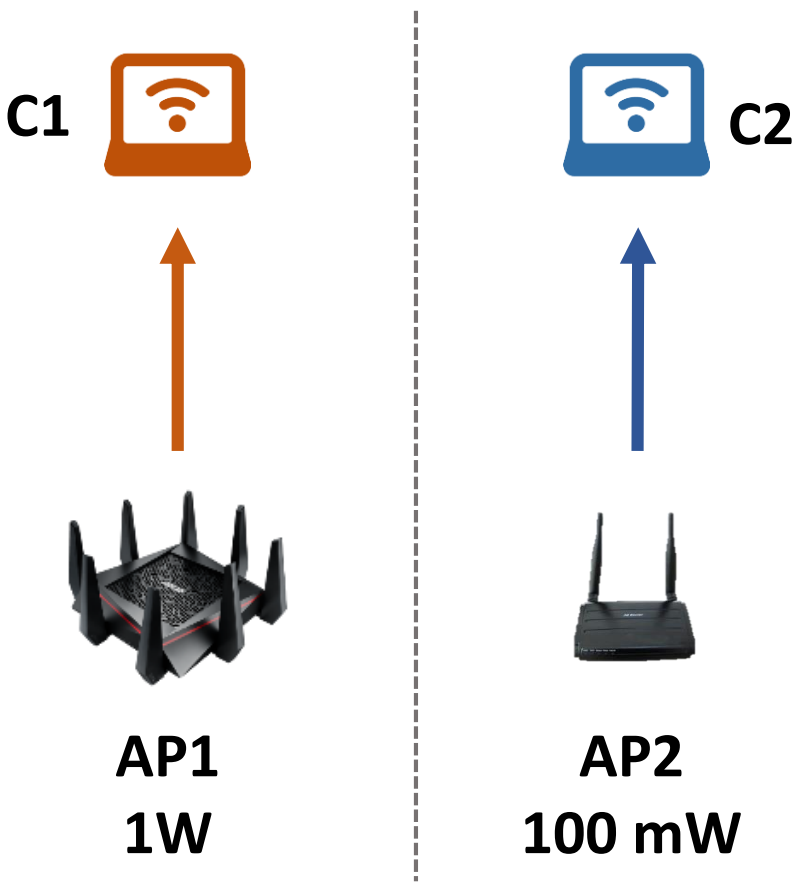
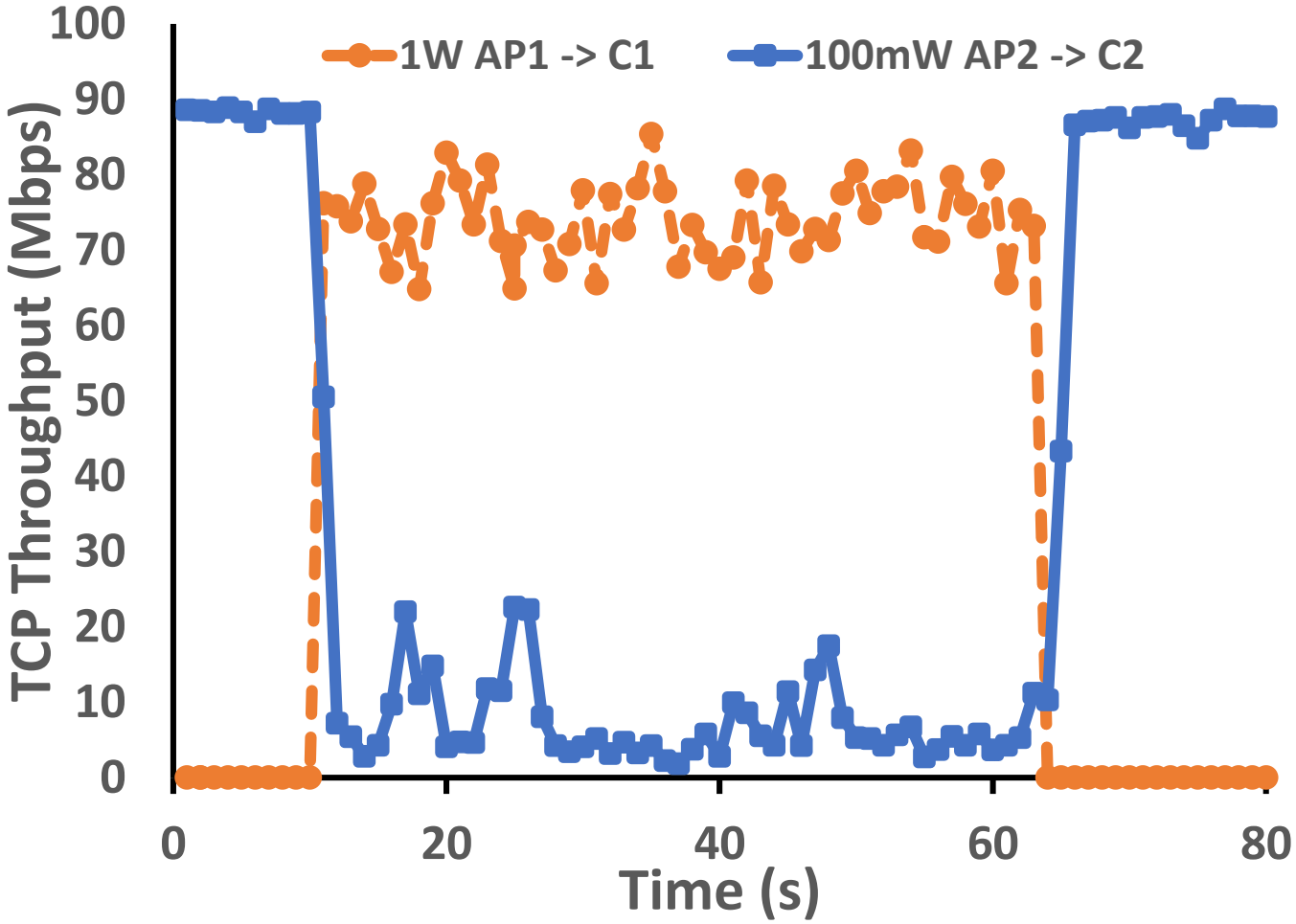
# Skip-Correlation for Multi-Power Wireless Carrier Sensing

Romil Bhardwaj, Krishna Chintalapudi, Ramachandran Ramjee



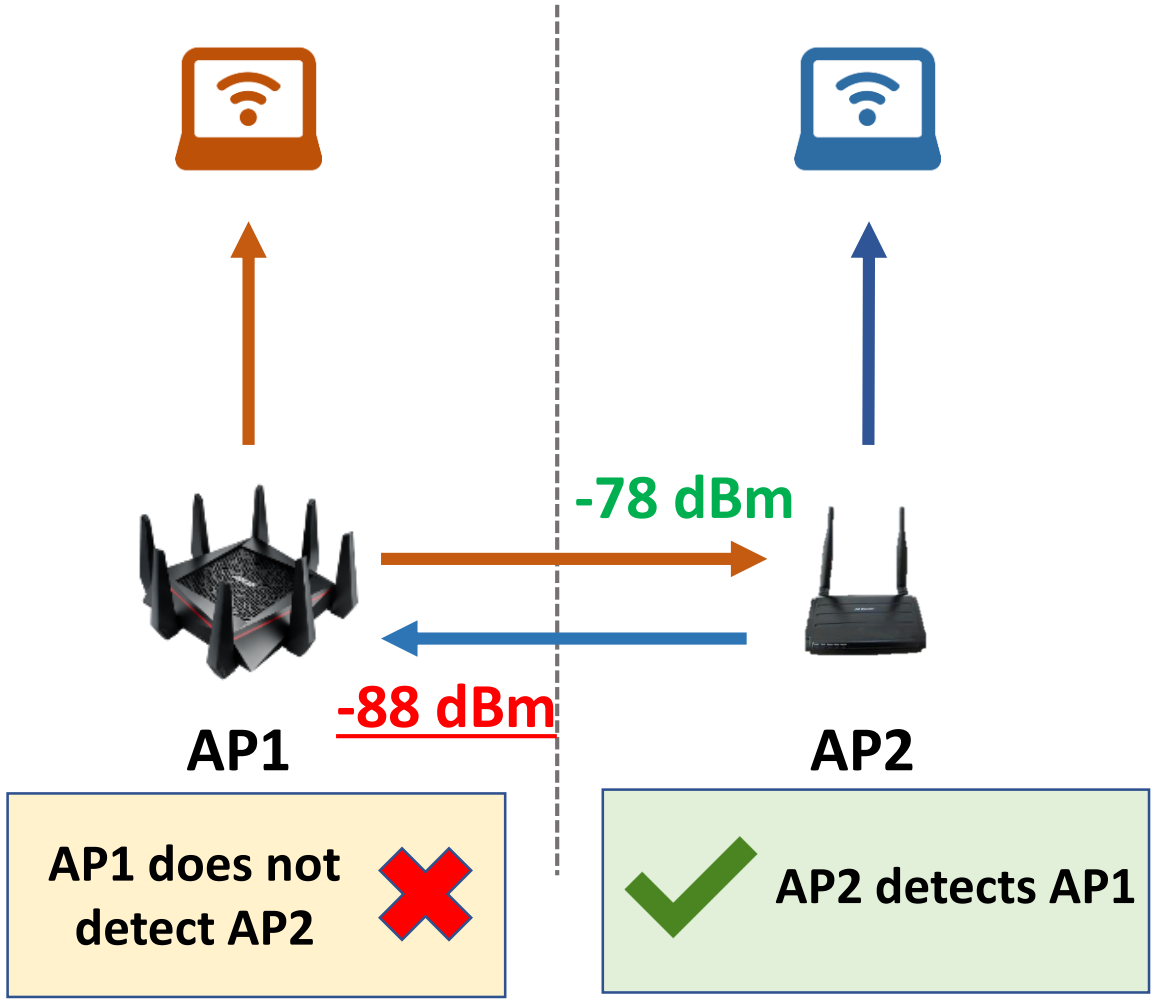
# Motivation


C1
C2
AP1
1W
AP2
100 mW


1W AP1 -> C1
100mW AP2 -> C2
TCP Throughput (Mbps)
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
Time (s)

# Why does this happen?

- Devices listen before they talk
  - Listening sensitivity?
- 802.11 defines Carrier Sensing Threshold (CST) at **-82 dBm**



