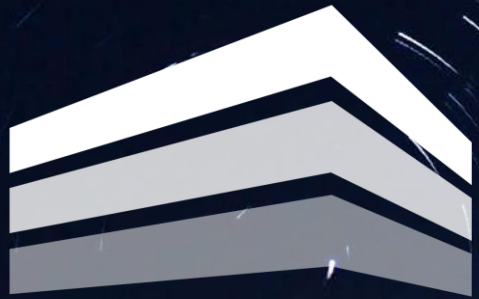
Simultaneous Multi-Channel Downlink Operation in Next Generation WLANs



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IEEE 802.11be Multi-Channel Operation

- IEEE 802.11be
  - Next-generation IEEE 802.11 standard project after IEEE 802.11ax

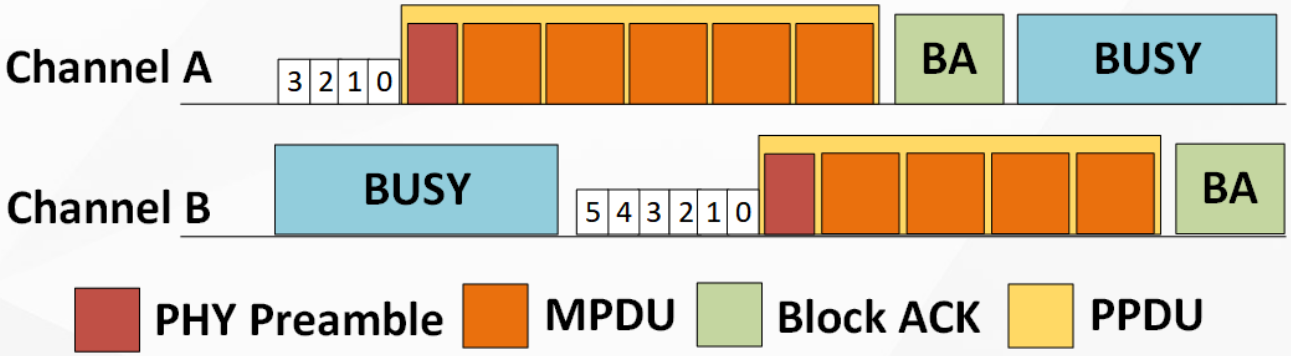
- Multi-Channel Operation
  - Emergence of dual-radio end user devices (STAs) and tri-band Access Points (APs)
  - Data from same traffic session over multiple channels using first available channel

- Asynchronous operation
  - By default, independent medium access on each channel
  - For certain channel combinations, simultaneous transmission and reception (**STR**) may not be possible at multi-channel devices due to in-device interference

- AP is typically many-antenna system and expected to be STR capable

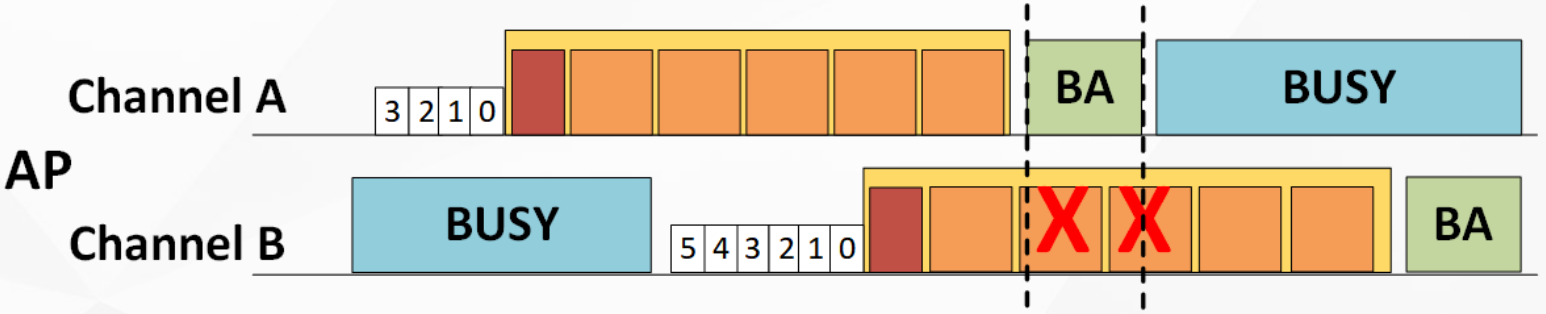
- **Non-STR STAs**
  - STAs may lack STR capability due to smaller form factor and simpler design

