. The AP scheduling phase.
3. The scheduled data transmission phase.

1. The Claiming Phase

- After receiving the TIM beacon, each STA can know whether it has some downlinked data that are to be received from the AP side in the current TIM interval or not.
- Nevertheless, AP doesn’t know whether a STA has uplinked data frame(s) to send or not.
- Thus, the STAs that have spontaneously uplinked data should notify AP in the claiming slot

Contention Process in the Claiming slot

- The STAs with only uplinked data would contend for channel access using the CSMA/CA mechanism.
- The one that wins the channel access privilege, i.e., transmitting without collision, sends the claiming control frame to AP.
- Then AP will schedule that STA's channel access in the corresponding Data RAW's slot.

2. The AP Scheduling Phase

- After the Claiming RAW is ended, AP schedules the sequences of STAs, for which AP already knows their need to access channel in the coming Data RAW, to access the channel according to their RBT values.

- If two or more STAs have the same RBT value, AP schedules these STAs to access channel according to the time stamps of the RBTs.

2. The AP Scheduling Phase

- At the end of the AP scheduling phase, i.e., before the start of Data RAW, AP should notify which STAs are the first ones to access channel in their corresponding slots respectively using an ACK frame in the end of the Claiming RAW.

- Thus, the STAs that belong to the RAW group and need to access channel in the coming Data RAW should wake up and listen to the ACK frame.

3. The Scheduled Data Transmission phase

- After AP broadcasting the ACK frame, that was notified as the first STA to access channel in its assigned data slot can immediately access channel for uplinked and/or downlinked data in its assigned data slot.

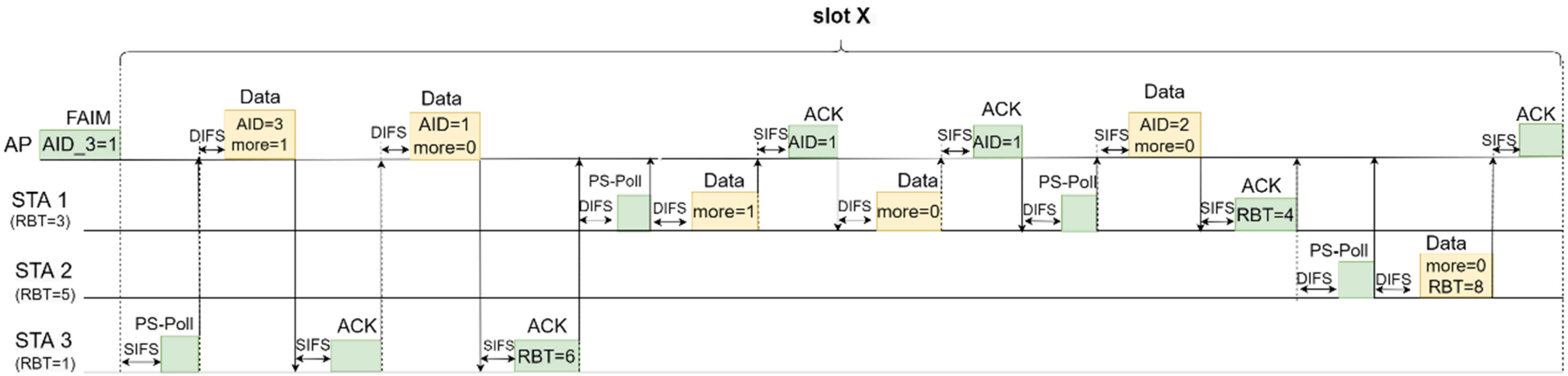
- The channel access of a STA in the scheduled data transmission phase can be divided into three types:

a) STA X only has uplinked data.

b) STA X only has downlinked data.

c) STA X has both downlinked and uplinked data frames.

An Example of the Channel Access Sequence



- The traffic demands is set as follows:

a) STA 1 has two uplinked data frames and a downlinked data frame.

b) STA 2 only has an uplinked data frame and has claimed to AP.

c) STA 3 has two downlinked data frames.