# Why is this important?



vs



January 20, 2015 08:00 ET

## The Global Public Wi-Fi Network Grows to 50 Million Worldwide Wi-Fi Hotspots

**iPass Wi-Fi Growth Map Adds a Global Wi-Fi Leaderboard Showing US Trailing France**

REDWOOD SHORES, CA--(Marketwired - Jan 20, 2015) - iPass Inc. (NASDAQ: IPAS), the world's largest commercial Wi-Fi network, today announced the iPass Wi-Fi Growth Map just marked a major global milestone, surpassing 50 million publicly available hotspots, increasing by 80% since 2013. As an enhancement to the Wi-Fi Growth Map, a dynamic real-time

dd-wrt.com

OpenWrt
Wireless Freedom

# A New Sensing Technique – Skip Correlation

**“A senses B if and only if B senses A”**

**(Carrier Sensing Symmetry)**

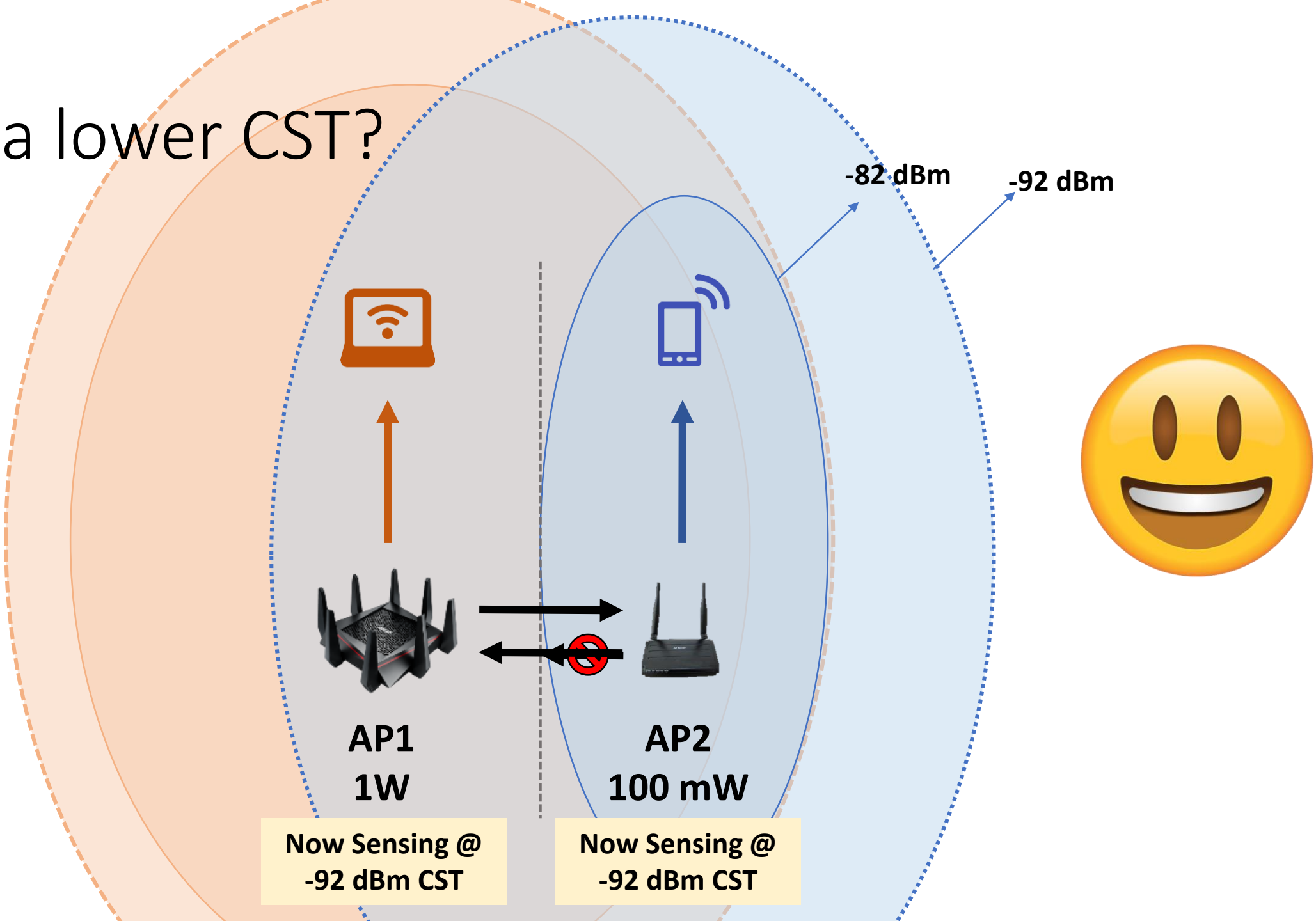
**No “Collateral” Damage**

**Causes no new, unnecessary interactions**

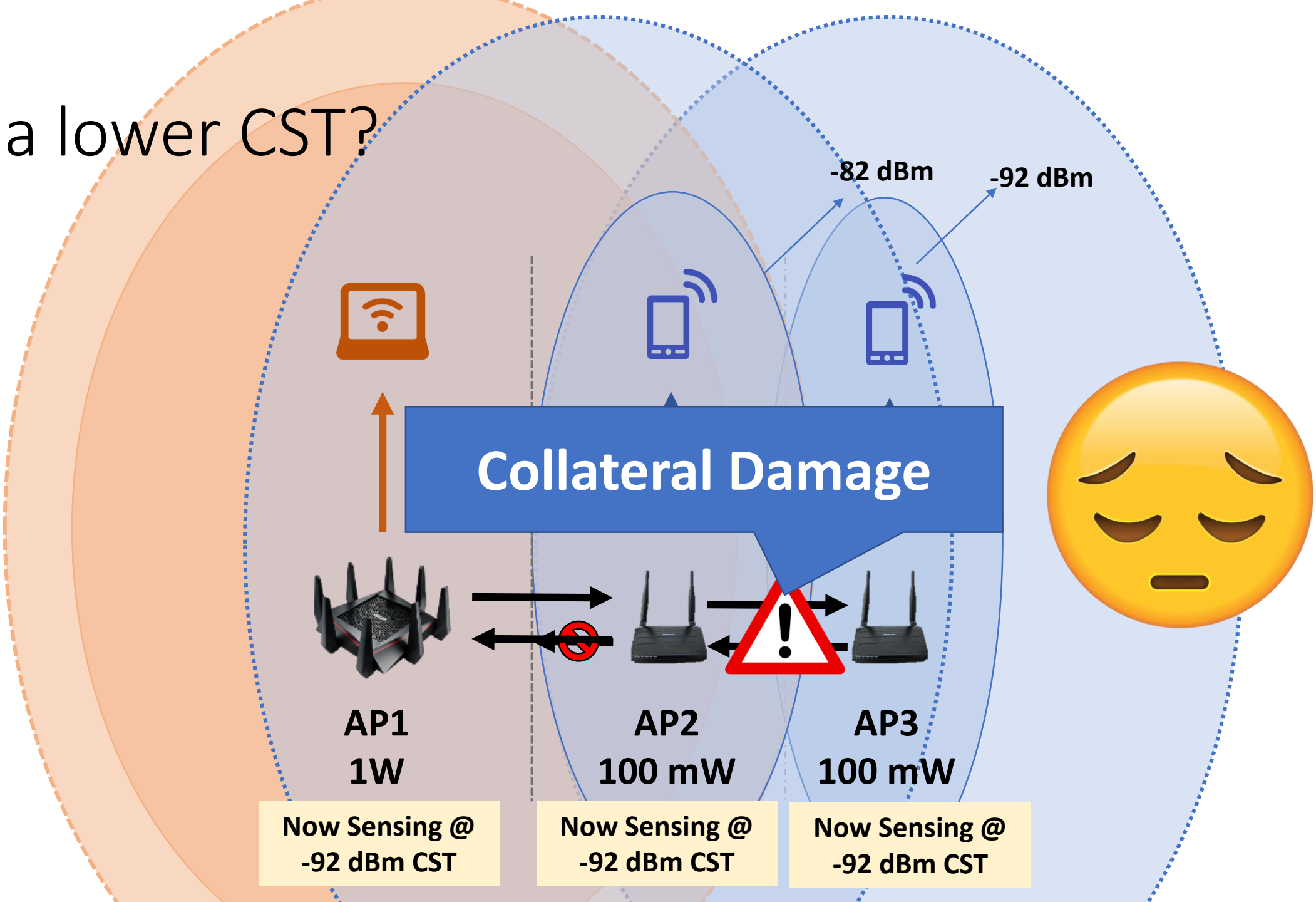
**Backward Compatible**

**Works with legacy devices, minor change to existing circuits**

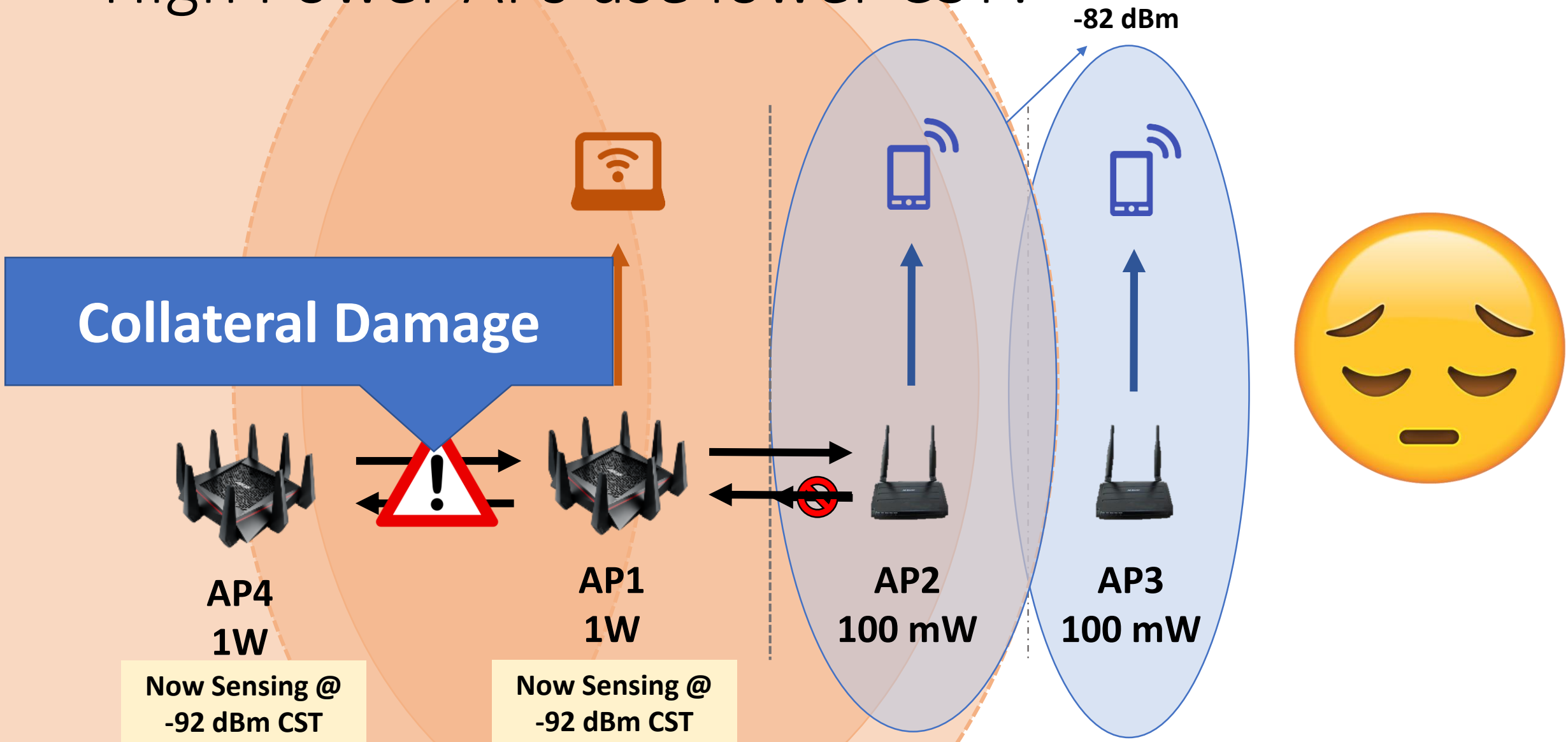
# Use a lower CST?



