Santa Clara University
Internet of Things
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Traffic Characterization for Efficient TWT Scheduling in 802.11ax IoT Networks

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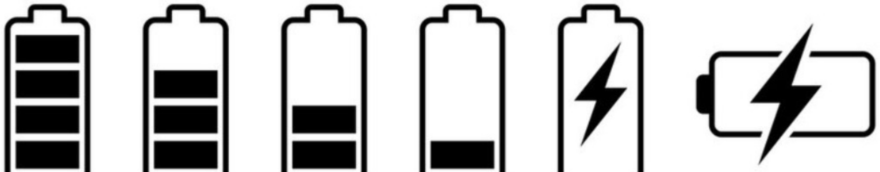
Introduction

- **The adoption of WiFi technology, especially for IoT connectivity**
  - WiFi technology provides **higher communication rates** compared to technologies such as Bluetooth and ZigBee
  - WiFi communication utilizes **unlicensed spectrums**
    - Deployments are considerably less expensive than cellular technologies
  - **An omnipresent infrastructure for connectivity**
    - **Distributed and customer-oriented deployment of WiFi networks** in residential and enterprise settings
    - Low deployment costs

Introduction



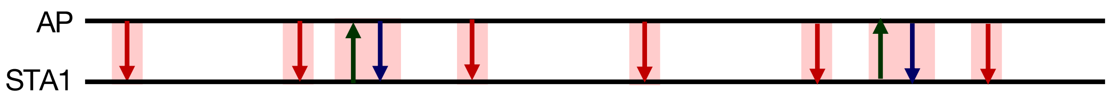
- **Many IoT devices rely on limited energy resources such as batteries or energy harvesting**

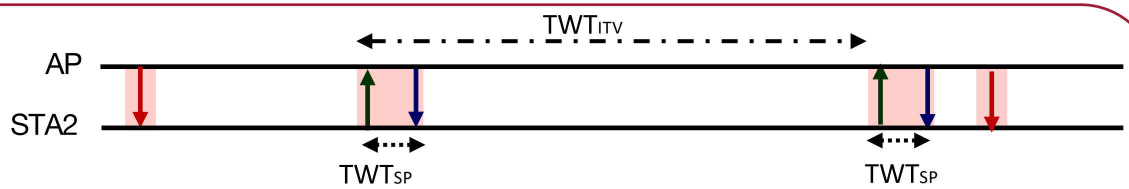
- **The 802.11 standard offers various power-saving modes:**
  - Power Save Mode (PSM)
  - Adaptive PSM (APSM)
  - Adaptive Power Save Delivery (APSD)

Introduction

802.11
b, g, n, ac

- STA wakes up every beacon





802.11 ax

- A new functionality introduced called Target Wake Time (TWT)
- Allows negotiation of sleep schedule
- STA does not need to wake up every beacon

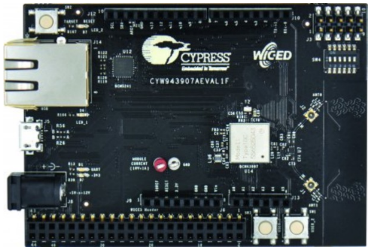
Notation	Meaning
	Beacons
	Uplink packets
	Downlink packets
	STA awake duration
TWT_{ITV}	TWT Interval
TWT_{SP}	TWT Service Period

- TWT allows STA to switch to low-power sleep state for a prolonged period
- How to accurately characterize traffic for allocating TWT_{SP} schedule?

Traffic Pattern Analysis

We study the following IoT applications (interference-free environment)

- **Sensing**
  - An RTOS development kit (CYW54907) collecting accelerometer readings
  - Periodically collects 3920 samples (equivalent to 5880 bytes), prepares packets, and then sends them via a TCP connection

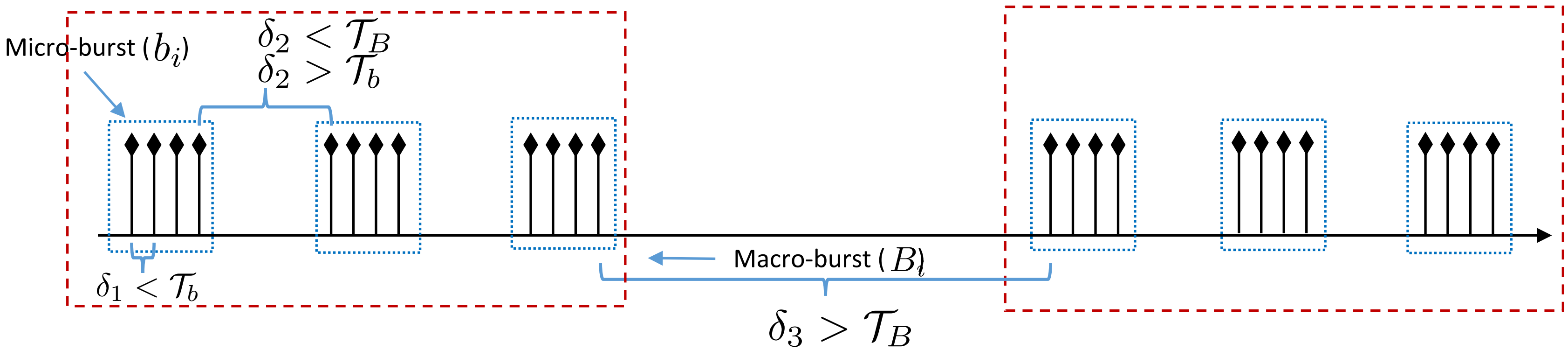


- **Camera**
  - A security camera using RPi camera module (version 2) attached to a RPi 3B+
  - Captures and sends images via a TCP connection
    - Each image is processed by the H.264 codec

