Bringing Multi-Antenna Gain to Energy-Constrained Wireless Devices

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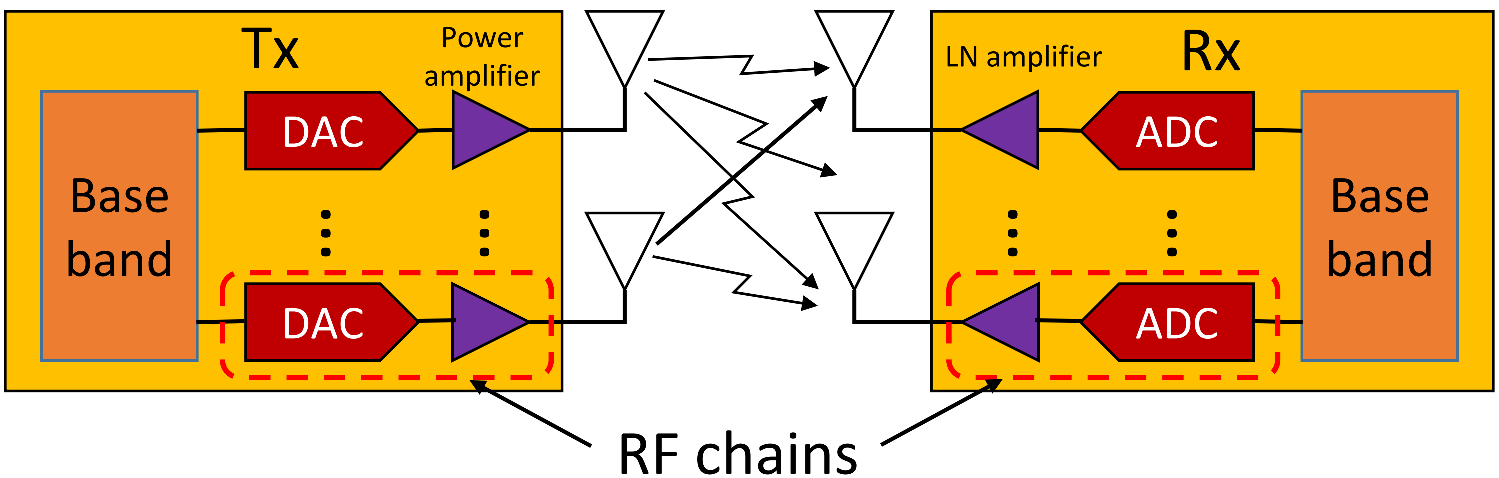
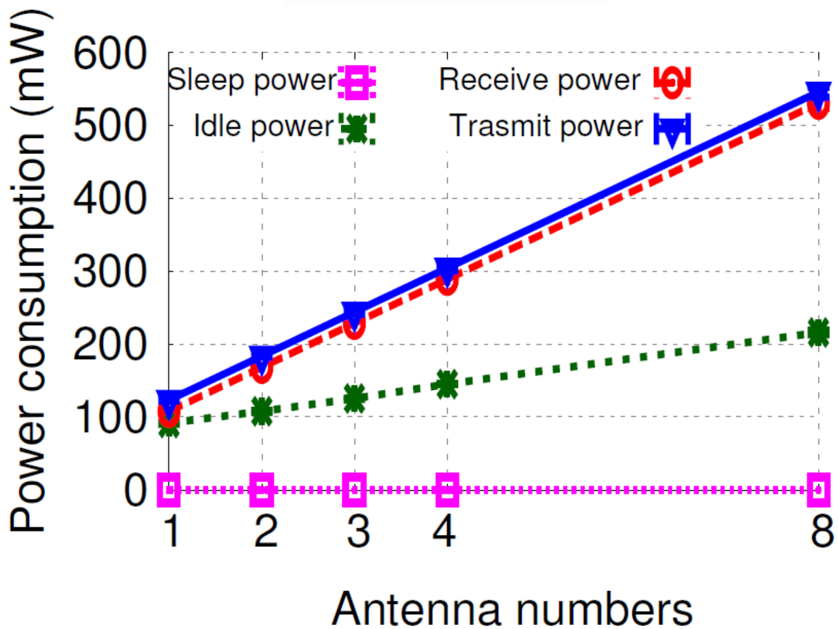
Power Consumption of MIMO

- MIMO boosts the wireless throughput by using parallel transmission (multiplexing gain) and redundancy (diversity gain)
- Each antenna needs an active RF chain consisting of power amplifier, ADC/DAC etc.



