Design and Evaluation of a Versatile and Efficient Receiver-Initiated Link Layer for Low-Power Wireless

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Presented by Lianmu Chen
Outline

• Introduction
• A-MAC Design Overview
• Implementation Details
• Backcast Evaluation
• Macrobenchmark Evaluation
• Conclusions
Introduction
A receiver-initiated MAC
Benefits

• Handle hidden terminals better than sender-initiated ones

• Support asynchronous communication w/o long-preambles

• Support extremely low duty cycles or high data rates

• Support many low-power services
  – Wakeup
  – Discovery
  – Unicast
  – Broadcast
  – Pollcast
  – Anycast
Drawbacks

• Probe (LPP) is more expensive than channel sample (LPL)
  ➔ Baseline power is higher

• Frequent probe transmissions
  ➔ Could congest channel & increase latency
  ➔ Could disrupt ongoing communications
  ➔ Channel usage scales with node density rather than traffic

• Services use incompatible probe semantics
  ➔ Makes concurrent use of services difficult
  ➔ Supporting multiple, incompatible probes increases power
Is it possible to design a general-purpose, yet efficient, receiver-initiated link layer?
A-MAC Design Overview
A-MAC communication over 802.15.4

RXTX turnaround time: 192 µs

Max data packet: 4.256 ms

ACK transmission time: 352 µs
A-MAC’s contention mechanism

Node 1
Sender
Listen P A D P-CW BO

Node 2
Receiver
P A × P-CW D

Node 3
Sender
Listen P A D P-CW D

Backcast
frame collision
A-MAC Communications

Benefits:

• Save energy:
  (1) only has to wait marginally longer than the radio’s RX/TX turnaround time;
  (2) IEEE 802.15.4 standard, a turnaround occurs in 192 μs, nearly 20 times faster than the 3.75 ms beacon-data turnaround time that RI-MAC requires with its software based protocol processing

• Distinguish between collisions and interference

  Therefore, A-MAC is far less susceptible to interference based false alarms than either LPL or RI-MAC.
Implementation Details
Problems

• Overreacting:
  - a sender will auto-ack *every probe it receives*, including probes from neighbors for which the sender has no pending traffic.

• Against Standards
  - the IEEE 802.15.4-2006 standard specifically prohibits this behavior, any frame that is broadcast shall be sent with its Acknowledgment Request subfield set to zero.

• Mixed radio support
  - because this behavior is prohibited, it enjoys somewhat mixed radio support: while the CC2420 [34] radio and AT86RF230 [3] radio Rev A silicon both support broadcast auto-acks, the Rev B silicon “fixes” this standards non-compliance and does not auto-ack broadcast frames.
## Unicast Communications

<table>
<thead>
<tr>
<th>Node 1 (Sender)</th>
<th>MAC=0x8002</th>
<th>DST=0x0002</th>
<th>SRC=0x0001</th>
<th>SEQ=0x23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Listen</td>
<td>P</td>
<td>A</td>
<td>D</td>
<td>P</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Node 2 (Receiver)</th>
<th>MAC=0x8002</th>
<th>DST=0x8002</th>
<th>SRC=0x0002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Listen</td>
<td>P</td>
<td>A</td>
<td>D</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Node 3 (Sender)</th>
<th>MAC=0x8002</th>
<th>DST=0x0002</th>
<th>SRC=0x0001</th>
<th>ACK=0x0023</th>
<th>FRM=0x0001</th>
</tr>
</thead>
<tbody>
<tr>
<td>Listen</td>
<td>P</td>
<td>A</td>
<td>D</td>
<td>P-CW</td>
<td>BO</td>
</tr>
</tbody>
</table>

**Backcast**

**frame collision**
A-MAC broadcast design is identical to Unicast, with an important difference: sender disables hardware address recognition but keeps hardware auto-acks enabled.

In this way, sender will auto-ack every probe it receives and it will send the data packet like in the unicast case.
Backcast Evaluation
Two important metrics:

• Received signal strength indicator (RSSI)
  Signal strength, measured by the radio over the first eight symbols of an acknowledgment (ACK) frame

• Signal quality (LQI)
  measured by the radio over the first eight symbols and is reported as a 7-bit unsigned integer that can be viewed as the average correlation value or chip error rate (values near 100 indicate an excellent link).
Large scale performance

Figure 7. The effect on LQI as the number of concurrent ACKs increases from 0 to 94 in a typical indoor deployment setting. The median value of LQI falls quickly for the first six nodes and then falls slowly. Beyond approximately 30 nodes, the LQI values stabilize at approximately 100. The data suggest that even in the presence of a large number of ACK collisions, the receiver can successfully decode the ACK frame. Note the y-axis ranges from 74 to 106.