- **Video Streaming**
  - A YouTube video is streaming on an Amazon Echo Show device

Traffic Pattern Analysis

- To build a generalized traffic analysis framework, we consider three inter-packet intervals



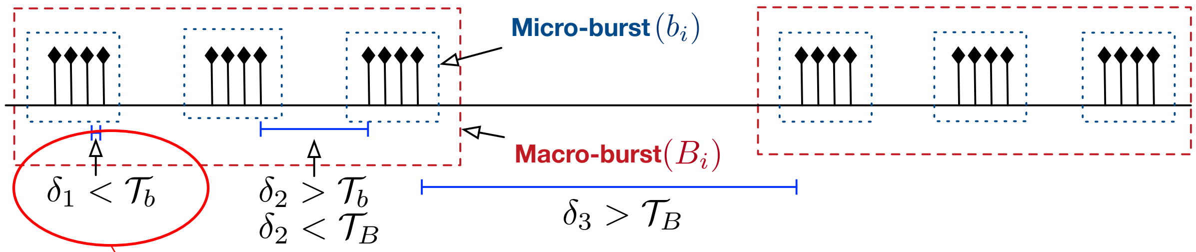
Traffic components:

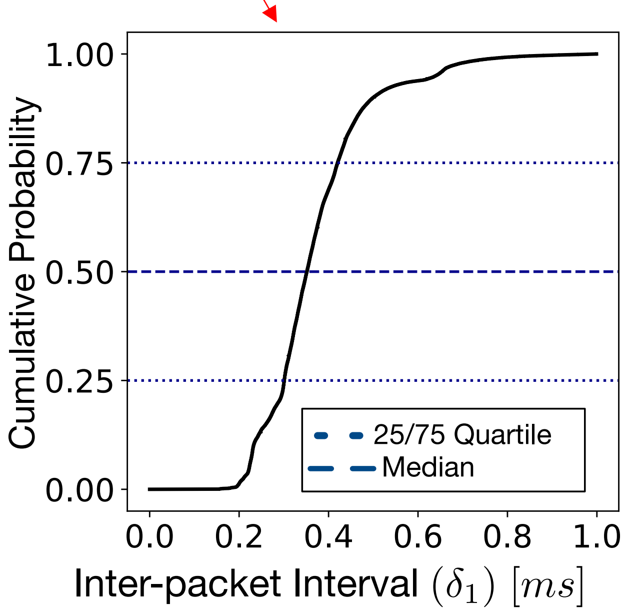
- Macro-burst $\Longrightarrow$ Power save mechanism employed
- Micro-burst $\Longrightarrow$ Contention or traffic generation pattern
- Packets within a Micro-burst $\Longrightarrow$ Packet preparation delay or Transmission parameters of 802.11

Traffic Pattern Analysis

Sensing

- Within a micro-burst, the mean interval between packets (δ_1) is about 400 μs





- Collecting 3920 samples from accelerometer
  - Equivalent to (3920 * 12 bits)/8 = 5880 bytes

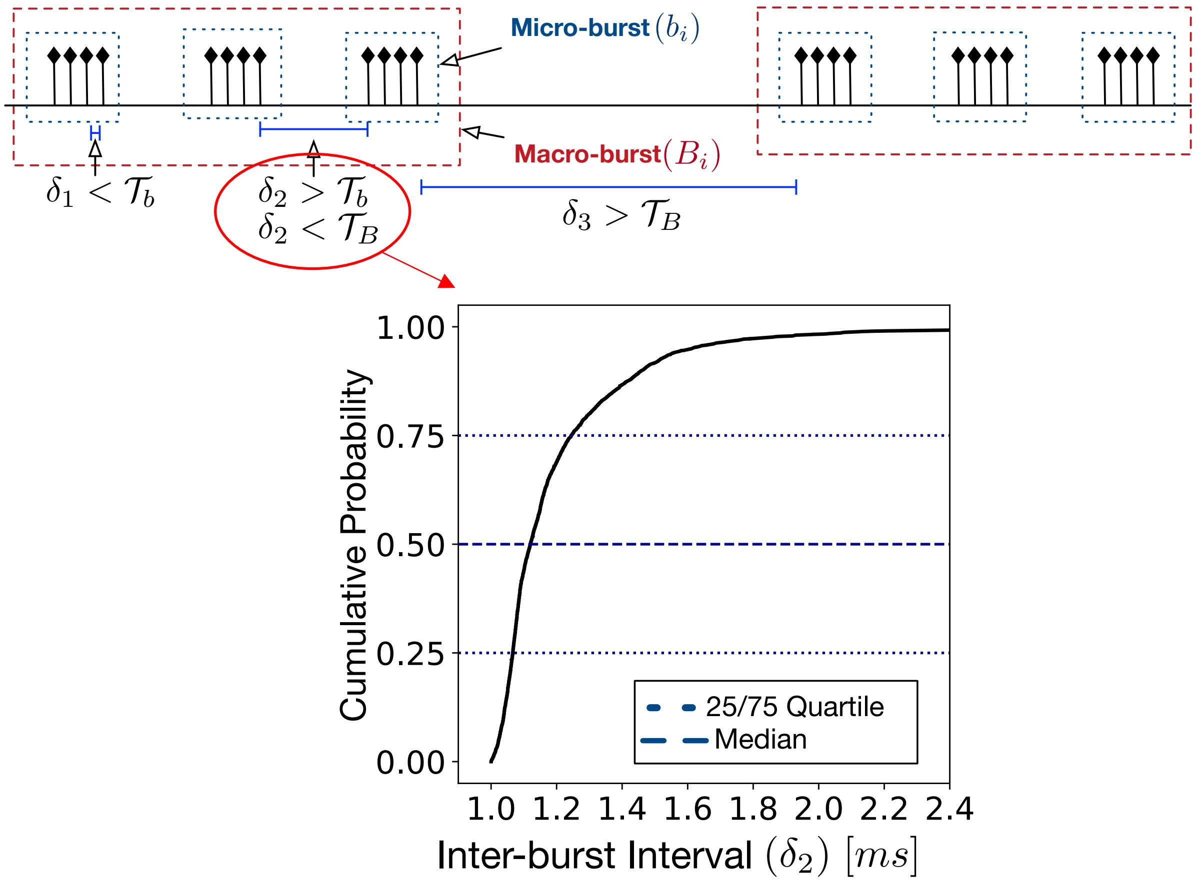
Main factors affecting inter-packet interval