- Power consumption $\propto$ # of active antennas

Power Consumption of MIMO



ZigBee

Device power consumption (W)				
Modes		Atheros 9380	Intel 5300	Linksys AE3000
Sleep		0.13	0.22	0.15
Rx Idle	1	0.68	1.27	0.84
	2	0.80	1.39	0.96
	3	0.94	1.53	1.10
Rx data	1	1.38	1.34	0.83
	2	1.42	1.48	1.31
	3	2.06	1.65	1.60
Tx data	1	1.44	1.44	0.87
	2	1.46	1.50	1.35
	3	2.09	1.99	1.92

WiFi

- Will energy per bit of MIMO be higher or lower than SISO?

Power Consumption of MIMO

- If TX (RX) time is roughly 10%, the energy cost per-bit compared with SISO,

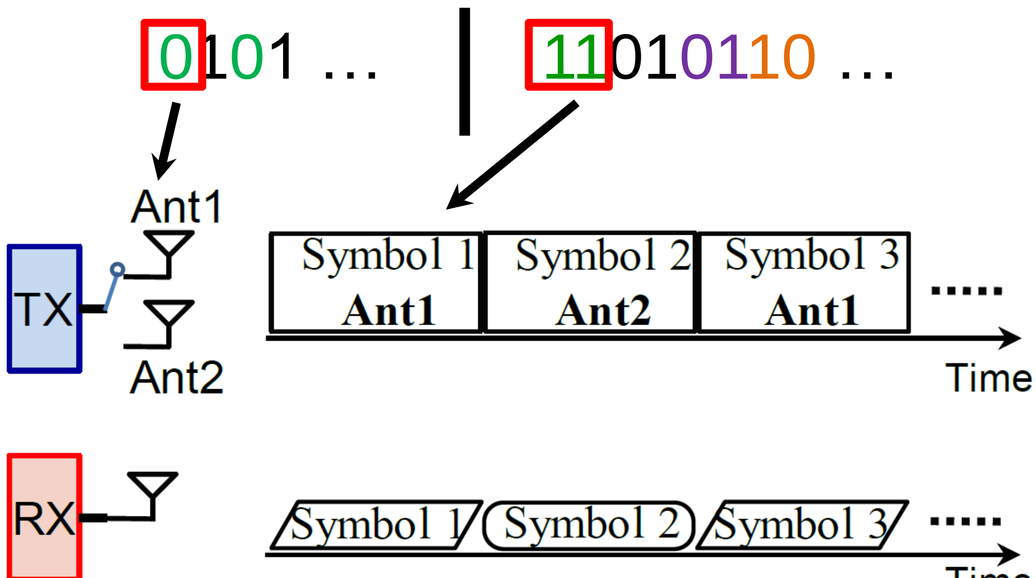
$$\underbrace{1.3 \times 80\%}_{\text{Idle}} + \underbrace{\frac{2.2}{3} \times 10\%}_{\text{Tx}} + \underbrace{\frac{2}{3} \times 10\%}_{\text{Rx}} = 1.2 \times$$

- Energy efficiency of MIMO is worse than SISO

- Can we achieve similar capacity gain as MIMO but with similar energy efficiency as SISO (using one RF chain)?