Asynchronous Operation at STR Device



- Medium Access on a channel
  - 802.11 backoff counter (boxed number) reaches zero
- Aggregated Data Frame
  - Initial PHY preamble followed by multiple MAC frames (MPDUs)
- Block Acknowledgement
  - Bitmap of per-MPDU acknowledgement

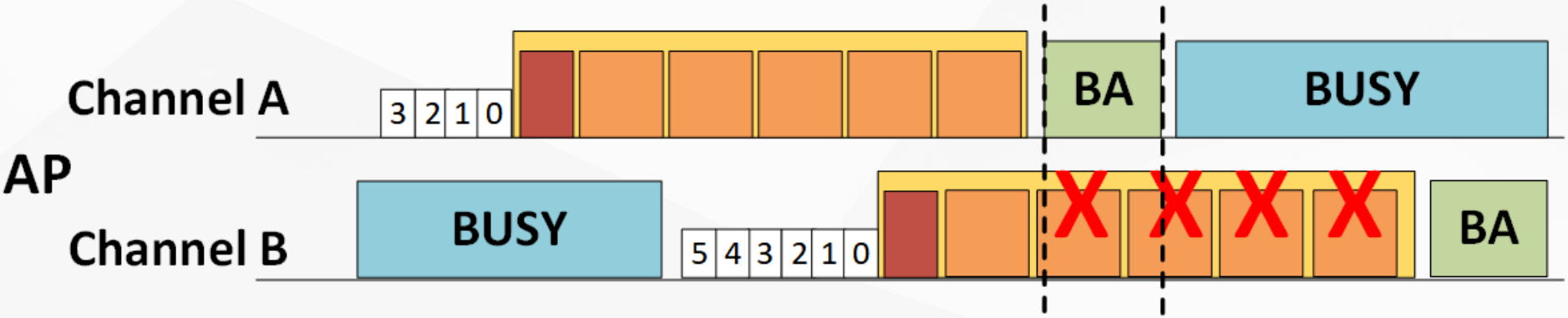
Simultaneous Downlink to non-STR STA



- AP can obtain medium access on each channel at different times
  - Transmit simultaneously to same non-STR STA e.g. high throughput app
- Uplink acknowledgement from non-STR STA on a channel creates in-device interference leading to data reception failure on other channel(s)
- Reception failure is dependent on Non-STR STA's receiver implementation

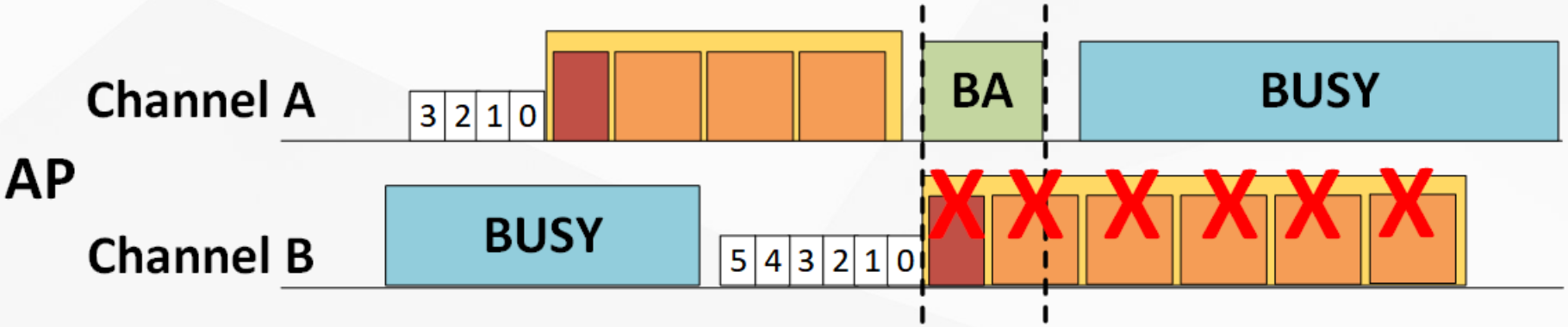
Non-STR STA Receiver Capability Challenge