- Prepare multiple packets
- Transfer packets from driver to NIC
- Send multiple packets – backoff and channel access contention

Traffic Pattern Analysis

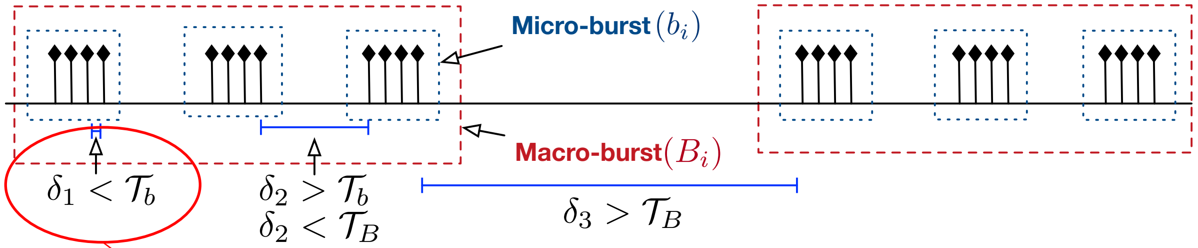
Sensing

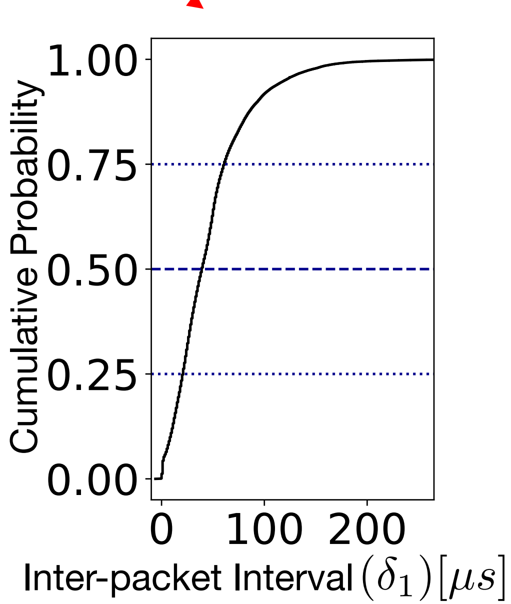
- The interval between micro-bursts is due to collecting 3920 samples
  - Communication between the processor and ADC over the Serial Peripheral Interface (SPI) to collect samples