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System Modeling of the Proposed Method

Overview of the Proposed Modeling

- The modeling and analysis are mainly through the estimation of throughput.
- To formulate the throughput of a subgroup's, i.e., a slot's, throughput, it needs to calculate the time spending on the data transmission for the corresponding data volume.
- Since those STAs that only have uplinked data (without downlinked data) need to participate the Claiming phase, the number of STAs that can have successful claiming to AP needs to be derived at first.
- Using Bianchi's proposed model, the probability τ that a STA transmits in a backoff count down's time slice can be expressed as follows:

$$\tau = \frac{2 * (1 - 2p)}{(1 - 2p)(W + 1) + p * W * (1 - (2p)^m)}$$

Data Transmission on Claiming slot

- In the proposed method, the size of contention window (CW) is fixed in the claiming slot, for which the CW is set to the minimal CW, i.e., m is equal to 0. Thus, the probability τ that a STA transmits in a backoff count down's time slice can be expressed as follows:

$$\tau = \frac{2}{W + 1}$$

- The probability P_{tr} that there is at least one transmission in the considered backoff count down's time slice containing n STAs is as follows:

$$P_{tr} = 1 - (1 - \tau)^n$$

Data Transmission on Claiming slot

- Then, the probability P_{tr-s} that a transmission is successful on the condition that there is at least one transmission in the considered backoff count down's time slice can be expressed as follows:

$$P_{tr-s} = \frac{C_1^n * \tau * (1-\tau)^{n-1}}{1-(1-\tau)^n} = \frac{n * \tau * (1-\tau)^{n-1}}{1-(1-\tau)^n}$$

- $P_{tr} * P_{tr-s}$ is the probability a transmission is successful in the considered backoff count down's time slice and $P_{tr} * (1 - P_{tr-s})$ is the probability a transmission is failed in the consider backoff count down's time slice.

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Data Transmission on Claiming slot

- Thus, the normalized throughput TH_n for the situation of n STAs participating contention can be expressed as follows:

$$TH_n = \frac{P_{tr} * P_{tr-s} * FS}{(1 - P_{tr}) * \sigma + P_{tr} * P_{tr-s} * AT_{tr-s} + P_{tr} * (1 - P_{tr-s}) * AT_c}$$

where (i) FS is the frame size, σ is the backoff count down's time slice (ii) AT_{tr-s} is the average time of successfully transmitting a packet and, and (iii) AT_c is the average time of a collision.

Data Transmission on Claiming slot

- TH_n means the amount of data that can be transmitted in a second.

- In other words, TH_n/FS denotes the number of frames that can be transmitted in a second.

- Thus, it can express the time spending on a successful claiming for data transmission in the situation of n STAs participating contention as the reciprocal of TH_n/FS, which is expressed as follows: :

$$time_n^{sc} = \frac{FS}{TH_n} \ldots\ldots (4)$$

Data Transmission on Claiming slot

Let there be $N_{UL} = \sum_{i=1}^{N_{all}} P_u^i * (1 - P_d^i)$ STAs having only uplinked data.

(1) N_{all} denotes the number of STAs in the slot, i.e., sub-group.

(2) P_u^i and P_d^i denote the probability that STA *i* has uplinked and downlinked data respectively in the time interval of a DTIM.

(3) It is assumed that the packet arrival probability is Poisson Distribution and thus $P_u^i = 1 - e^{-\lambda_u t}$ and $P_d^i = 1 - e^{-\lambda_d t}$, where λ_u (λ_d) is the uplinked (downlinked) packet arrival rate of STA i and t is the time length of DTIM.

Data Transmission on Claiming slot

The claiming procedure is showed as follow's steps:

(i) N_{UL} STAs contend and one of the STAs has successful claimed to AP.

(ii) The remaining $N_{UL}-1$ STAs contend, and one of the STAs has successfully claimed to AP.

(iii) So on and so forth till the last STA sends its claiming frame to AP.

Data Transmission on Claiming slot

- The ideal situation is that all N_{UL} STAs have successfully claimed to AP.
- Nevertheless, the claiming slot may not have enough time for all N_{UL} STAs to send their claiming frames to AP.
- Thus, it needs to find the maximum number of STAs that can send their claiming frames to AP as follows:

$$\max_{\alpha} \sum_{k=0}^{\alpha} time_{N_{UL}-k}^{sc} < time_{c\_s}, \alpha < N_{UL}$$

where $time_{c\_s}$ is the time period of a claiming slot.

- Thus, the number of STAs that can have successful claims to AP is:

$$N_{c\_s} = \alpha + 1$$

Data Transmission on Scheduled sub-slot

With the claiming information, AP can know that there are:

(i) N_{c_s} STAs that have uplinked data to AP.

(ii) $N_{DL} = \sum_{i=1}^{N_{all}} P_d^i * \left(1 - P_u^i\right)$ STAs that only have downlinked data to AP.