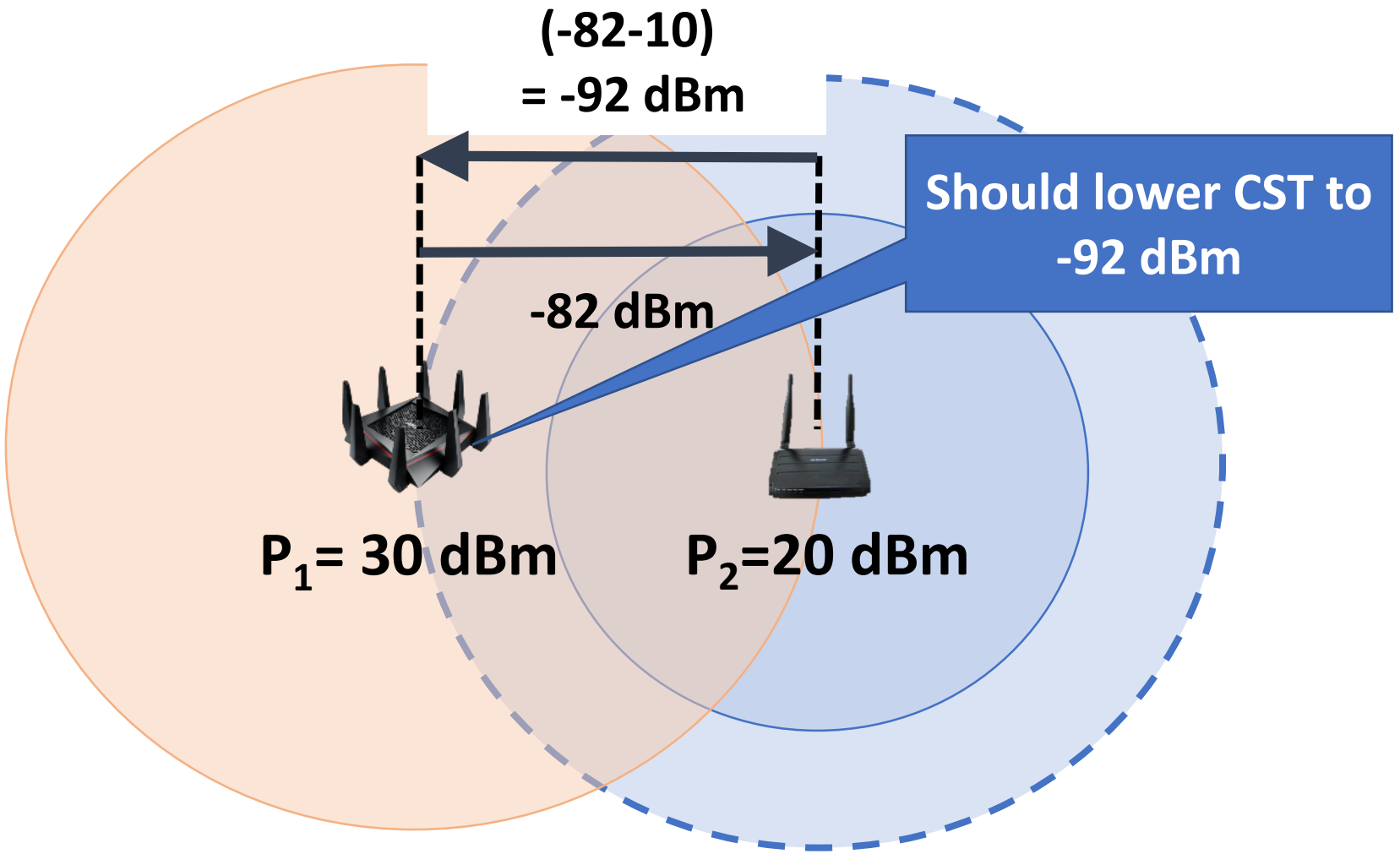
# Use a lower CST?



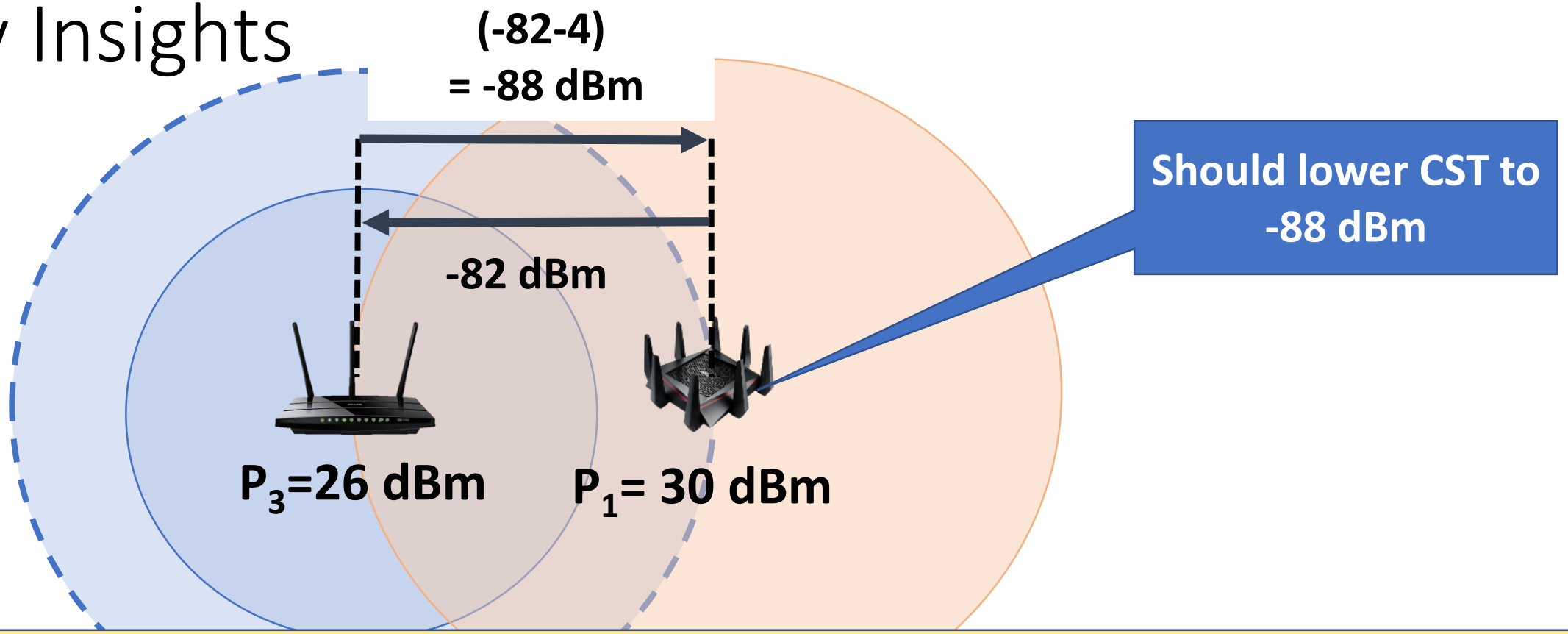
# High Power APs use lower CST?



# Key Insights



# Key Insights



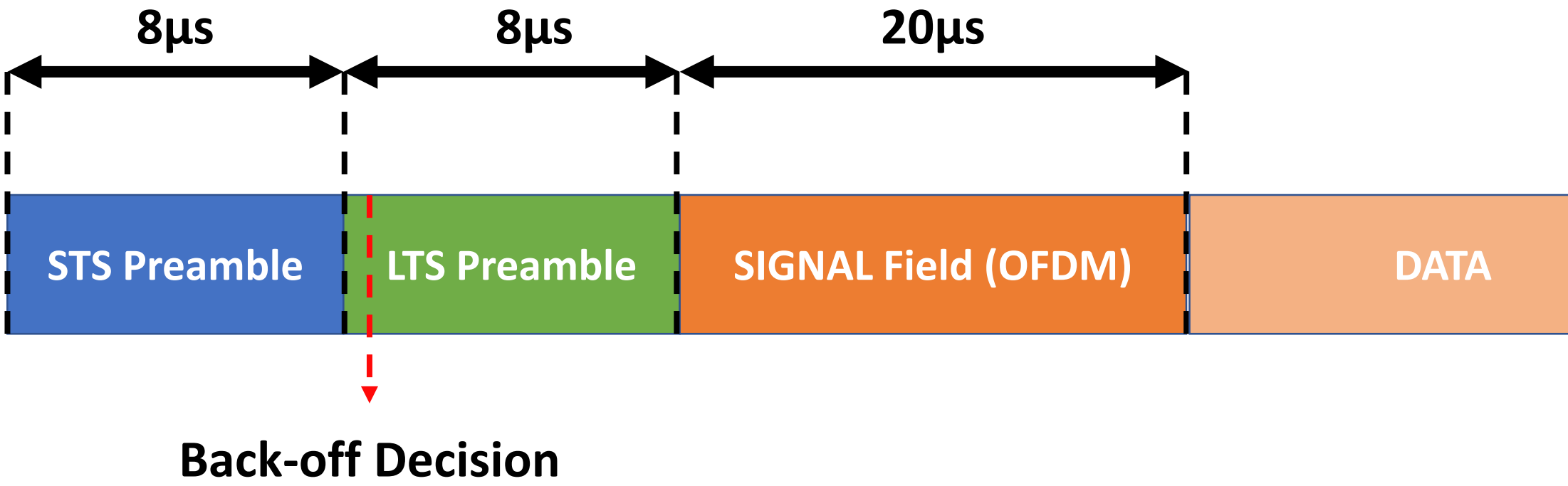

$$\text{CST}(P_1, P_2) = \begin{cases} -82, & P_1 \leq P_2 \\ -82 - (P_1 - P_2), & P_1 > P_2 \end{cases}$$

# Counter-Intuitive Insight

Dynamic CST is dependent on the receiver's AND transmitter's transmit powers!