Our Design: Halma

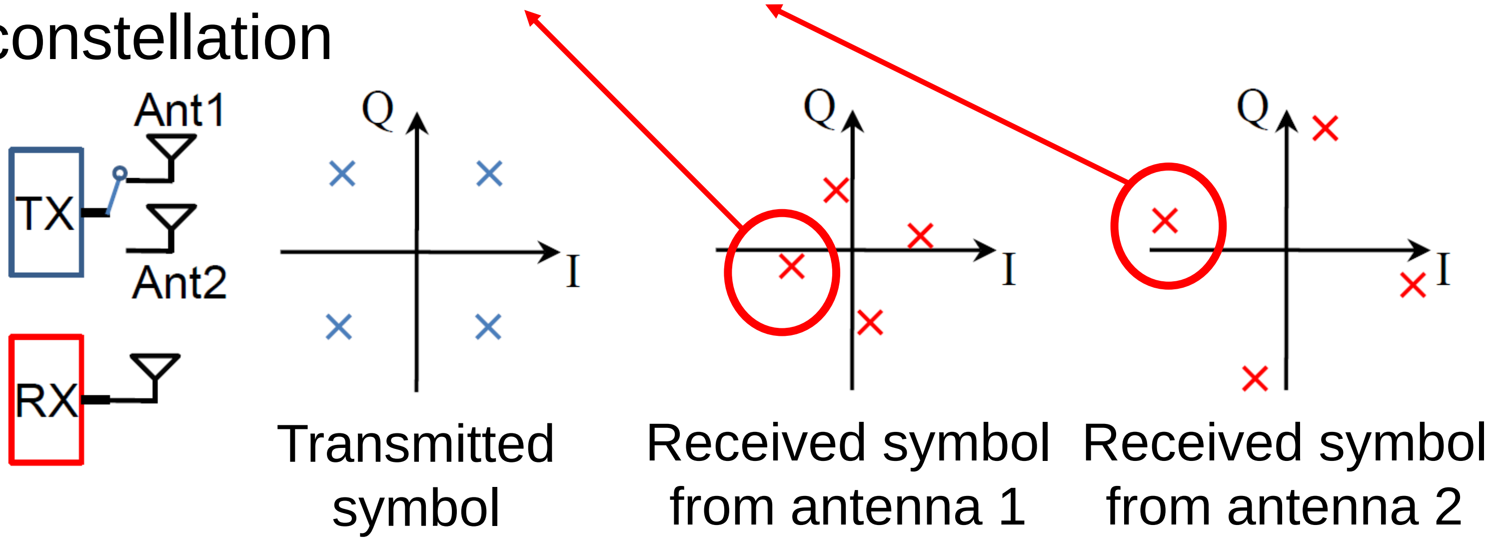
- Data are transmitted sequentially over different antennas – Antenna Index Coding (AIC)



- Create an extra data stream by the antenna hopping

Feasibility

- Intuitively, each transmit antenna has unique channel signature(magnitude+phase), which distorts the original constellation



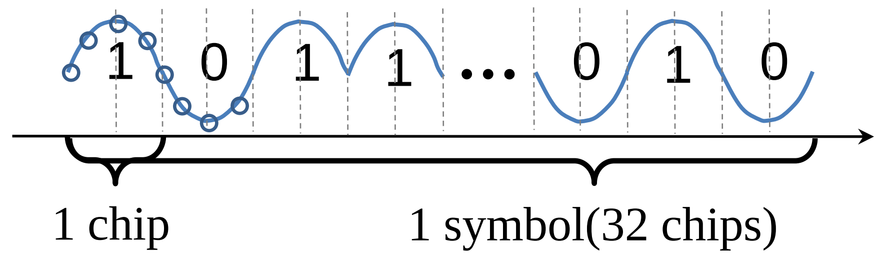
- Feasibility experiment

Ant. Idx	1	2	3	4
1	97.55	2.07	1.44	1.31
2	2.00	93.97	1.44	1.81
3	1.38	1.54	95.87	1.34
4	1.32	2.04	1.07	95.54