- In worst case, uplink block ACK on a channel can cause non-STR STA's receiver on other channel to go out of synchronization with receiving signal
  - Reception failure of **rest of the data transmission**



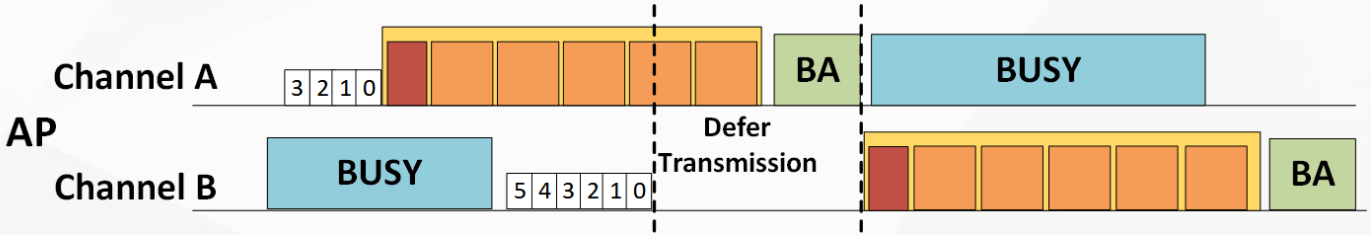
Preamble Overlap Challenge

- Independent of non-STR STA's receiver capability, the start of downlink transmission (PHY preamble) on a channel may coincide with uplink block acknowledgement on other channel
- In this extreme case, the entire aggregated data frame is lost

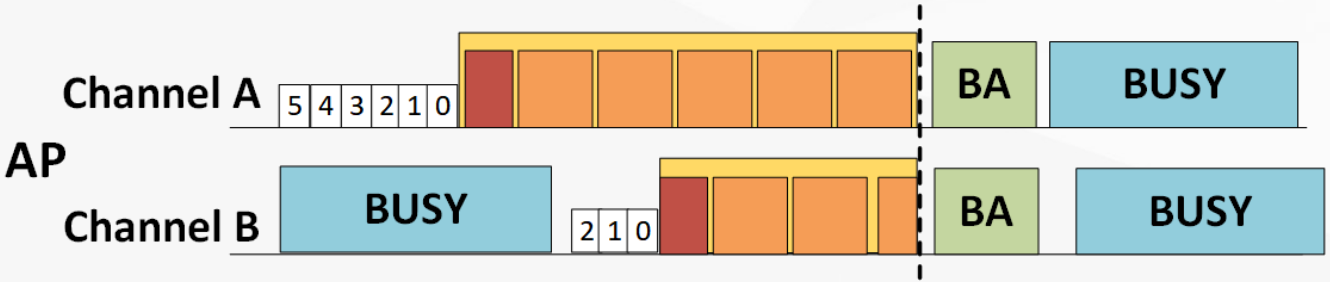


Baseline Strategies

- **Defer Transmission on Second Link**
  - AP defers transmission on other channel to same non-STR STA
  - If channel is busy, access opportunity might be lost



- **Ending Alignment**
  - AP always aligns the ending of simultaneous transmissions to a non-STR STA
  - Potential medium under-utilization if non-STR STA does not go out of sync