# Determining Transmitter's Power is Hard!

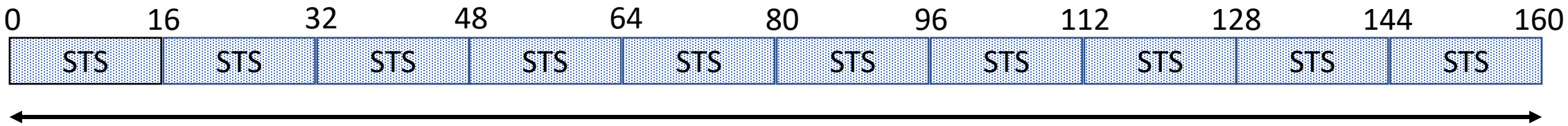
- Cannot encode power in the SIGNAL Field



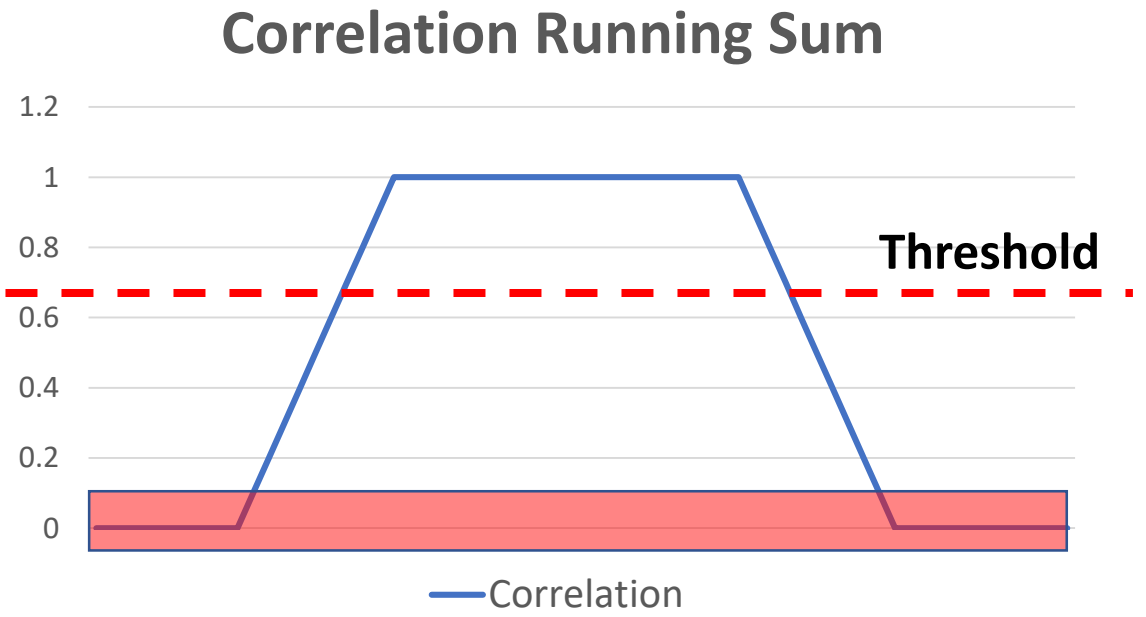
# Skip Correlation

# Carrier Sensing 101

**Wi-Fi STS Preamble**

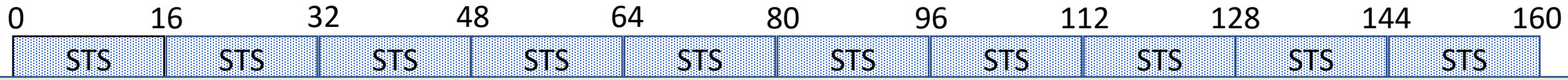



$$\text{AutoCorrelation} = \sum_{i=1}^{\frac{L}{2}} S_{recv}(i) S_{recv}\left(i + \frac{L}{2}\right)$$



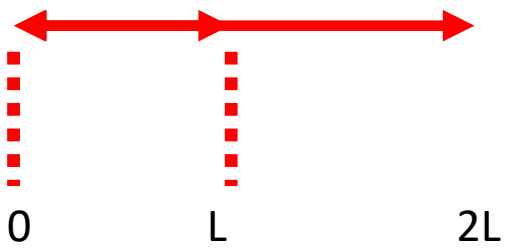
# Changing the Correlation Length

**Wi-Fi STS Preamble**

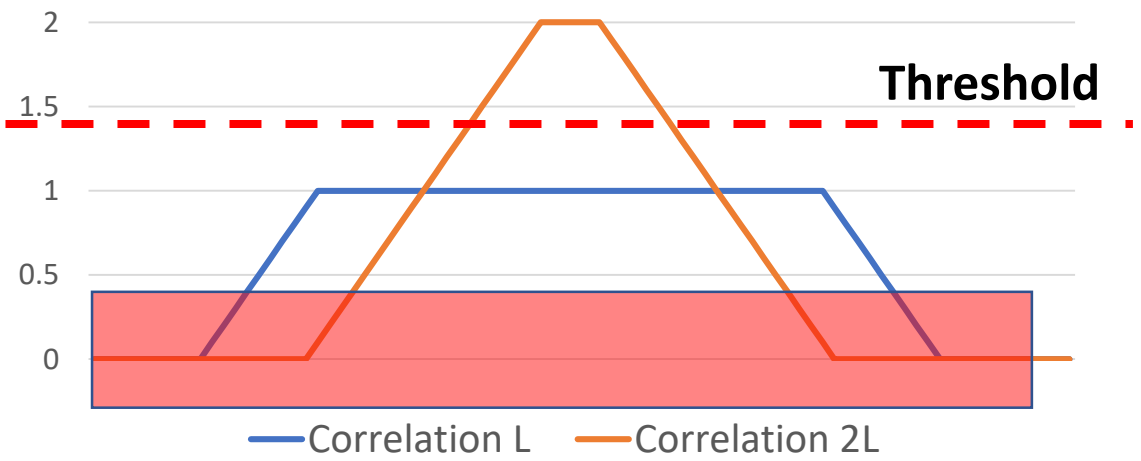



$$Correlation\ SNR \propto Length$$

$$\sum_{i=1}$$

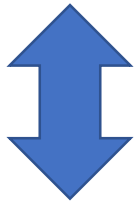



**Correlation Window**



# Correlation Length & Packet Detection

Correlation Length **L** -> 90% detection probability @ **-82** dBm



Correlation Length **2L** -> 90% detection probability @ **-85** dBm

**Doubling L is same as lowering CST by 3 dB!**

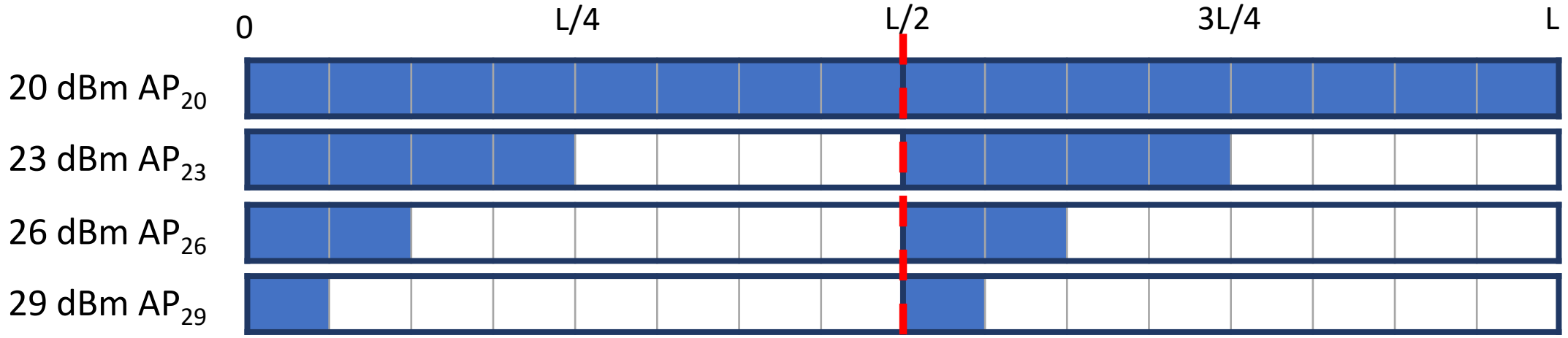
# Skip Correlation

$$\text{CST}(P_a, P_b) = \begin{cases} -82, & P_a \leq P_b \\ -82 - (P_a - P_b), & P_a > P_b \end{cases}$$