Traffic Pattern Analysis

Camera

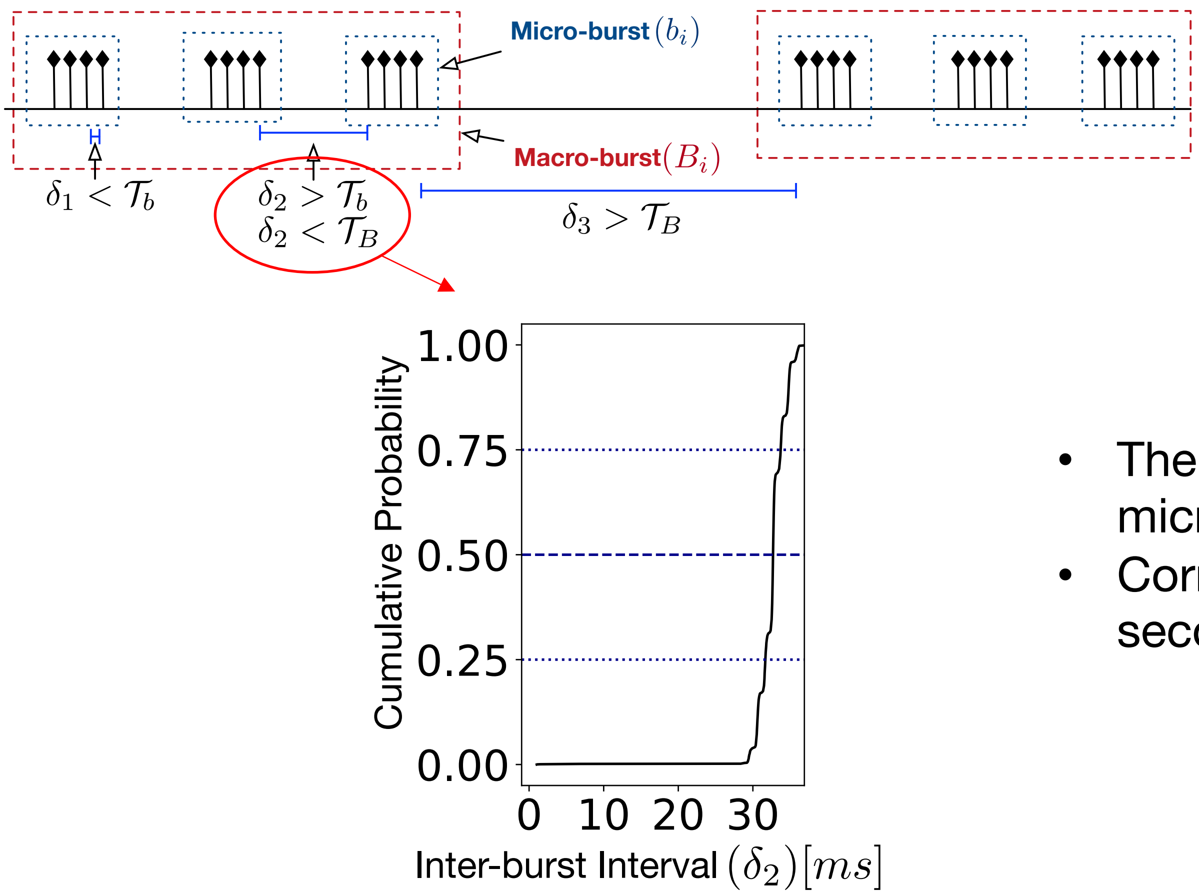




- The camera captures a frame
- Prepares multiple packets to send the frame

Traffic Pattern Analysis

Camera



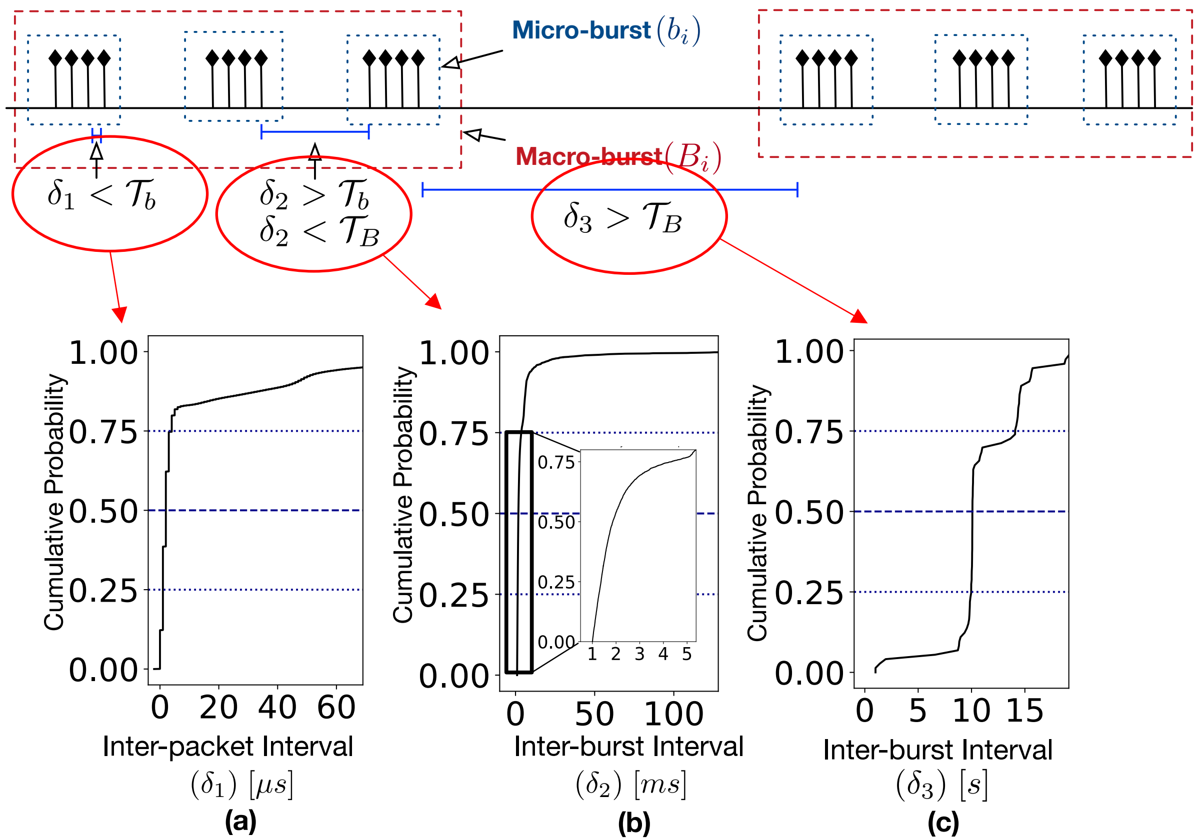
(b)

- The interval between microbursts (δ_2) is about 33 ms
- Corresponds to 30 frames per second

Traffic Pattern Analysis

Video Streaming

- The mean interval between packets of a micro-burst (δ_3) is 9 us
- The mean interval between micro-bursts (δ_2) is 2 ms
- The mean interval between macro-bursts (δ_1) is 10 seconds



Traffic Pattern Analysis

- In sum, these experiments show that traffic characterization can be used for:
  - Allocating TWT service periods based on each STA's demands
  - Utilizing inter-packet intervals by other STA to enhance throughput
  - Enhancing packet aggregation performance

Existing Methods

- Channel Utilization (CU) estimation
- Buffer Status Report (BSR)
- Packet sniffing