(iii) $N_{UL\&DL} = \sum_{i=1}^{N_{all}} (P_d^i \ * \ P_u^i\ )$ STAs simultaneously have uplinked and downlinked data.

Data Transmission on Scheduled sub-slot

- Let the RBT values of STAs $st_1, st_2, \ldots, st_n$ be $RBT_{st_1} \leq RBT_{st_2} \leq RBT_{st_3} \leq \cdots \leq RBT_{st_n}$.
- Then the scheduled channel access sequence is $st_1, st_2, \ldots, st_n$.
- The channel access time of scheduled STAs $time_{s\_a}$ should not exceed the data slot and is expressed as follows:

$$time_{s\_a} = \max_{k} \sum_{i=1}^{k} \begin{Bmatrix} time_{ul}^{i} * P_u^i * \left(1 - P_d^i\right) * Port_{c\_s} \\ +time_{dl}^{i} * P_d^i * \left(1 - P_u^i\right) \\ +\left(time_{ul}^{i} + Ttime_{dl}^{i}\right) * P_u^i * P_d^i \end{Bmatrix} < time_{d_{slot}} \ldots (3)$$

1. $time_{ul}^{i}$ ($time_{dl}^{i}$) is the uplinking (downlinking) time of STA i, which includes the time for uplinked (downlinked) data frame's transmission and control messages' transmission.
2. P_u^i and P_d^i denote the probability that STA *i* has uplinked data and downlinked data respectively in the time interval of a DTIM.
3. $Port_{c\_s}$ is the portion of successfully claiming STAs in the claiming slot, which is equal to N_{c_s}/N_{UL}.
4. $time_{d_{slot}}$ is the duration of a data slot.

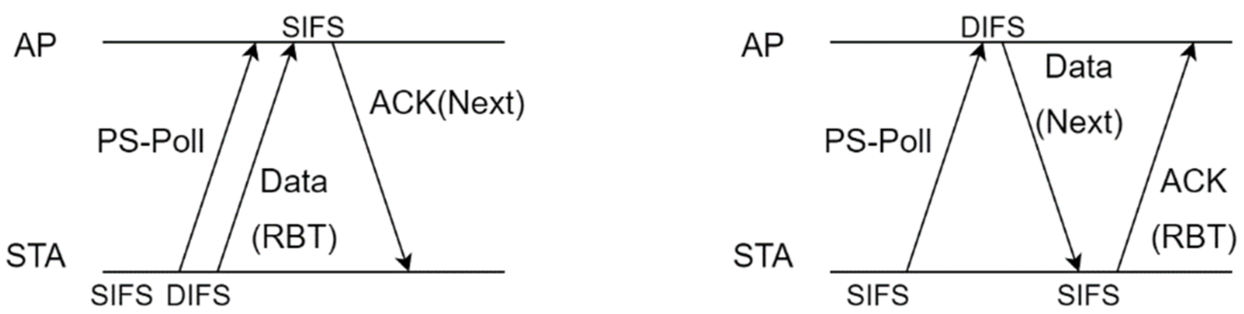
Data Transmission on Scheduled sub-slot

- The time flow charts for the situations of uplinked and downlinked data is depicted in the following Figure.
- Then, the time spending on sending an uplink data frame is as follows:

$$time_{UL} = t_{SIFS} + t_{PS-Poll} + t_{DIFS} + t_{Data} + t_{SIFS} + t_{ACK}$$

- The time spending on sending a downlinked data frame is as follows:

$$time_{DL} = t_{SIFS} + t_{PS-Poll} + t_{DIFS} + t_{Data} + t_{SIFS} + t_{ACK}$$



Data Transmission on Scheduled sub-slot

- If there are more than one uplinked or downlinked data frame, these data frames can be transmitted without sending the PS-Poll frame again, which can be notified by setting more bit to be equal to 1.
- Thus, the transmission time of STA i $time_{ul}^{i}$, which has AUD_{ul}^{i} uplinked data frames, can be expressed as follows:

$$time_{ul}^{i} = t_{SIFS} + t_{PS-Poll} + AUD_{ul}^{i} * (t_{DIFS} + t_{D_i} + t_{SIFS} + t_{ACK})$$

- Let the data arrival pattern of the uplinked data be the Poisson distribution. The probability P_{k_i} of a STA i having k uplinked data frames to send to AP in a DTIM period $time_{Dtim}$ is expressed as follows:

$$P_{k_i} = {(\lambda_u^i * time_{DTIM})^k * e^{-\lambda_u^i * time_{DTIM}}} \Big/ {k!}$$