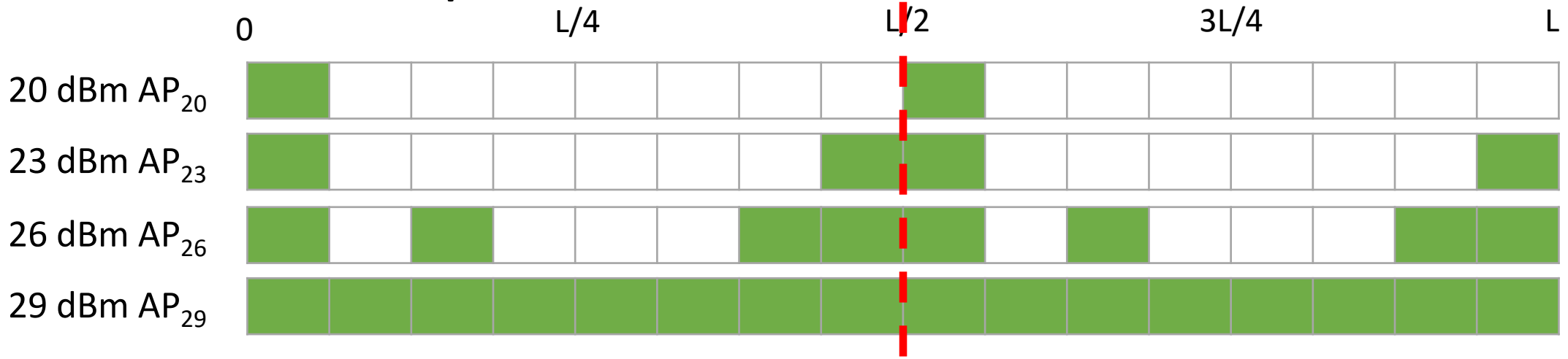
| Transmitter | Receiver |
| --- | --- |
| High Power – Short preambles | Skip Correlate Dependent on Receiver's Tx Power |
| Low Power – Long preambles | |

# Skip Correlation Example - 4 Power Levels

**Transmit Preambles**



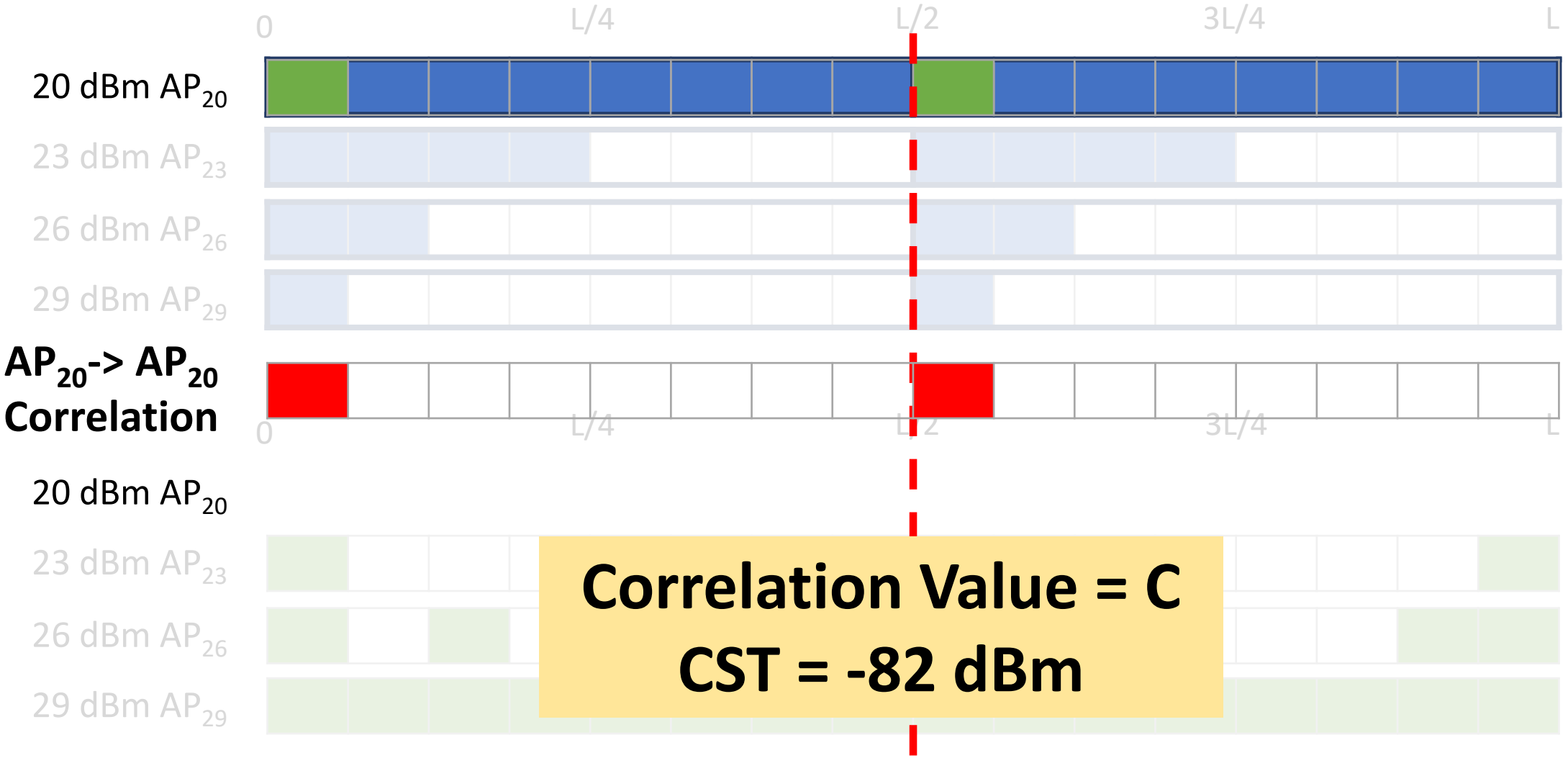

**Receive Correlation Sequence**



# $AP_{20}$-> $AP_{20}$

**Transmit Preambles**

$$\text{CST}(P_1,P_2) = \begin{cases} -82, & P_1 \le P_2 \\ -82 - (P_1 - P_2), & P_1 > P_2 \end{cases}$$



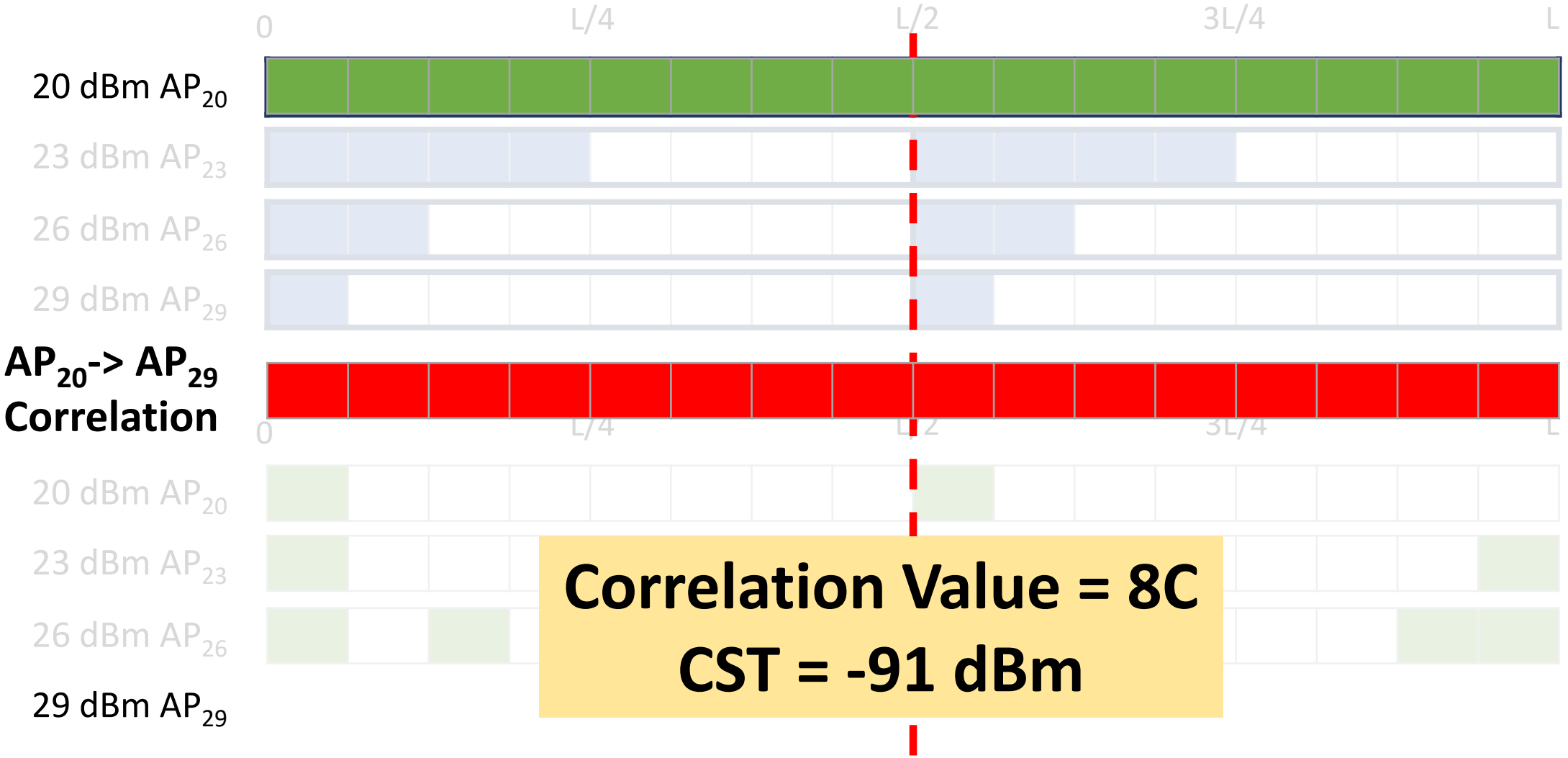

**Correlation Value = C**

**CST = -82 dBm**

# $AP_{20}$-> $AP_{29}$

**Transmit Preambles**

$$\text{CST}(P_1, P_2) = \begin{cases} -82, & P_1 \leq P_2 \\ -82 - (P_1 - P_2), & P_1 > P_2 \end{cases}$$