- Do not provide high accuracy

Gradual TWT adjustment

- High communication overhead
- Cannot quickly address traffic variations

Assumptions about STAs

- Unrealistic
- Impossible

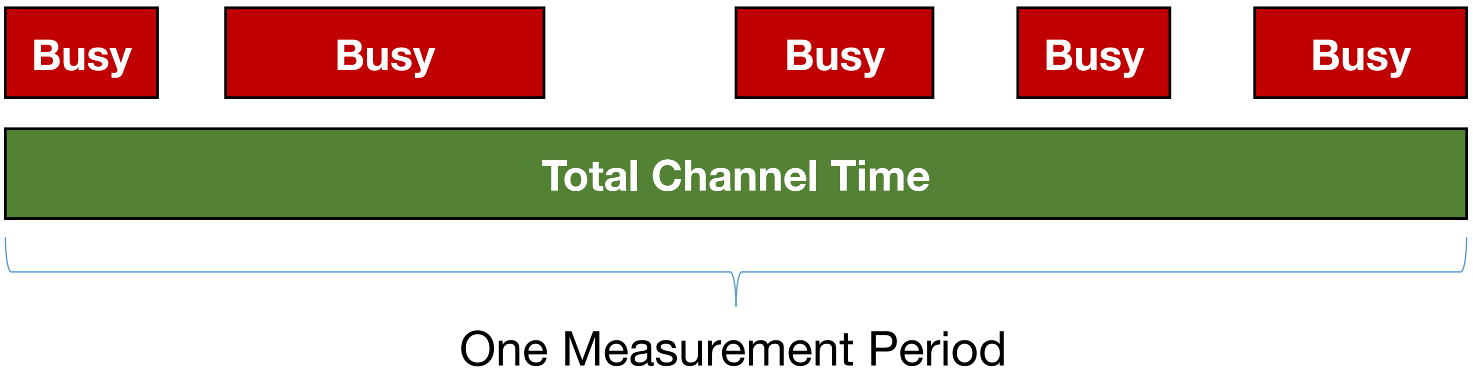
Traffic classification (e.g., using machine learning)

- High processing overhead
- Difficult implementation

Existing Methods

Channel Utilization (CU)

- Channel Utilization (CU) is defined as $t_{activity}/t_{total}$



- CU values can be collected from the driver via various methods such as the ‘proc’ file system (`procfs`) in Linux
- **The information provided by CU is cumulative**
  - **It cannot be used to characterize per-STA traffic patterns**

Existing Methods

Packet Sniffing

- Using one or more additional NICs to sniff packets

- Shortcomings:
  - The timestamps of sniffed packets do not represent the actual packet generation instances by STAs
  - Additional hardware (NIC) and processing resources
  - Mismatch between sniffed packets and those exchanged by the AP's main NIC

Existing Methods

Buffer Status Report (BSR)

```
> Qos Control: 0x0c10
v HT Control (+HTC): 0x0000750f
    .... .... .... .... .... .... .... ...1 = VHT: True
    .... .... .... .... .... .... .... ..1. = HE: True
  v Aggregate Control: 0x1d43
      Control ID: 3: Buffer status report
    v Buffer Status Report: 0x000001d4
        .... .... .... .... .... .... .... 0100 = ACI Bitmap: 0x4
        .... .... .... .... .... .... ..01 .... = Delta TID: 0x1
        .... .... .... .... .... .... 11.. .... = ACI High: 0x3
        .... .... .... .... .... ..01 .... .... = Scaling Factor: 0x1
        .... .... .... ..00 0000 00.. .... .... = Queue Size High: 0x00
        .... ..00 0000 00.. .... .... .... .... = Queue Size All: 0x00
> CCMP parameters
```

- **Introduced in 802.11ax (a.k.a., WiFi 6)**
- **Queue Size All (QSA)** field of BSR conveys the cumulative amount of data in all queues
- BSR also conveys information such as the Queue size of the highest-priority Access Category (AC)

Existing Methods

Buffer Status Report (BSR)

Shortcomings of using BSR for traffic characterization:

- We selected several COTS 802.11ax NICs and empirically analyzed them
  - Intel AX200 and Realtek RTL8852A **transmit BSR intermittently**
    - Based on the amount of traffic queued
  - In contrast, Compex WLT639 **includes a BSR in every packet**

- None of the evaluated AP and STAs support requesting or generating BSR manually
- Also, we observed that for those 802.11ax devices that include BSR in each packet, **all the MPDUs included in an A-MPDU report the same value**
  - Even though the payloads they are carrying have been generated at different time instances.
  - The reported value is the state of queues before the transmission of A-MPDU

Source-assisted Traffic Characterization (SATRAC)

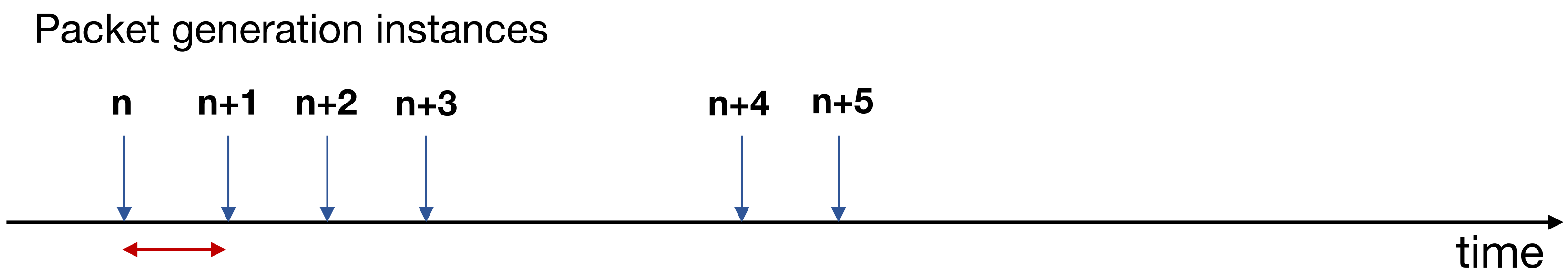
Overview

- Basic idea:
  - Keep track of packet generation time instances in each STA
  - Convey to AP
  - The AP can construct the traffic pattern of the STA
- This method is unaffected by packet preparation delay, channel access contention, interference, and packet loss
- Each STA modifies packets in their protocol stack's data-path
  - Adds timing information
  - Similar to in-band network telemetry (INT)