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Data Transmission on Scheduled sub-slot

- Then, the number of average uplinked data frames that STA i sends to AP is expressed as follows:

$$AUD_{ul}^{i} = \sum_{k=1}^{\infty}(P_{k_i} * k) \Big/ \sum_{i=1}^{\infty} P_{k_i}$$

- The transmission time of STA j $time_{dl}^{j}$, which has ADD_{dl}^{j} downlink data frames, can be expressed as follows:

$$time_{dl}^{j} = t_{SIFS} + t_{PS-Poll} + ADD_{dl}^{j} * \left(t_{DIFS} + t_{D_i} + t_{SIFS} + t_{ACK}\right)$$

- Let the data arrival pattern of the downlinked data be the Poisson distribution. The probability P_{k_j} of a STA j having k data frames to receive from AP is expressed as follows: :

$$P_{k_j} = (\lambda_d^j * time_{DTIM})^k * e^{-\lambda_d^j * time_{DTIM}} \Big/ k!$$

- Then, the number of average downlinked data frames that STA j receives from AP is expressed as follows:

$$ADD_{dl}^{j} = \sum_{k=1}^{\infty}(P_{k_j} * k) \Big/ \sum_{i=1}^{\infty} P_{k_j}$$

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Data Transmission on Scheduled sub-slot

- The value k of Equation 3 has been derived. Thus, the total data volume transmitted on the Data slot $DV_{scheduled}$ can be expressed as follows:

$$DV_{scheduled} = \sum_{i=1}^{k} \left\{ \begin{array}{c} AUD_{up}^{i} * FS * P_{u}^{i} * (1 - P_{d}^{i}) * Port_{c\_s} \\ +ADD_{dl}^{j} * FS * P_{d}^{i} * (1 - P_{u}^{i}) \\ + \left(AUD_{up}^{i} + ADD_{dl}^{j}\right) * FS * P_{u}^{i} * P_{d}^{i} \end{array} \right\}$$

(i) $AUD_{up}^{i}/ADD_{dl}^{i}$ is the number of uplinked/downlinked data frames of STA *i*.

(ii) FS is the size of a data frame.

(iii) $Port_{c\_s}$ is the portion of successfully claiming STAs in the claiming slot.

- Then, the expected throughput of a slot can be expressed as follows:

$$Th_{total}^{exp} = \frac{DV_{scheduled}}{time_{d_{slot}}}$$

where $time_{d_{slot}}$ is the time of data slot.

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Performance Evaluation

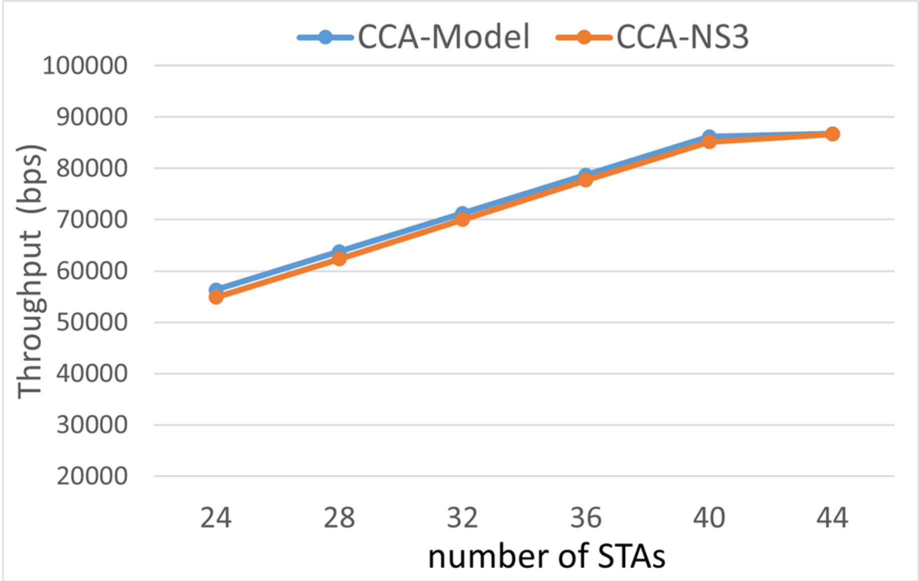
The Simulation Environment and Parameters' Setting

- The simulation environment deployed an AP and different numbers of stations to build the 802.11ah network.
- The proposed system model was implemented using MATLAB and NS-3 was adopted to simulate the environment of 802.11ah.
- Related parameters and their corresponding values are depicted in the Table.