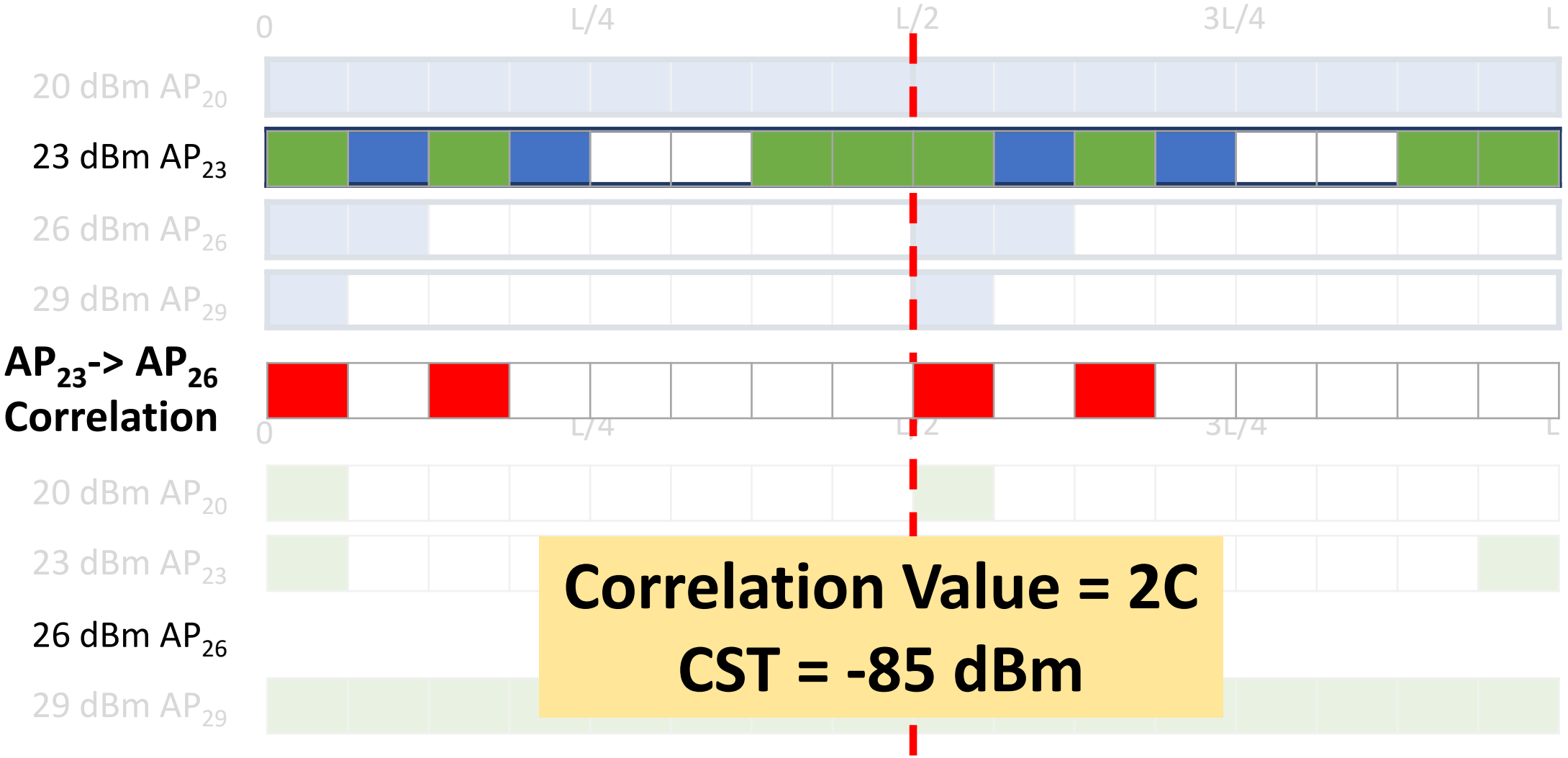

**Correlation Value = 8C**

**CST = -91 dBm**

# $AP_{23}$-> $AP_{26}$

**Transmit Preambles**

$$\text{CST}(P_1,P_2) = \begin{cases} -82, & P_1 \le P_2 \\ -82 - (P_1 - P_2), & P_1 > P_2 \end{cases}$$



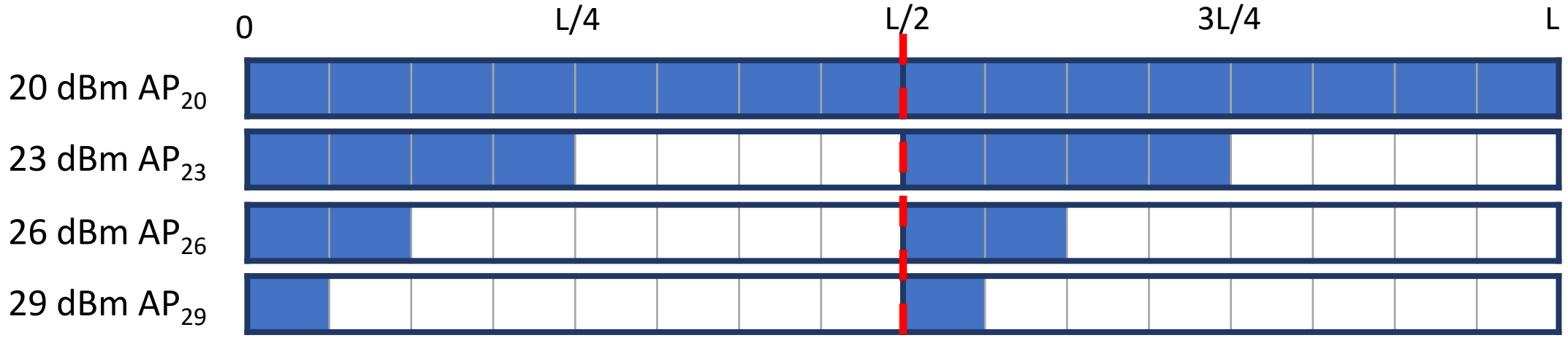

**Correlation Value = 2C**

**CST = -85 dBm**

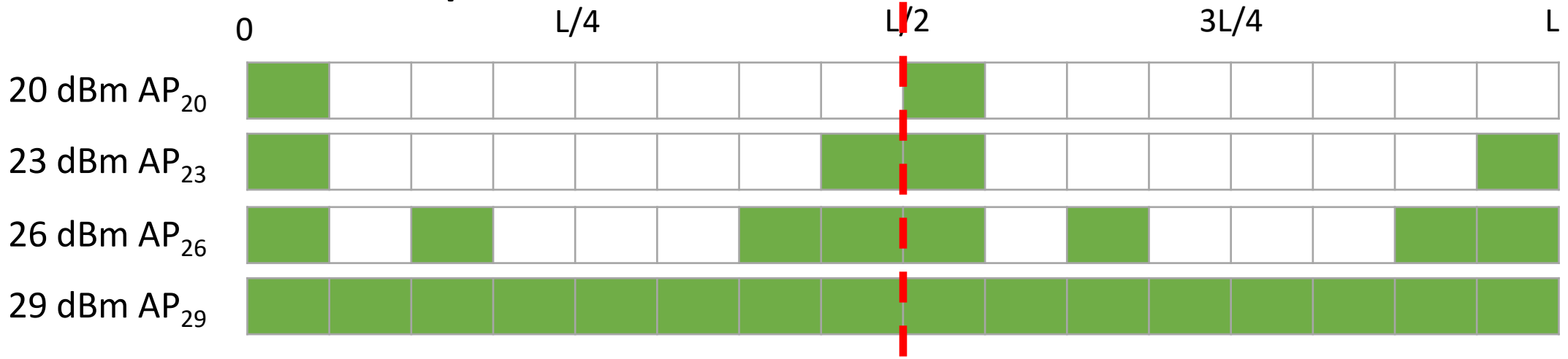
# Skip Correlation

$$\mathrm{CST}(P_1,P_2)=\begin{cases}-82, & P_1 \le P_2\\ -82-(P_1-P_2), & P_1 > P_2\end{cases}$$

**Transmit Preambles**




**Receive Correlation Sequence**



# All Tx-Rx Pairs

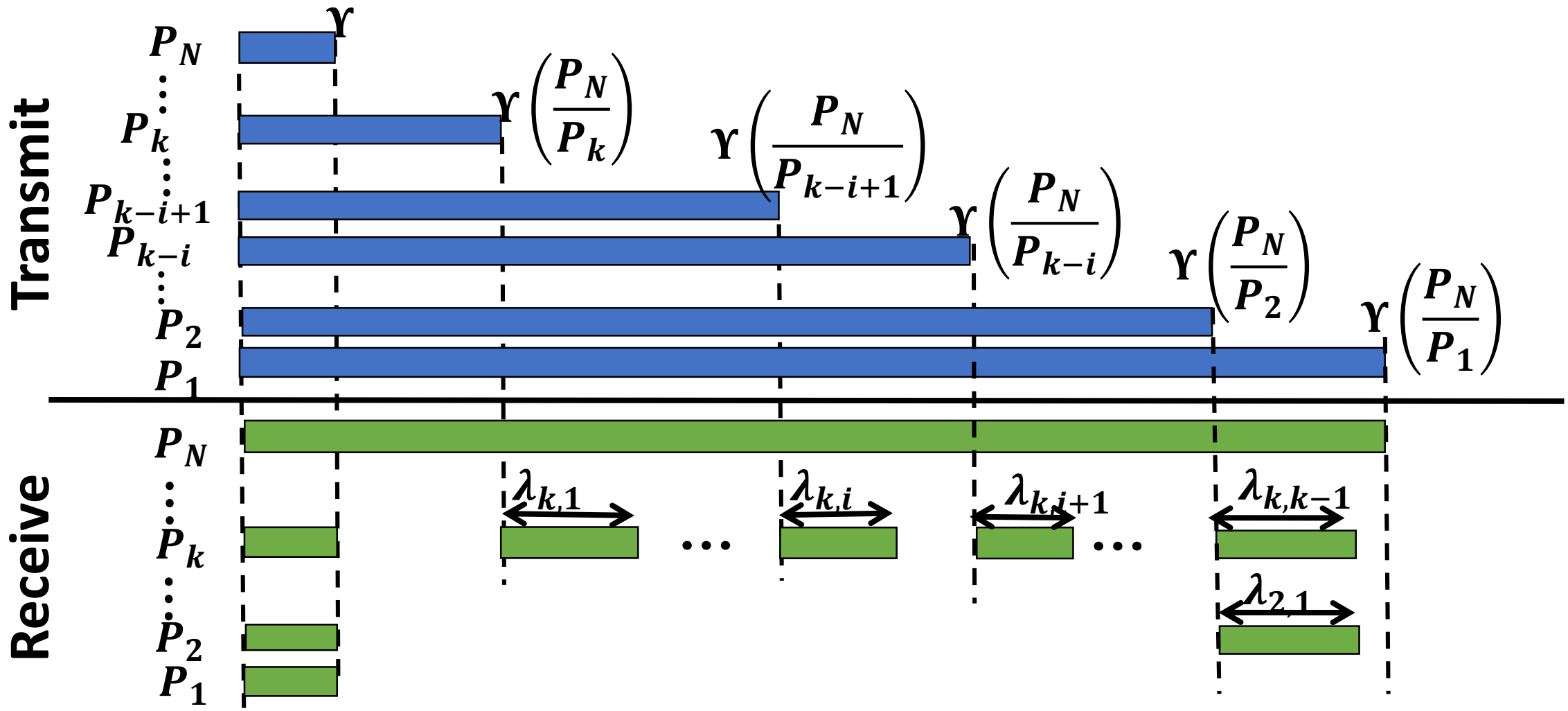
$$\text{CST}(P_1, P_2) = \begin{cases} -82, & P_1 \leq P_2 \\ -82 - (P_1 - P_2), & P_1 > P_2 \end{cases}$$