Source-assisted Traffic Characterization (SATRAC)

Overview

- Instead of including an absolute timestamp in each packet, **we include only a 2-byte value**
- This value encodes **the the difference between the generation time of the current packet and the previous packet of the same flow**

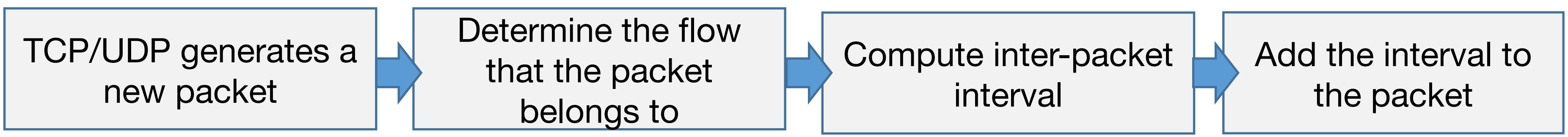


- The interval between each two consecutive packets generation instances is encoded as a 2-byte value and added to the second packet
- Here, the interval between n+1 and n is included in packet n+1

Source-assisted Traffic Characterization (SATRAC)

Overview

- Each STA computes a unique 5-tuple hash value for each flow and keeps track of the timestamp of the last generated packet

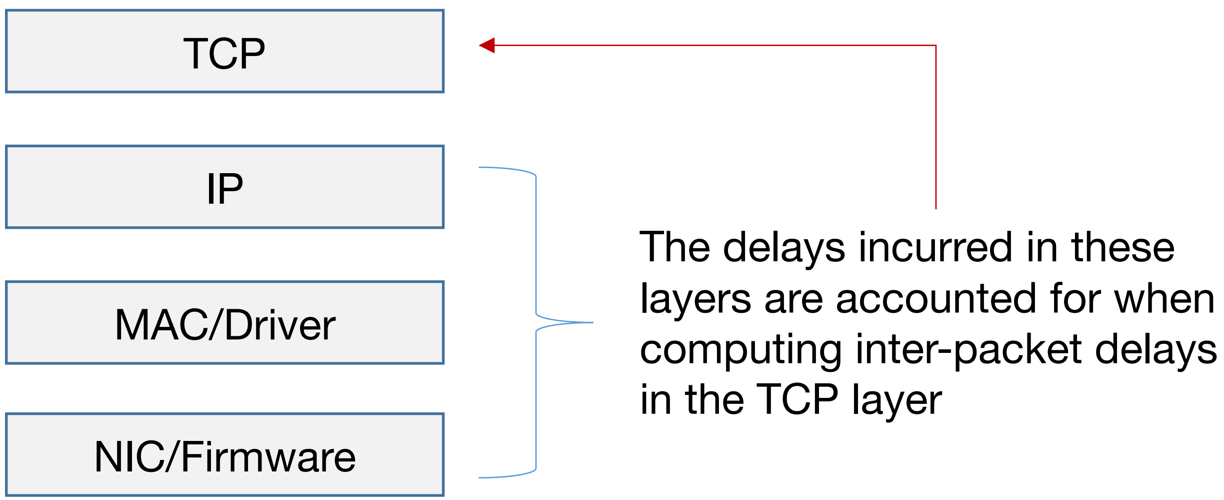


- Where is this information added to?
  - TCP Options field, or
  - IPv4 Options field, or
  - IPv6 Next Header

Source-assisted Traffic Characterization (SATRAC)

Packet Preparation Delays

- Add timing information in the TCP layer when the TCP protocol prepares the TCP header
- To account for packet preparation delay, we add the delays caused by the IP layer, MAC layer, and driver-to-NIC handoff to the timing information



Source-assisted Traffic Characterization (SATRAC)