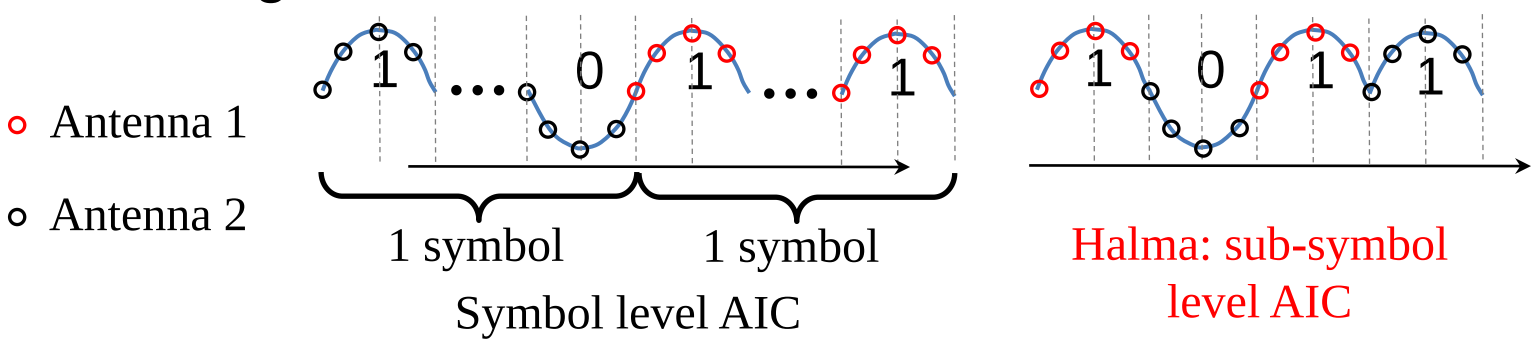
Accuracy of antenna identification

Antenna Index Coding (AIC): ZigBee

- Baseband signal of the ZigBee



- AIC in ZigBee



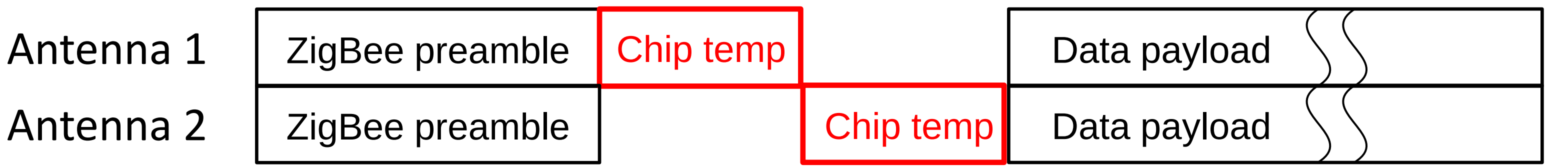
- Theoretical capacity gain using sub-symbol level AIC:

$$1 + 32log_2(\#of\_antenna)/Antenna\_hopping\_freq$$

  - For 2 antennas and antenna hopping every 8 samples: Capacity gain = 5x

Antenna Index Decoding: ZigBee

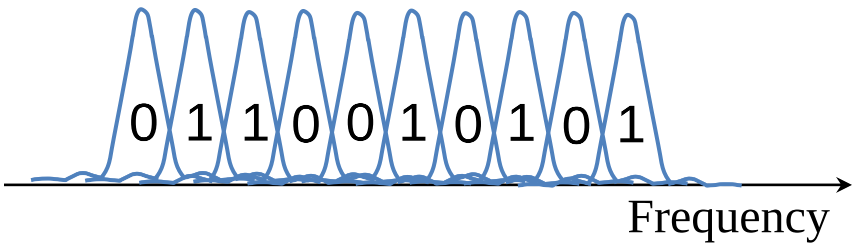
- Matching to the pattern of channel distortion
  - Insert chip template after legacy ZigBee preamble



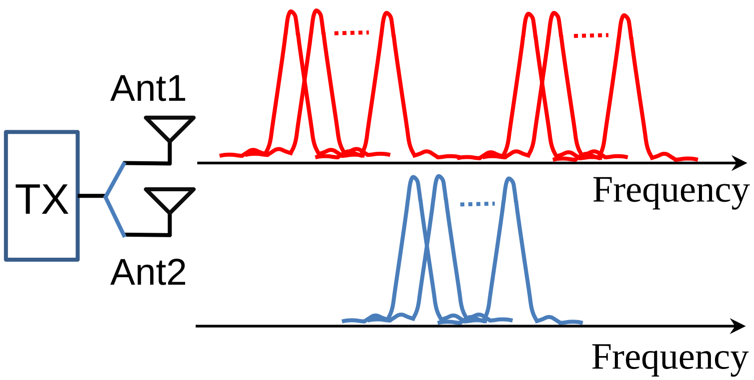
  - Decode data symbol using correlation
  - Decode antenna index by matching symbol distortion to templates
- More considerations to improve decoding reliability
  - Variations of channel signature caused by noise
  - Lack of sample-level synchronization in legacy ZigBee
    - ★ Starting positions of data symbols and chip template are not aligned

