Skip-Correlation for Multi-Power Wireless Carrier Sensing

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Motivation

TCP Throughput (Mbps) vs Time (s)

- 1W AP1 -> C1
- 100mW AP2 -> C2
Why does this happen?

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

- AP1 detects AP2
- AP1 does not detect AP2
- AP2 detects AP1

**AP1**: -88 dBm  
**AP2**: -78 dBm
Why is this important?

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

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
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?

AP1
1W

Now Sensing @ -92 dBm CST

AP2
100 mW

Now Sensing @ -92 dBm CST

-82 dBm

-92 dBm
Use a lower CST?

Collateral Damage

AP1
1W
Now Sensing @ -92 dBm CST

AP2
100 mW
Now Sensing @ -92 dBm CST

AP3
100 mW
Now Sensing @ -92 dBm CST
High Power APs use lower CST?

Collateral Damage

- AP4 1W Now Sensing @ -92 dBm CST
- AP1 1W Now Sensing @ -92 dBm CST
- AP2 100 mW
- AP3 100 mW
Key Insights

$P_1 = 30 \text{ dBm}$

$P_2 = 20 \text{ dBm}$

$(-82-10) = -92 \text{ dBm}$

Should lower CST to -92 dBm
Key Insights

$P_1 = 30 \text{ dBm}$

$P_3 = 26 \text{ dBm}$

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

$(-82 - 4) = -88 \text{ dBm}$

Should lower CST to $-88 \text{ dBm}$
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

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

Correlation Running Sum

Threshold
Changing the Correlation Length

Wi-Fi STS Preamble

Correlation $SNR \propto Length$

Correlation Window

Threshold

$i=1$
Correlation Length & Packet Detection

Correlation Length $L \rightarrow 90\%$ detection probability @ -82 dBm

$\downarrow$

Correlation Length $2L \rightarrow 90\%$ detection probability @ -85 dBm

Doubling $L$ is same as lowering CST by 3 dB!
Skip Correlation

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

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Receiver</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Power – Short preambles</td>
<td>Skip Correlate\Dependent on Receiver's Tx Power</td>
</tr>
<tr>
<td>Low Power – Long preambles</td>
<td></td>
</tr>
</tbody>
</table>
Skip Correlation Example - 4 Power Levels

**Transmit Preambles**

- **20 dBm AP₂₀**
- **23 dBm AP₂₃**
- **26 dBm AP₂₆**
- **29 dBm AP₂₉**

**Receive Correlation Sequence**

- **20 dBm AP₂₀**
- **23 dBm AP₂₃**
- **26 dBm AP₂₆**
- **29 dBm AP₂₉**
\[
\text{CST}(P_1, P_2) = \begin{cases} 
-82, & P_1 \leq P_2 \\
-82 - (P_1 - P_2), & P_1 > P_2 
\end{cases}
\]

Correlation Value = C

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

Correlation Value = 2C

CST = -85 dBm
Skip Correlation

Transmit Preambles

<table>
<thead>
<tr>
<th>Power (dBm)</th>
<th>Receive Correlation Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>20 dBm AP_{20}</td>
</tr>
<tr>
<td>23</td>
<td>23 dBm AP_{23}</td>
</tr>
<tr>
<td>26</td>
<td>26 dBm AP_{26}</td>
</tr>
<tr>
<td>29</td>
<td>29 dBm AP_{29}</td>
</tr>
</tbody>
</table>

Receive Correlation Sequence

CST(P_1,P_2) = \begin{cases} 
-82, & P_1 \leq P_2 \\
-82 - (P_1 - P_2), & P_1 > P_2 
\end{cases}
All Tx-Rx Pairs

Cross-Sector Throughput (CST) formula:

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

<table>
<thead>
<tr>
<th>Receiver Tx Power</th>
<th>Transmitter Tx Power</th>
<th>Effective Correlation Length (L) and CST (dBm) using Skip Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 dBm</td>
<td>20 dBm</td>
<td>L, -82</td>
</tr>
<tr>
<td>23 dBm</td>
<td>23 dBm</td>
<td>L, -82</td>
</tr>
<tr>
<td>26 dBm</td>
<td>26 dBm</td>
<td>L, -82</td>
</tr>
<tr>
<td>29 dBm</td>
<td>29 dBm</td>
<td>L, -82</td>
</tr>
<tr>
<td>20 dBm</td>
<td>23 dBm</td>
<td>2L, -85</td>
</tr>
<tr>
<td>23 dBm</td>
<td>23 dBm</td>
<td>L, -82</td>
</tr>
<tr>
<td>26 dBm</td>
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</tr>
<tr>
<td>29 dBm</td>
<td>29 dBm</td>
<td>L, -82</td>
</tr>
<tr>
<td>20 dBm</td>
<td>26 dBm</td>
<td>4L, -88</td>
</tr>
<tr>
<td>23 dBm</td>
<td>26 dBm</td>
<td>2L, -85</td>
</tr>
<tr>
<td>26 dBm</td>
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<td>29 dBm</td>
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<td>L, -82</td>
</tr>
<tr>
<td>20 dBm</td>
<td>29 dBm</td>
<td>8L, -91</td>
</tr>
<tr>
<td>23 dBm</td>
<td>29 dBm</td>
<td>4L, -88</td>
</tr>
<tr>
<td>26 dBm</td>
<td>29 dBm</td>
<td>2L, -85</td>
</tr>
<tr>
<td>29 dBm</td>
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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

Nexus 5x
Samsung Galaxy S3

TP-Link Archer C7 AP
802.11n
WARP AP

A → B  B can sense A

20dBm
23dBm
26dBm

A
B
Without Skip Correlation
With Skip Correlation
Sensing Symmetry Experiments

Detection Probability

$\log_{10}(C)$

$C_{th}$

$\langle A_{20}, B_{20} \rangle$
$\langle B_{20}, A_{20} \rangle$
$\langle A_{20}, B_{23} \rangle$
$\langle B_{23}, A_{20} \rangle$
$\langle A_{26}, B_{23} \rangle$
$\langle B_{23}, A_{26} \rangle$
$\langle A_{29}, B_{26} \rangle$
$\langle B_{26}, A_{29} \rangle$
$\langle A_{29}, B_{29} \rangle$
$\langle B_{29}, A_{29} \rangle$
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