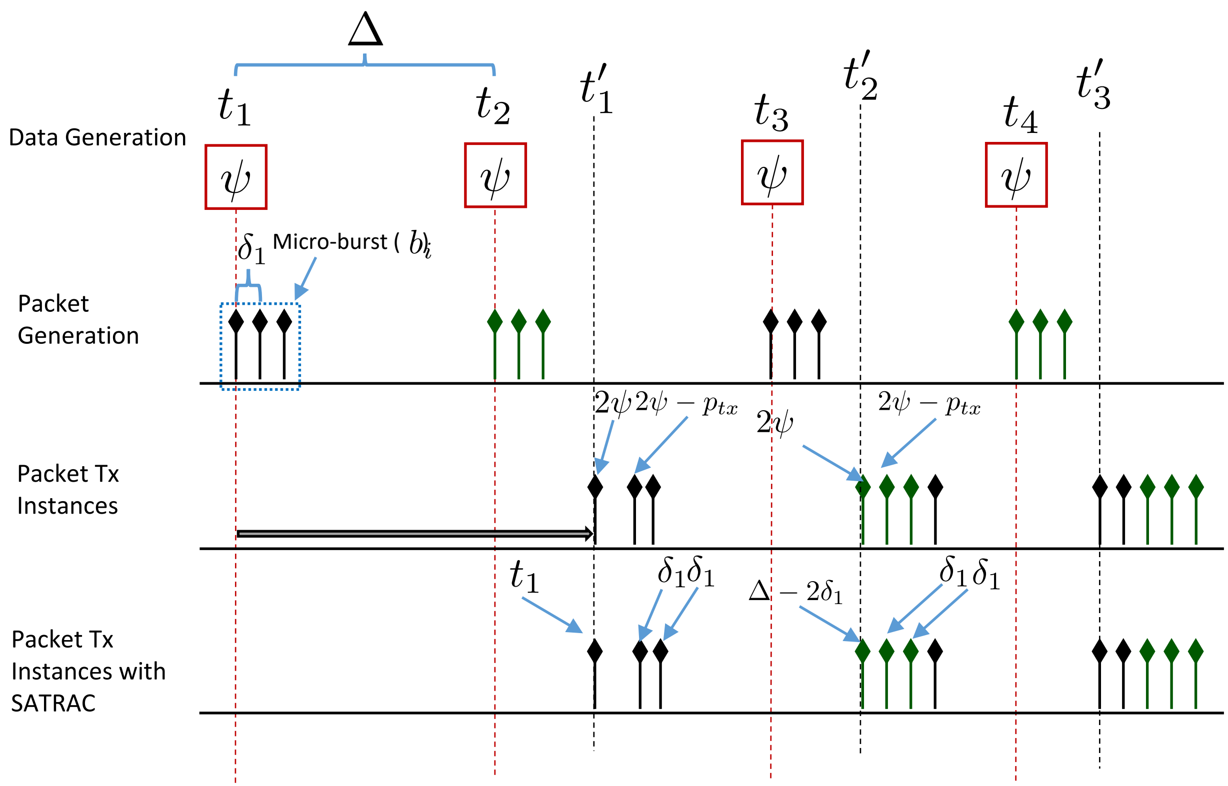
eBPF

- We leverage **eBPF** and build an application-agnostic middleware for **setting the TCP Options field**

- Since APs run Linux, a similar eBPF program extracts and parses the values included in TCP Options field of packets received from STA to characterize uplink traffic

Source-assisted Traffic Characterization (SATRAC)

Comparison of Traffic Characterization Methods



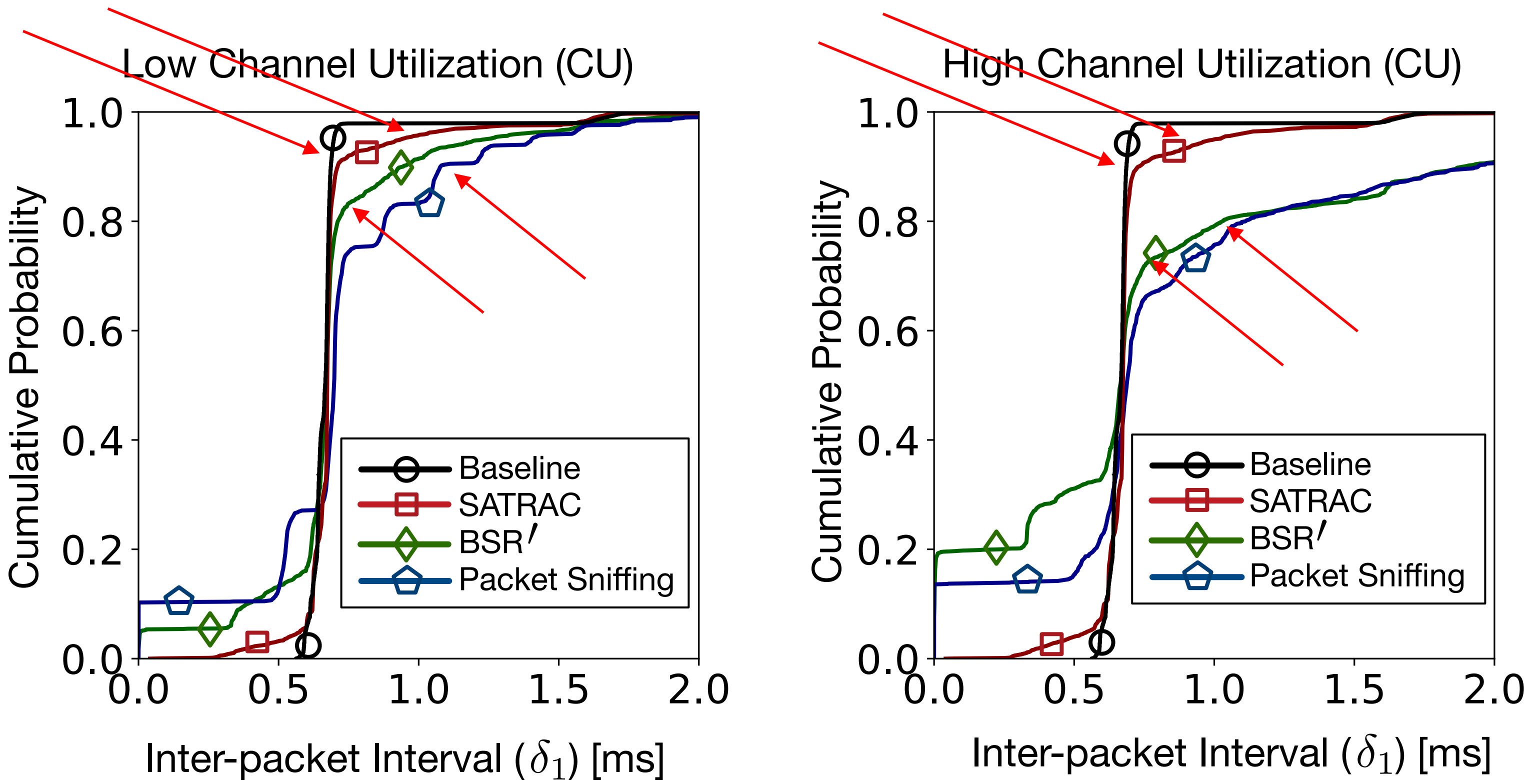
Source-assisted Traffic Characterization (SATRAC)