Antenna Index Coding (AIC): WiFi

- OFDM modulates data symbols in the frequency domain



- AIC in WiFi
  - Time domain samples are not separable
  - Perform AIC in the frequency domain



Antenna Index Decoding: WiFi

- Similar to the ZigBee – template
  - Reuse packet preamble format from 802.11n

WiFi STF (sync preamble)	LTF Tx 1	LTF Tx 2	....	OFDM symbol 1	OFDM symbol 2	....

Channel distortion estimation for each antenna

- Different from the ZigBee
  - Received packet is fully synchronized
  - Have both channel magnitude and phase pattern *w.r.t* each TX antenna

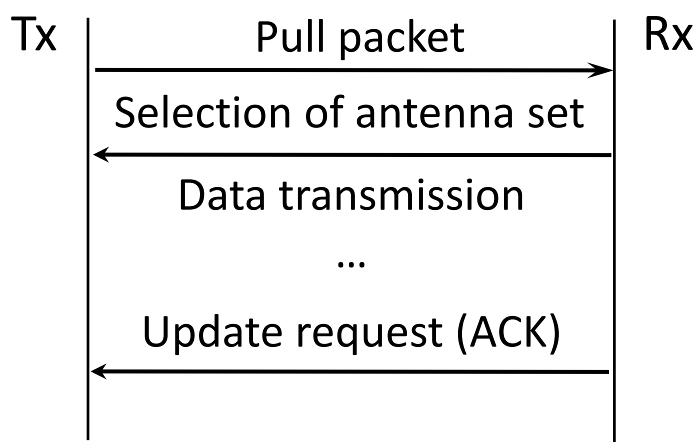
Adaptive Antenna Hopping (AAH)

- Why do we need this MAC level mechanism?

$$\mathit{Overall\_bitrate} = \mathit{Antenna\_hopping\_rate} \uparrow + \mathit{Data\_rate} \downarrow$$

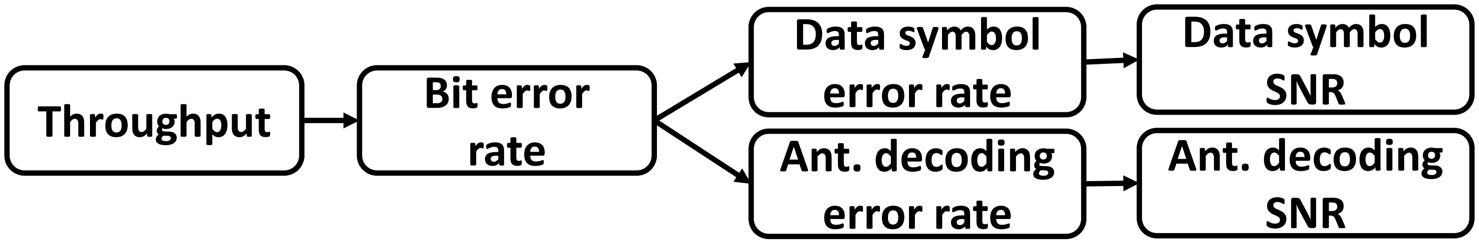
  - Channel conditions should be as *dissimilar* as possible
  - But, antennas with highly disparate gains (very high and very low SNR) will reduce overall throughput

- AAH: Adaptively choose antenna set that maximizes throughput



Model-based Antenna Evaluation

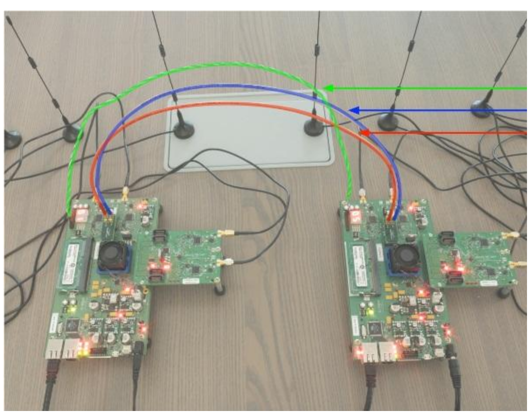
- Evaluate quality (throughput) of a given antenna subset