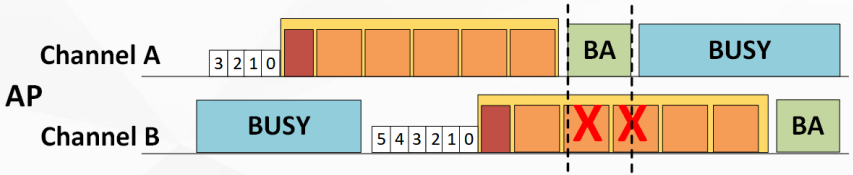
Contributions

To maximize the multi-channel medium utilization for downlink transmissions to non-STR STAs, we propose Constraint-aware Aligned Downlink Ending (**CADEN**)

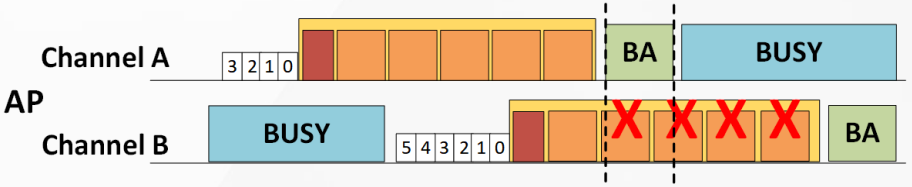
- **Non-STR STA Capability indication**
  - Novel signaling information about potential reception failure
- **PHY Preamble Overlap Prevention**
  - AP defers transmission to prevent overlap of uplink acknowledgement from a non-STR STA on one channel and PHY preamble to same STA on other channel
- **Adaptive Ending Alignment**
  - AP utilizes capability indication from non-STR STA and medium access conditions
- Using custom ns-3 simulator, we analyze CADEN's performance

CADEN Procedure at non-STR STA

- Depending on receiver capability at non-STR STA, it may suffer only overlap loss or out of synchronization loss



(a) Overlap loss



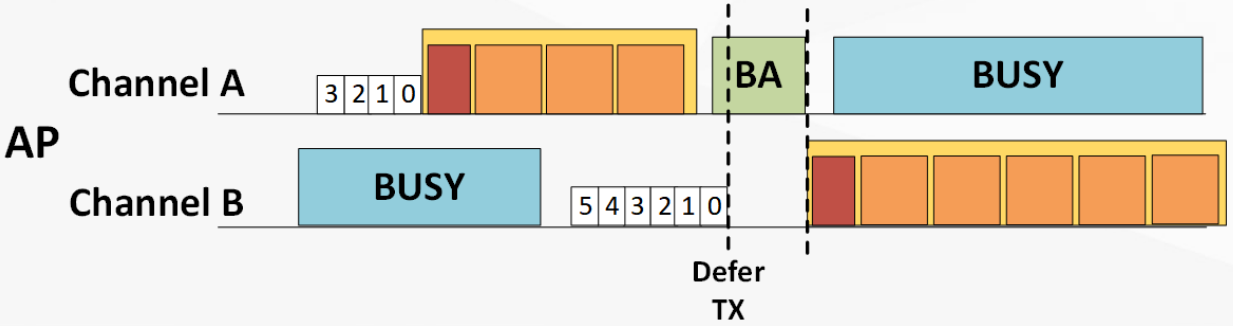
(b) Out of synchronization loss

- In CADEN, non-STR STA indicates to AP that AP either
  - shall always align
    - Non-STR STA indicates this requirement if it suffers out-of-sync loss or if it may suffer significant overlap loss
  - may not align its simultaneous downlink transmissions to this non-STR STA
    - Non-STR STA indicates this requirement if it determines the overlap loss is tolerable

CADEN Procedure at AP (1/2)

- AP's adaptive behavior for simultaneous downlink transmissions depends on
  - non-STR STA's reception capability
  - time domain overlap of downlink data and uplink Block ACK
  - Data rate used for channel on which medium access is obtained