Parameter	Value
CWmin	16
CWmax	1024
MAC Header Type	legacy header
MAC header	14 bytes
Payload Size	100 bytes
Claiming slot	20ms
backoff count down's time slice	52us
SIFS	160us
Wi-Fi Mode	MCS10, 1 Mhz

Simulation results – low uplink – (a)

- “RBT-TRCA-Model” denotes the results using the proposed system model, for which the results were derived using MATLAB.
- “RBT-TRCA-NS3” denotes the simulation results using the NS3-based implementation.
- Referring to Figure (a), the throughput is linearly increased when the number of STAs is from 24 to 40.
- When the number of STAs are 40 and 44, the slot reaches the overloaded situation, i.e., the data slot time is not enough for all STAs to access channel, and thus the throughput would remain the same.



Arrival rate	uplink	downlink
0.075 pkt/s	100%	25%
0.1 pkts/s	0%	25%
0.15 pkt/s	0%	50%

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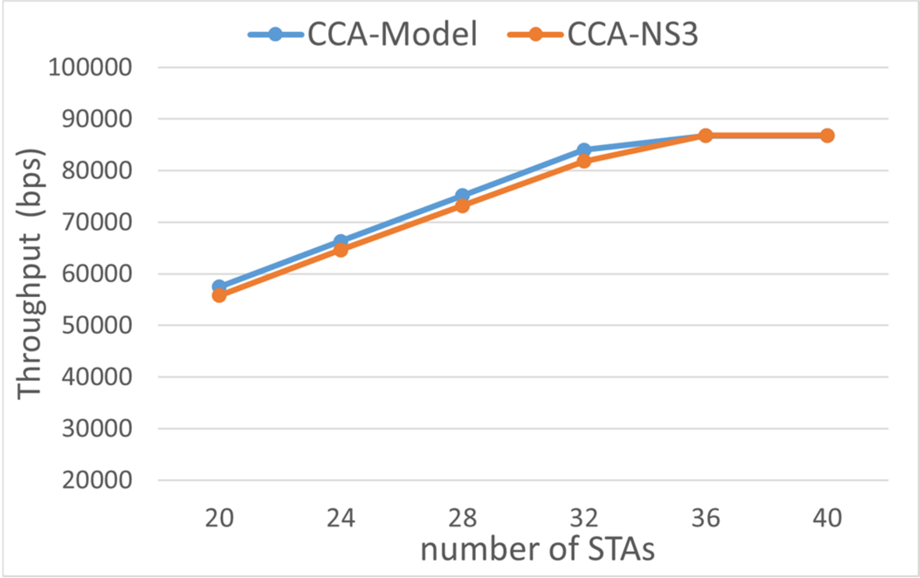
Simulation results – high uplink – (b)

- Since Figure-(b) has the higher uplink traffic demands than Figure-(a), the data frames that can be scheduled to transmit of Figure-(b) is higher than that of Figure-(a) when the number of STAs are same, i.e., from 24 to 40.

- Thus, Figure-(b) has the smaller number of STAs, i.e., 36, than that of Figure-(a), i.e., 40, when the overloaded situation is reached.



Arrival rate	uplink	downlink
0.075 pkt/s	0%	25%
0.1 pkts/s	0%	25%
0.15 pkt/s	100%	50%

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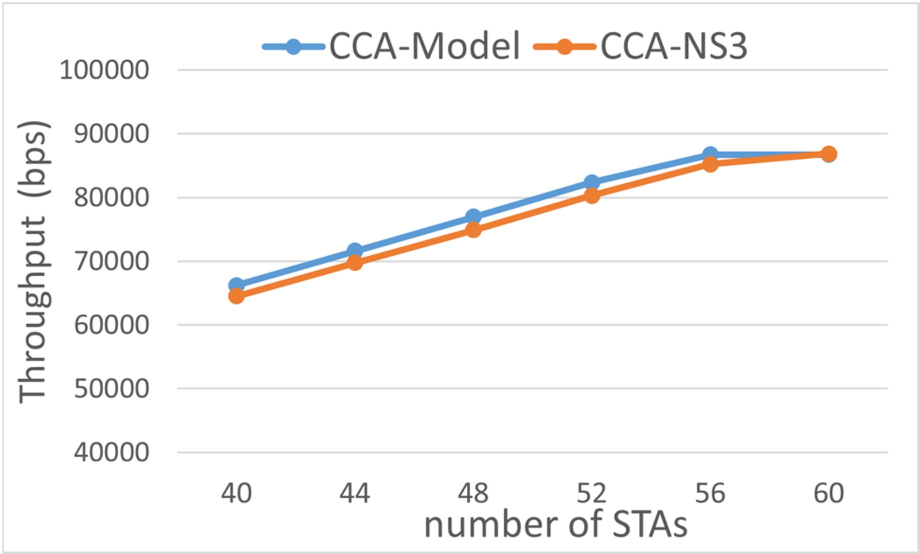
Simulation results – low downlink – (c)