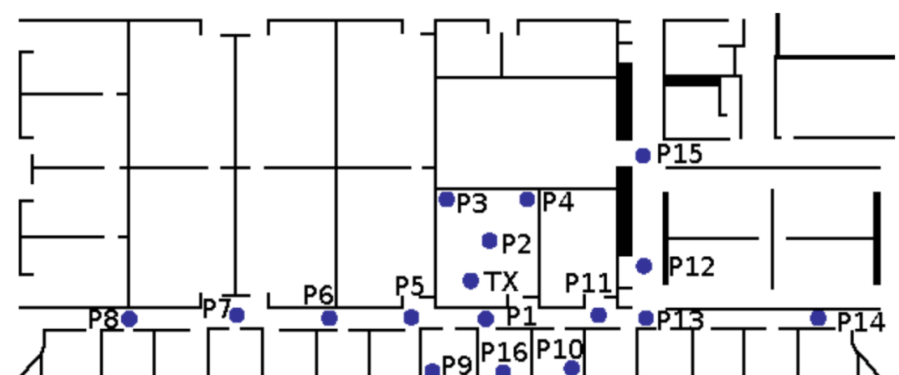


- Antenna decoding SNR = $\dfrac{\text{Dissimilarity}}{\text{Noise\_floor}}$
  - Dissimilarity = Euclidean “distance” of channel signatures
- Data symbol SNR (effective SNR*)
- Model the throughput
  - Avg_error = $\dfrac{\text{Expect\_error\_bit\_numbe}}{\text{Total\_number\_of\_bits}}$
  - Throughput = $\mathcal{F}$(pkt_rate, pkt_size, Avg_error)

Implementation and Evaluation

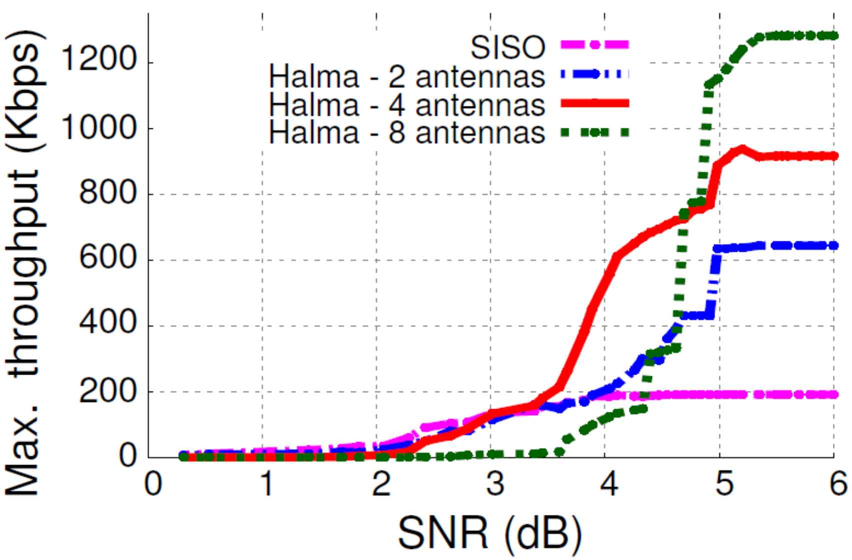
- Prototype Halma on the WARP software radio platform
- Realize Halma for both ZigBee and for WiFi.
  - Modified PHY layer to include antenna templates
  - Antenna index coding and decoding
  - Trace-based MAC for adaptive antenna hopping
- Evaluate in a testbed with 6 WARP boards.
  AP is equipped with up to 8 antennas.