- **PHY Preamble Overlap Prevention**
  - AP has precise knowledge of start and end of potential Block ACK from non-STR STA
  - If PHY preamble in downlink will overlap with Block ACK, AP defers the transmission
  - Backoff counter remains at zero and AP will re-attempt transmission immediately after Block ACK reception ends or timeout is reached on other channel



CADEN Procedure at AP (2/2)

- **Mandatory Ending alignment**
  - AP always aligns ending of downlink transmissions if indicated by non-STR STA

- **Adaptive Ending Alignment**
  - AP applies this procedure when non-STR STA indicates AP may not align
  - AP determines number of MPDUs that non-STR STA will fail to receive if alignment is not performed
    - Based on modulation and coding rate, and start and end of Block ACK
  - AP aligns the ending **if estimated MPDU loss is above pre-defined loss threshold**

- MPDU reception failure at non-STR STA can occur on ongoing transmission if the later data transmission is short and ends earlier than ongoing transmission
  - AP employs padding in this scenario if MPDU loss is above threshold

Performance Evaluation

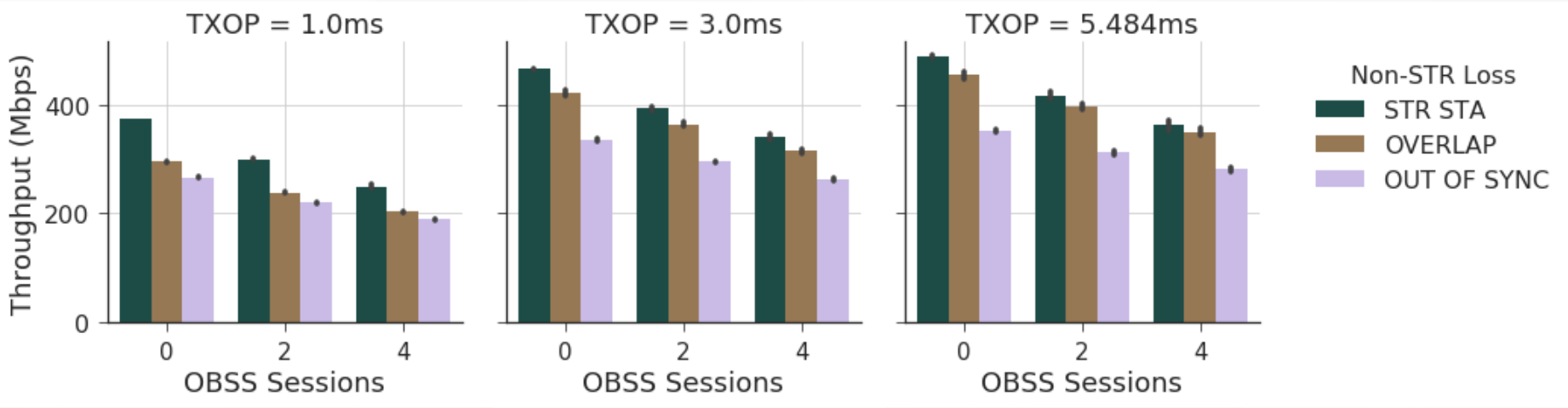
- Implemented CADEN and alternative strategies in ns-3 simulator

- Network model
  - Single AP operating a two-channel BSS
  - Each channel occupies 80 MHz
  - PHY data rate of 480 Mbps for transmissions per channel
  - Varying number of interfering neighboring BSS (OBSS) traffic flows

- Traffic model
  - To isolate multi-channel downlink performance, we focus on single non-STR STA
  - Full-buffered downlink traffic generated at AP addressed to non-STR STA
  - Varying transmission opportunity (TXOP) time used to represent different apps
  - OBSS traffic flow uses channel access for a random duration up to 5 ms