**Transmitter Tx Power**

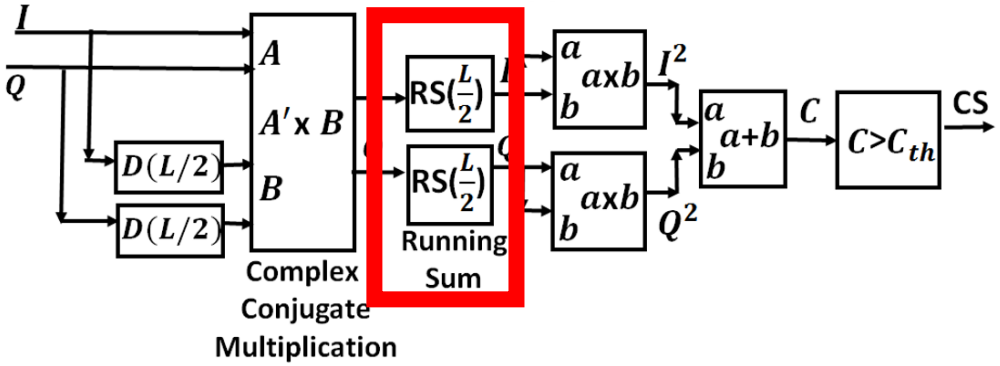
| Receiver Tx Power | 20 dBm | 23 dBm | 26 dBm | 29 dBm |
|---|---|---|---|---|
| 20 dBm | L, -82 | L, -82 | L, -82 | L, -82 |
| 23 dBm | 2L, -85 | L, -82 | L, -82 | L, -82 |
| 26 dBm | 4L, -88 | 2L, -85 | L, -82 | L, -82 |
| 29 dBm | 8L, -91 | 4L, -88 | 2L, -85 | L, -82 |

**Effective Correlation Length (L) and CST (dBm) using Skip Correlation**

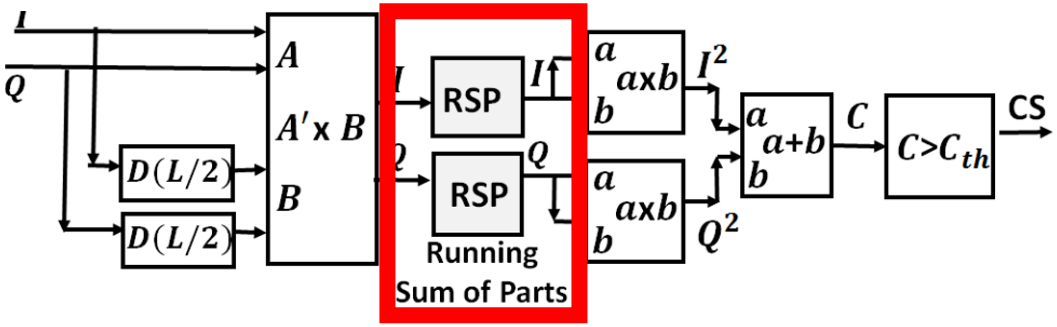
# Not Just 4 Power Levels..



# Minimal Change in Silicon




**Regular Wi-Fi Auto-Correlator**

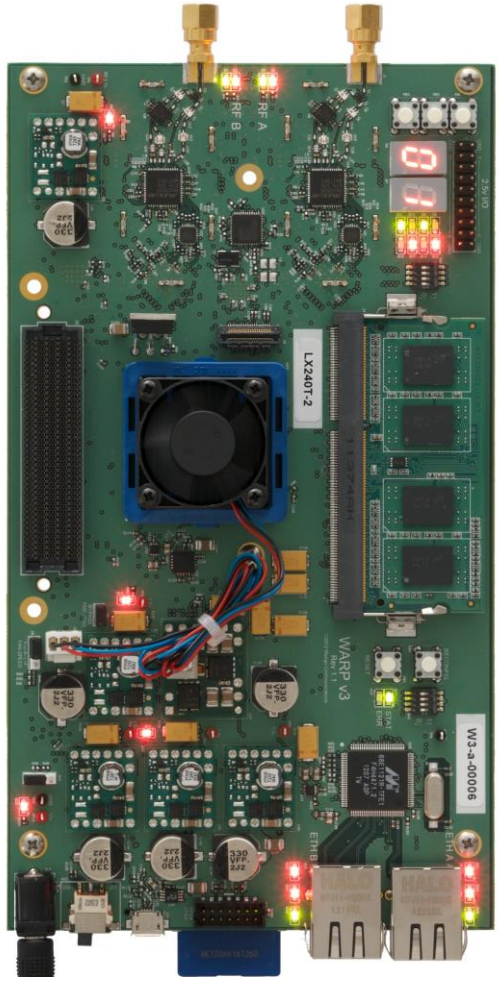



**Skip Correlator**

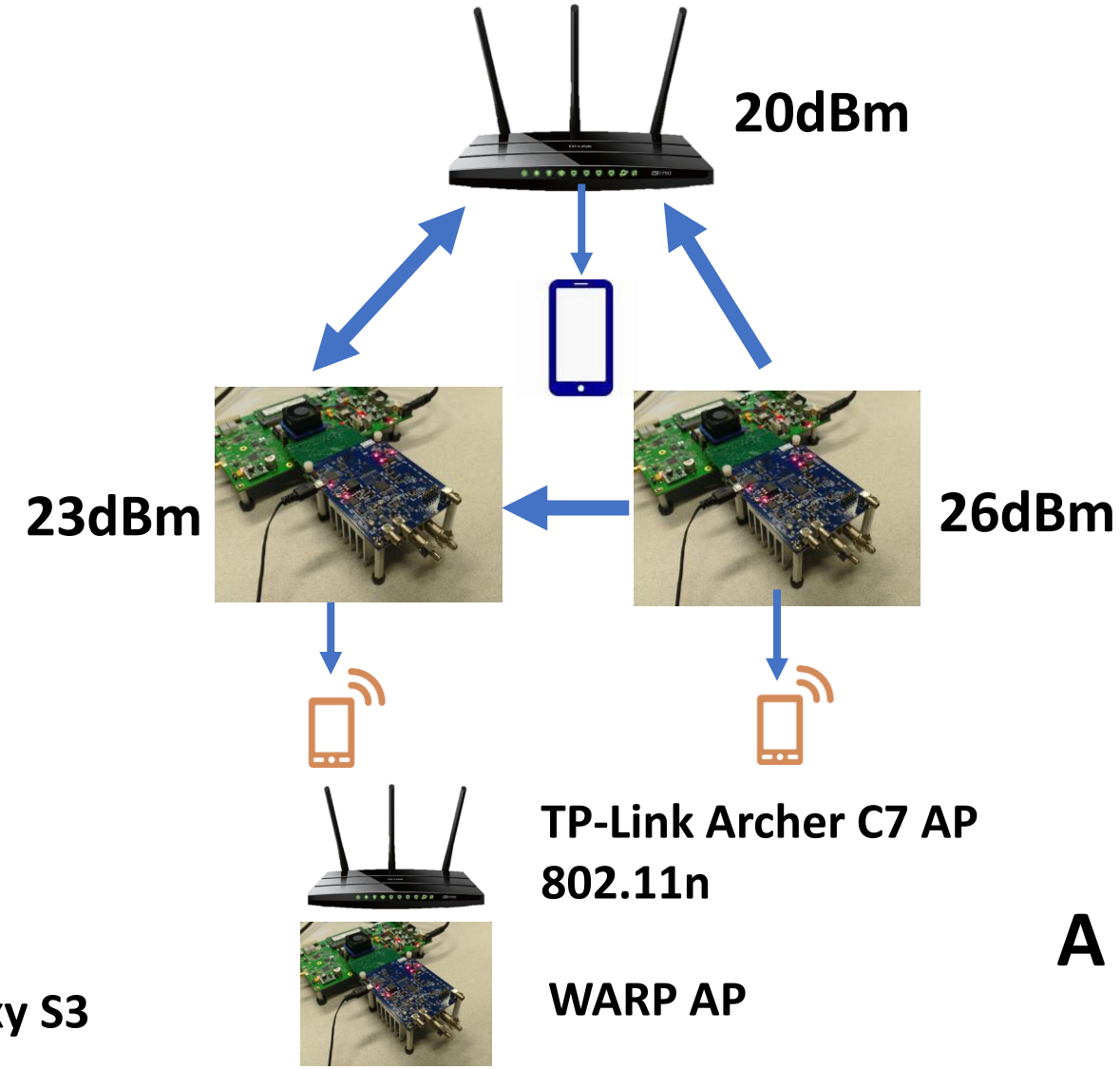
12 adders = 0.03% increase in FPGA utilization