Empirical Comparison

- An 802.11ax (WiFi 6) testbed: one AP and multiple STAs
- We consider two CU scenarios
  - **Low**: the measured CU is around 15%
  - **High**: the measured CU is around 70%
- A STA runs a program that generates and sends a 1400-byte message every 500 us
  - Voice Access Category – no packet aggregation
- To establish a **baseline** for accuracy comparison, we denote the actual data generation instances by the application as *baseline*

Source-assisted Traffic Characterization (SATRAC)

Empirical Evaluation of Timing Accuracy



(a) **(b)**

Source-assisted Traffic Characterization (SATRAC)

Empirical Comparison of TWT Allocation Efficiency

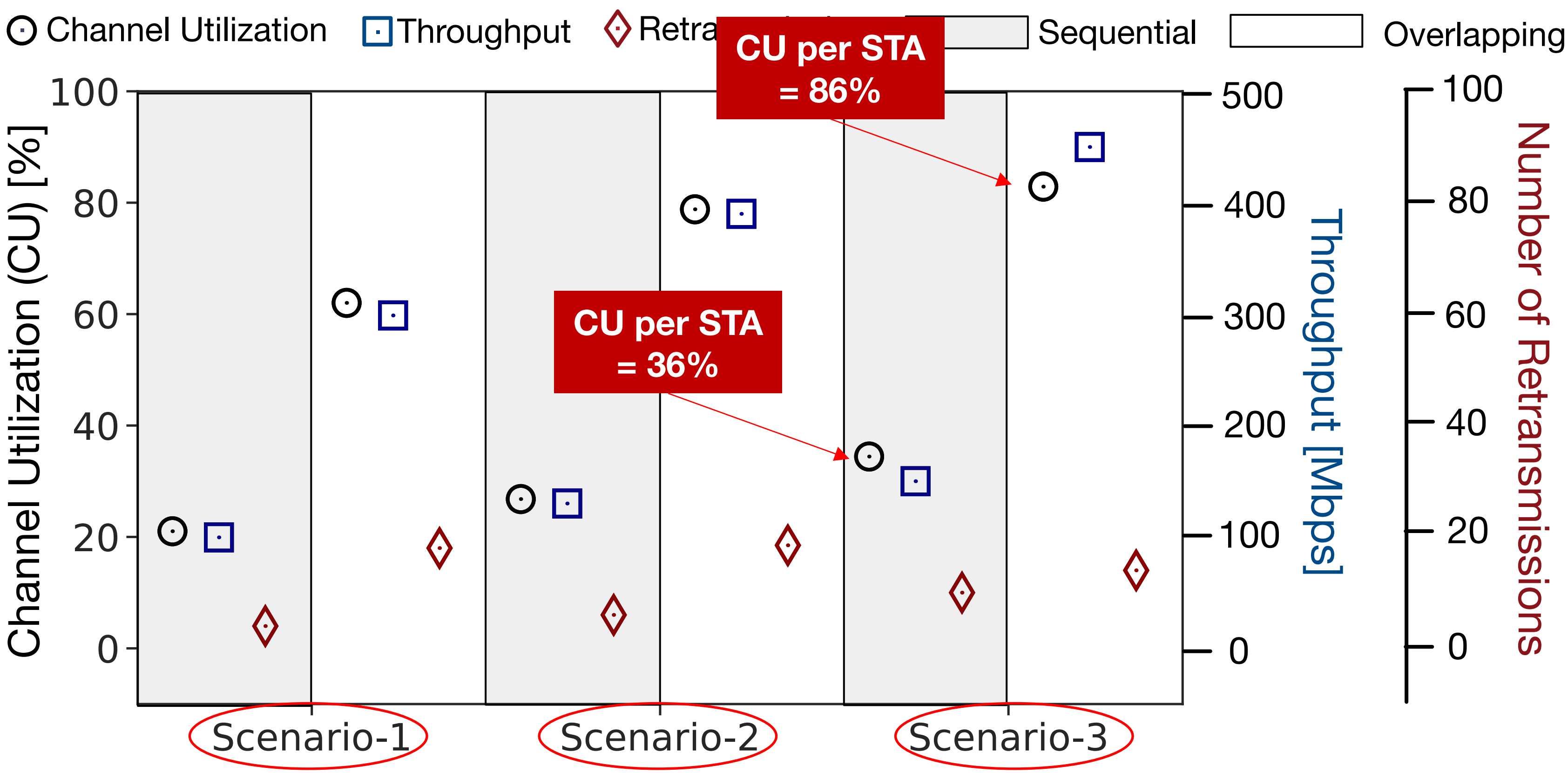
- An 802.11ax (Wi-Fi 6) testbed: one AP and multiple STAs

- **Sequential Allocation of TWT Service Period**
  - Similar to the existing works, we assign non-overlapping service periods to the STA

- **Overlapping Allocation of TWT Service Periods using SATRAC**
  - We enable the AP to characterize traffic using SATRACT
  - Determine the possibility of higher channel utilization, and assign overlapping service periods to the STA

Source-assisted Traffic Characterization (SATRAC)

Empirical Comparison of TWT Allocation Efficiency



Conclusion

- To meet applications' demands while enhancing energy efficiency and throughput
  - Traffic characterization is required for the allocation of TWT service periods to IoT STAs

1. We empirically studied traffic burstiness and the causes of inter-packet delays in WiFi-based IoT networks
2. Analyzed the shortcomings of existing traffic characterization methods
3. Introduced a novel approach based on packet modification in STAs' protocol stack
4. Empirically measure the accuracy of the proposed method and analyzed its effect on TWT allocation

- Not only for TWT allocation, but the proposed method can also be used for Resource Units (RU) allocation

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