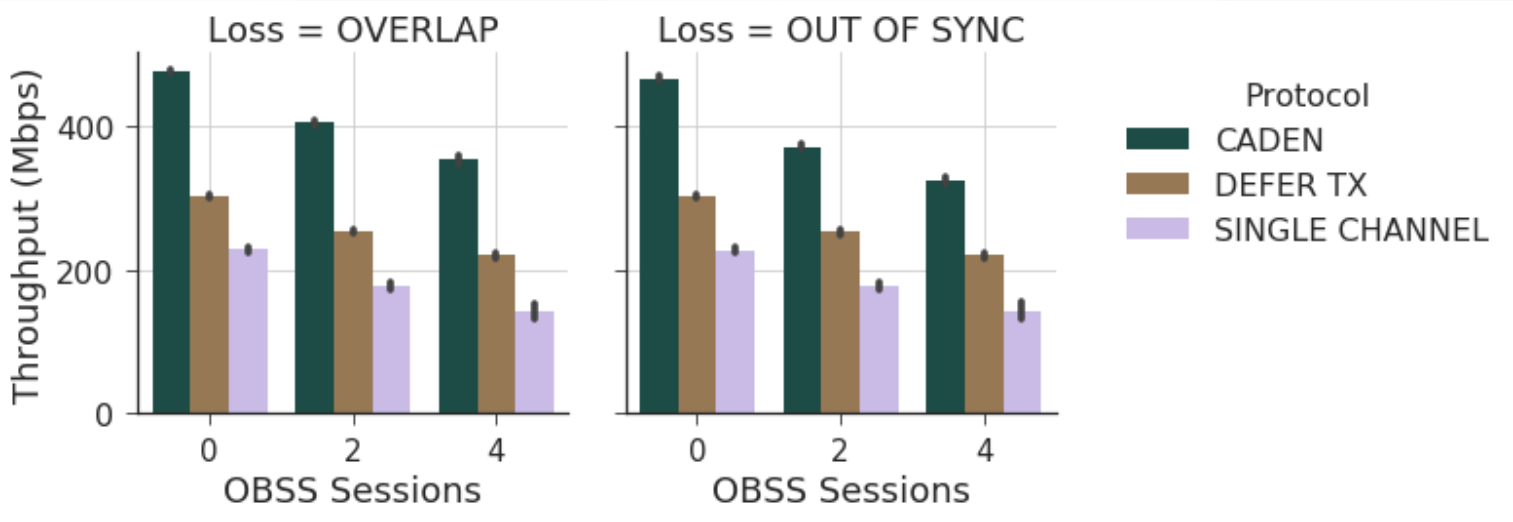
- Over 100 separate runs of 10 seconds in network time per configuration

Non-STR STA Reception Analysis



- STR STA represents the ideal benchmark as STA can receive while transmitting
- Significant performance degradation for non-STR STA with asynchronous op.
  - Worst for out-of-sync loss as all MPDUs starting from overlap with uplink Block ACK are lost
- For shorter TXOP durations, the probability of in-device interference increases leading to preamble reception failure as well as MPDU reception failure

Comparison with Alternative Strategies



- Defer TX better than single channel operation
  - Although simultaneous transmissions are not performed, AP still performs medium access on two channels providing multi-channel gain
- CADEN outperforms Defer TX which does not utilizing the obtained medium access as OBSS traffic flows can acquire the medium during deferral period

Conclusion and Related Work

- **Proposed CADEN protocol to address the challenges introduced by asynchronous multi-channel operation in data delivered to client devices with simultaneous transmit-receive constraints**

- In our previous work [1], we proposed mechanisms for improving the uplink medium access of non-STR STAs participating in asynchronous multi-channel operation

- Several topics for further research including
  - Non-STR Access Point operation for example in personal hotspots
  - Transmit and receive chain sharing within a multi-channel device

[1] S. Naribole et al., “Simultaneous Transmit-Receive Multi-Channel Operation in Next-Generation WLANS”, *IEEE WCNC* 2020