- Since Figure-(c) has the lower downlink traffic demands, most of the STAs use the claiming way to uplink their data, i.e., contend for the privilege to send the claim frame to AP.
- When a high number of STAs access channel in the claiming slot, the channel would be congested and thus some of the STAs cannnot send their claim frames to AP during of the claiming slot.
- It is the reason that Figure-(c) has the larger number of STAs, i.e, 56, than that of Figure-(a) and (b) when the overloaded situation is reached.

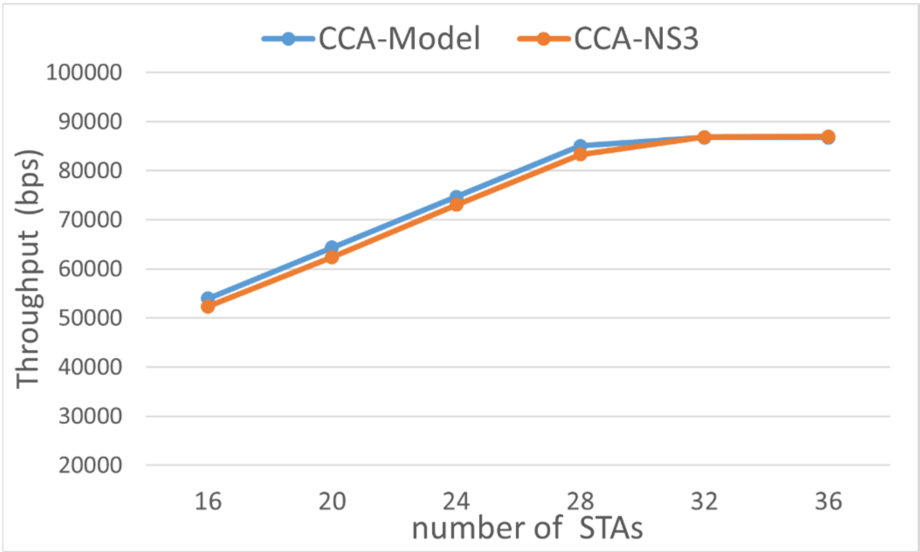


Arrival rate	uplink	downlink
0.075 pkt/s	25%	100%
0.1 pkts/s	25%	0%
0.15 pkt/s	50%	0%

Simulation results – high downlink – (d)

- Since the STAs in Figure-(d) has the higher downlinked traffic demands, it has the higher probability that AP can know STAs' intentions to transmit data and AP can schedule these STAs to access channel.

- Thus, Figure-(d) has the smallest number of STAs, i.e., 32, than that of Figure-(a), (b) and (c), when the overloaded situation is reached.



Arrival rate	uplink	downlink
0.075 pkt/s	25%	0%
0.1 pkts/s	25%	0%
0.15 pkt/s	50%	100%

Conclusion

Conclusion

- In the proposed work, a formal modeling has been devised for analyzing the scheduling phase of the proposed RBT-TRCA method.
- Using the proposed RBT-TRCA method, STAs can use the Claiming RAW's slot to transmit their claiming control frames to AP to indicate their intentions for uplinking data, which belongs to the Triggered RAW approach; AP can schedule STAs to access channel according to their RBT values.
- In this way, the collision rate can be decreased and the communication between STAs and AP can be more efficient.
- To validate the proposed system modeling for the proposed RBT-TRCA method, four kinds of testing configurations have been analyzed and evaluated.
- It has shown that the analysis model's results are similar to the NS-3-based simulation results.

Conclusion

[1] C. M. Huang, R. S. Cheng and Y. J. Pan

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[3] Chung-Ming Huang* and Chia-Han Hsieh

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