# Implementation

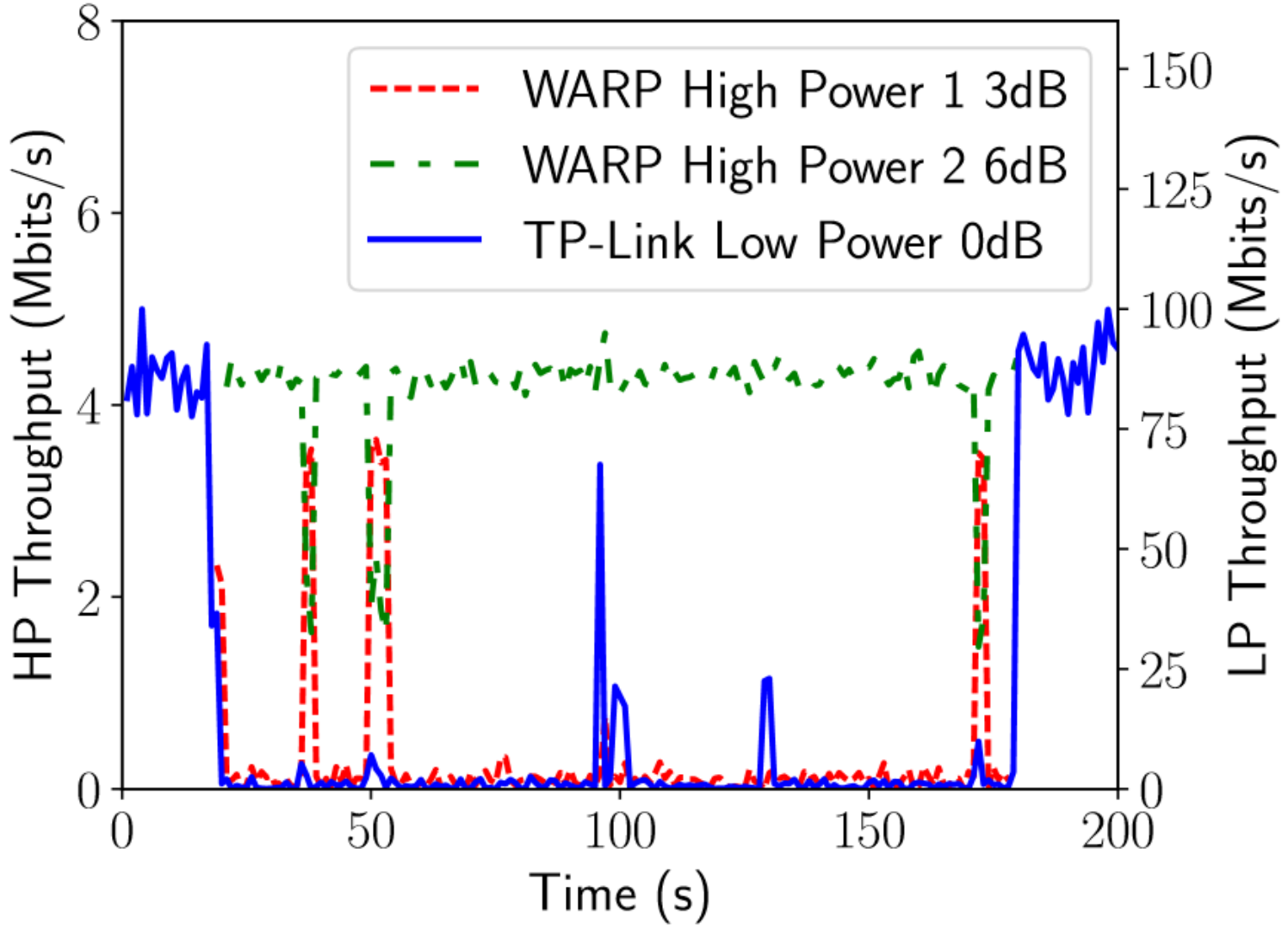
- Implemented on the WARP v3 FPGA
- Supports 4 power levels, 0 to 9 dB in increments of 3 dB
- Backward compatible design



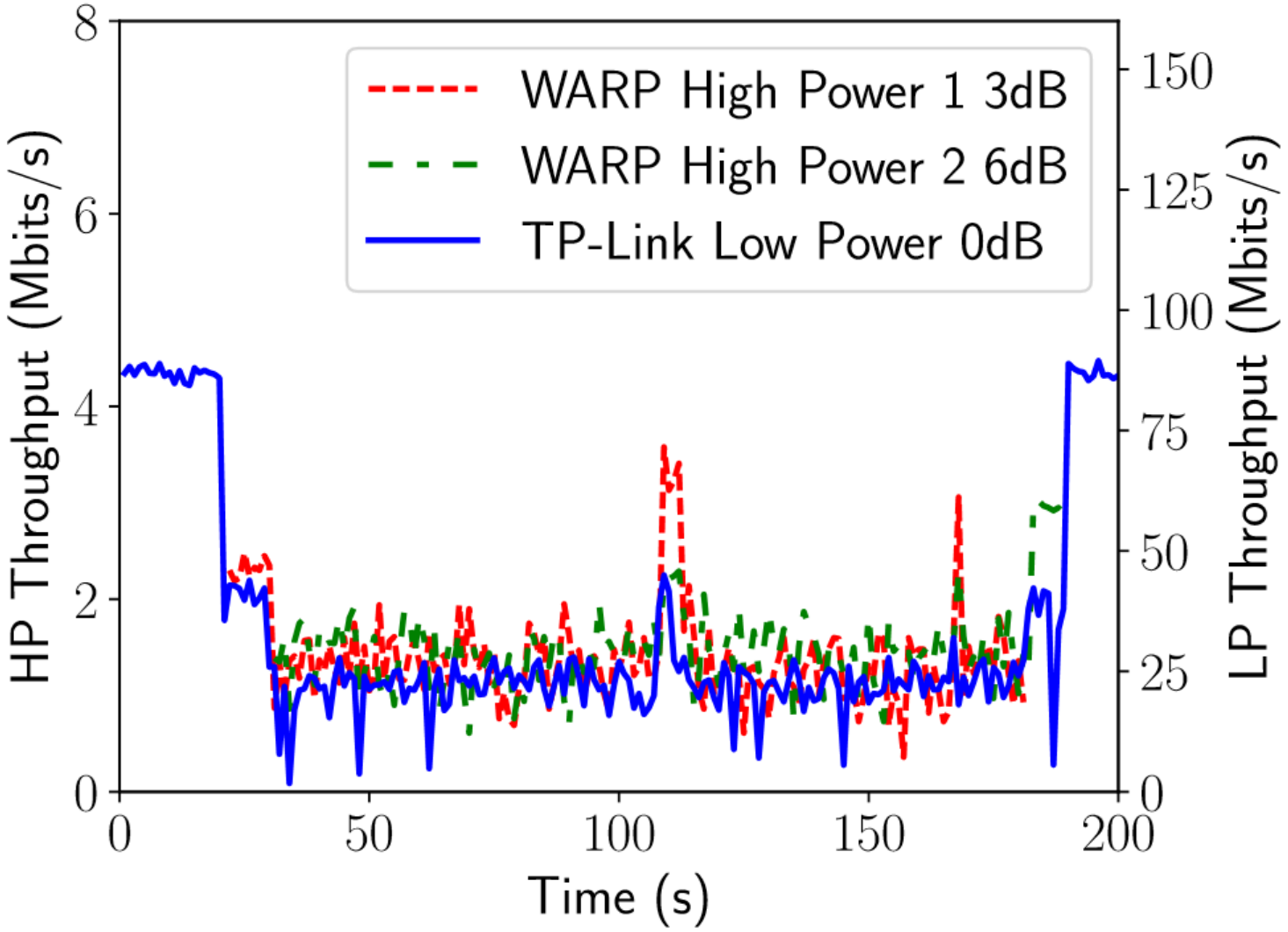
# Throughput Experiments



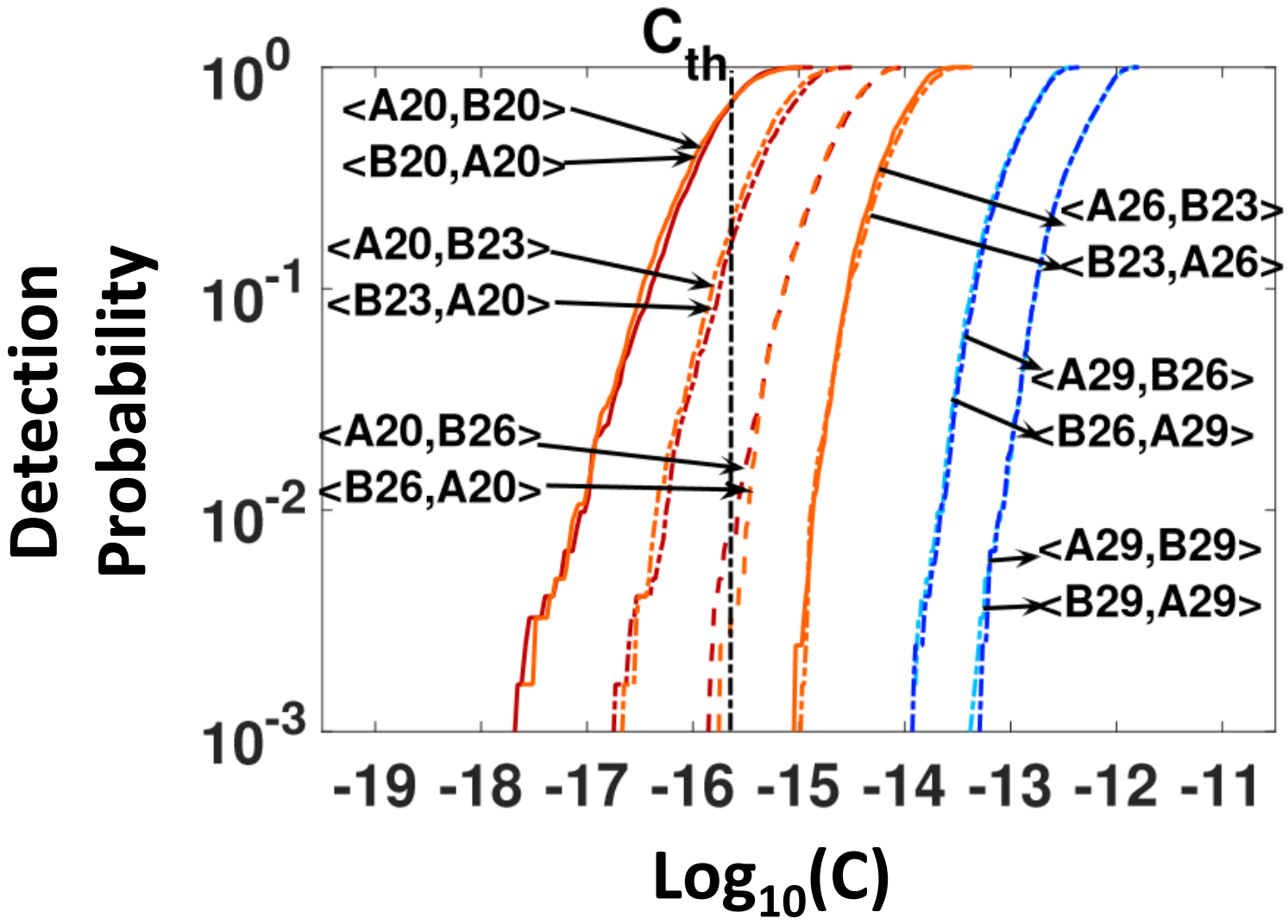
# Without Skip Correlation



# With Skip Correlation



# Sensing Symmetry Experiments



# Skip Correlation Summary

- **Carrier Sense Threshold**
  - Dynamic
  - Tx Rx power level dependent
- **Skip Correlation**
  - Realizes dynamic CST
  - Leverages L and CST Relationship
- **Experiments**
  - Sensing symmetry, even with legacy devices
  - Simple implementation