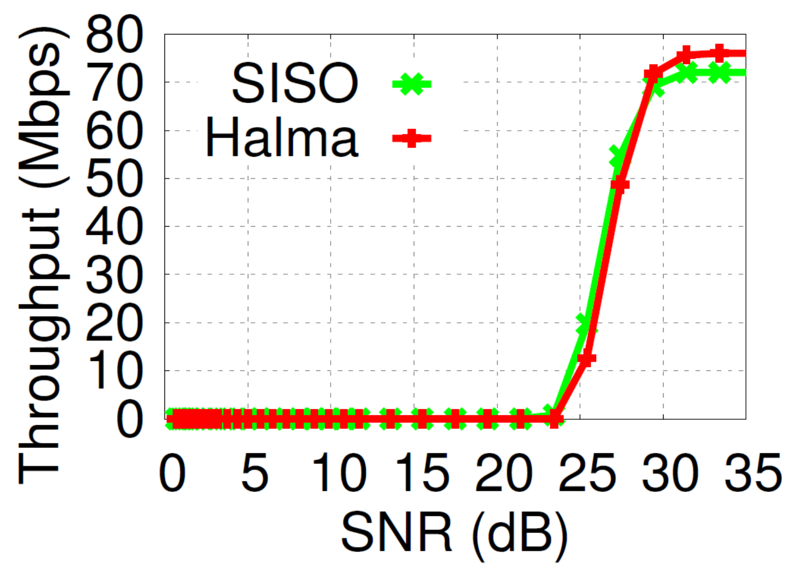


Performance: Throughput Gain

- ZigBee: 3.1x, 4.7x and 6.4x throughput gain with 2, 4 and 8 antennas!
- WiFi: 1.3x throughput gain with 4 antennas with BPSK modulation



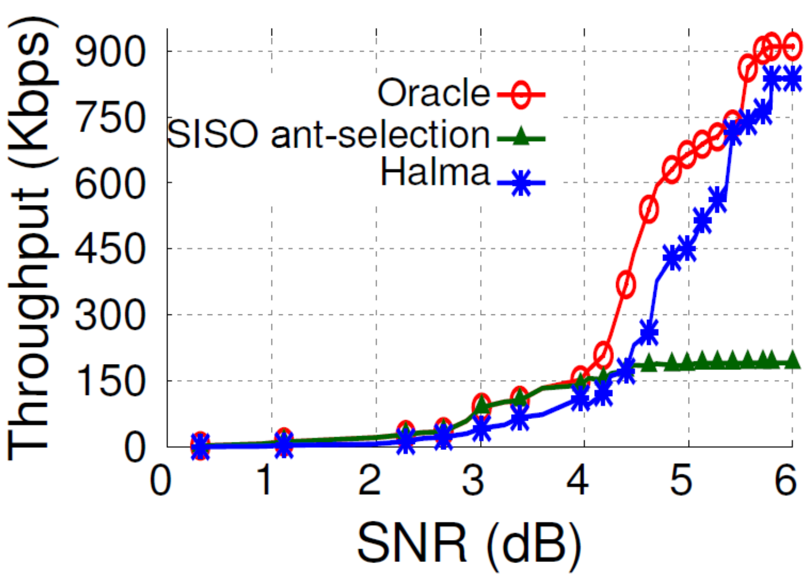
ZigBee



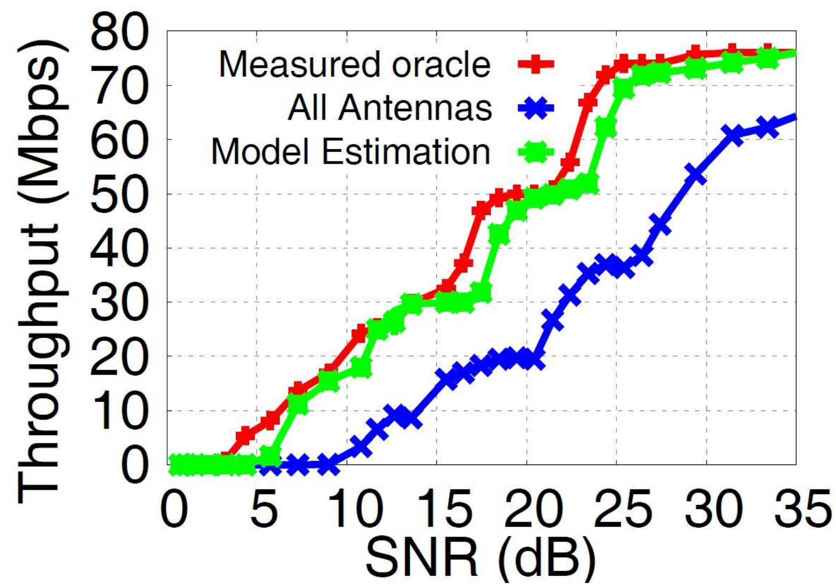
WiFi: BPSK modulation

Performance: Adaptive Antenna Hopping

- Throughput model closely approximates the oracle
- Outperform SISO for more than 80% locations
- 30% improvement compared to using all antennas