Conclusion: The statistical superposition of an increasing number of signals does not lead to destructive interference, making backcast a robust synchronization primitive.
Robustness to External Interference

<table>
<thead>
<tr>
<th>Primitive Operation</th>
<th>w/o 802.11 interference</th>
<th>w/ 802.11 interference</th>
<th>Increase in Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>TinyOS LPL</td>
<td>175 μA</td>
<td>3,030 μA</td>
<td>17.3×</td>
</tr>
<tr>
<td>RI-MAC LPP</td>
<td>383 μA</td>
<td>12,576 μA</td>
<td>54.7×</td>
</tr>
<tr>
<td>A-MAC LPP</td>
<td>206 μA</td>
<td>230 μA</td>
<td>1.12×</td>
</tr>
</tbody>
</table>

Table 1. The effect of interference on idle listening current in an office environment using three different synchronization schemes
Figure 10. LPL preamble sampling techniques leave receivers susceptible to noisy wireless environments, such as those caused by 802.11 interference. Figures (a) and (b) show the macroscopic and microscopic behavior of the TinyOS 2.1 sampling algorithm when the channel is clear: the receiver immediately returns to sleep. Figures (c) and (d) show the macroscopic and microscopic behavior while a file transfer is in progress using a nearby 802.11 access point. Of the seven channel samples visible in this trace, five are unnecessarily lengthened due to channel noise.
Macrobenchmark Evaluation
Table 2 shows between one and four senders contending to transmit to a single receiver for both RI-MAC and A-MAC.

<table>
<thead>
<tr>
<th>MAC</th>
<th>No. of Senders</th>
<th>Packet Delivery Ratio</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Avg</td>
<td>Min</td>
<td>Max</td>
<td></td>
</tr>
<tr>
<td>RI-MAC</td>
<td>1</td>
<td>99.9%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>97.5%</td>
<td>97.3%</td>
<td>97.7%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>95.6%</td>
<td>95.0%</td>
<td>96.8%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>90.7%</td>
<td>90.3%</td>
<td>90.9%</td>
<td></td>
</tr>
<tr>
<td>A-MAC</td>
<td>1</td>
<td>99.9%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>99.3%</td>
<td>98.2%</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>99.3%</td>
<td>98.3%</td>
<td>99.5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>98.5%</td>
<td>96.7%</td>
<td>99.5%</td>
<td></td>
</tr>
</tbody>
</table>
Multiple Parallel Unicast Flows

Table 3 shows **A-MAC throughput and packet delivery ratio** as a function of the **number of different whitelisted channels** that are available for use, the **number of sender:receiver pairs** transferring data concurrently, and the receivers’ **probe interval**.
Asynchronous Network Wakeup

Figure 11 shows the wakeup times of 59 nodes in a multihop testbed across a range of sampling/probing intervals.
Collection Tree Protocol Performance

N = 59  \( T_{\text{data}} = 60 \, \text{s} \)  \( T_{\text{probe}} = 500 \, \text{ms} \)

Table 4. CTP performance over LPL and A-MAC.

<table>
<thead>
<tr>
<th></th>
<th>LPL</th>
<th>A-MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Duty Cycle</td>
<td>6.36%</td>
<td>4.44%</td>
</tr>
<tr>
<td>Average Packet Delivery Ratio</td>
<td>95.1%</td>
<td>99.7%</td>
</tr>
<tr>
<td>Average Hop Count</td>
<td>7.34</td>
<td>4.85</td>
</tr>
<tr>
<td>Maximum Hop Count</td>
<td>14</td>
<td>13</td>
</tr>
</tbody>
</table>

(a) CDF of CTP Duty Cycles
Inference Vulnerability

Channel 18

Channel 26

Sampling

Probing

Backcast

Sampling

Probing

Backcast
Effect of Density on Packet Delivery

Same collision domain (between 0, 1, 2, 3, 8, 13, and 18) who simply transmit probes with varying probe periods (32 ms, 64 ms, 128 ms, and 256 ms)
Conclusion

• Backcast provides a new synchronization primitive
  – Common abstraction underlying many protocols
  – Can be implemented using a DATA/ACK frame exchange
  – Works even with a 8, 12, 94 colliding ACK frames
  – Faster, more efficient, and more robust than LPL, LPP
• A-MAC augments Backcast to implement
  – Unicast
  – Broadcast
  – Network wakeup
  – Robust pollcast
• Results show
  – Higher packet delivery ratios
  – Lower duty cycles
  – Better throughput (and min/max fairness)
  – Faster network wakeup
  – Higher channel efficiency
Thank you

Questions?