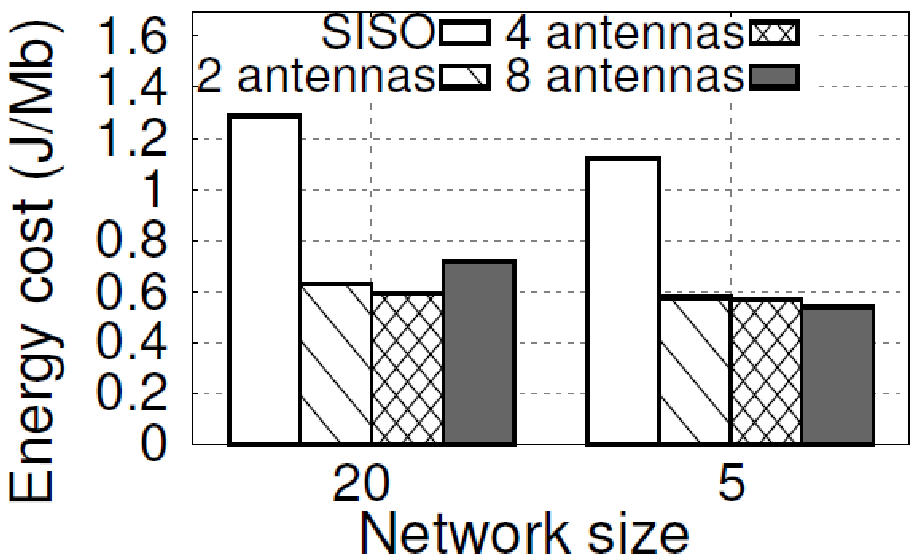
ZigBee



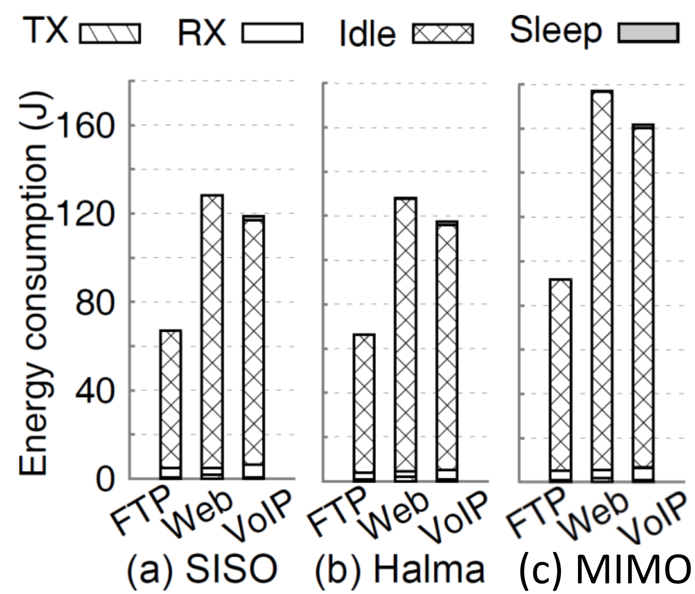
WiFi

Performance: Energy Saving

- ZigBee: Save energy per bit by more than 50%
- WiFi: Reduce energy consumption by 25% over MIMO



ZigBee



WiFi

Conclusion

- Explore the feasibility of bringing multi-antenna benefits to single RF-chain wireless devices.

- Adaptive antenna hopping mechanism to ensure robustness and efficiency of communication.

- Capacity can scale super-linearly with # of antennas. Power consumption remains similar to SISO. Energy-per-bit much lower than SISO and MIMO.

Thank you!