Low-Power System Design

227-0781-00L
Fall Semester 2019

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Plan for Today

• MAC Layer Techniques
  – Contention-based Rendezvous – Bootstrapping: LPL/LPP
  – Dedicated acknowledgements, multiple channels: A-MAC
  – Arbitration using controlled collisions: StrawMan
  – Distributed scheduling: DOZER
  – Constructive interference: A-MAC
  – Network Flooding: GLOSSY

• Present metrics used for performance analysis
Networked Embedded Systems

MAC LAYER TECHNIQUES – CONTENTION-BASED RENDEZVOUS
Simple Sender-Initiated MAC

- Sender triggers communications by transmitting data
- Receiver is listening
Simple Receiver-Initiated MAC

- Receiver triggers exchange by transmitting a probe
- Sender receives probe and sends data
- Low-power probing (LPP)
MAC Layer Decision: Stay awake or go to sleep?

Sender-Initiated: Channel Sampling

Receiver-Initiated: Channel Probing
Optimizing LPL: Shorter Preamble Sampling

• Bookkeeping to avoid sending out long preambles
  – Maintaining the phase offset (clock) to selected neighbors
  – Start transmitting a message just before receiver wakes
  – Synchronized transmit/receive
  – Piggybacking of local phase offset on ACKs of the underlying CSMA protocol

• Benefits
  – WiseMAC is able to squeeze out up to 80% (20 out of 25 ms) of TX cost and up to 67% (10 out of 15 ms) of RX costs
  – Shortening the preambles also reduces overhearing by nodes other than the sender/receiver pair
Receiver vs. Sender-initiated Tradeoff

• Receiver-initiated Pro’s
  – Handle hidden terminals better than sender-initiated ones
  – Support asynchronous communication w/o long-preambles
  – Support extremely low duty cycles or high data rates

• Receiver-initiated Con’s
  – 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
Scaling to Larger Networks

Example Receiver-Initiated: Channel Probing

Data frame collision
MAC LAYER TECHNIQUES – DEDICATED ACKNOWLEDGEMENTS, MULTIPLE CHANNELS
802.15.4 Receiver-Initiated Link Layer

Is it possible to design a general-purpose, yet efficient, receiver-initiated link layer?

A-MAC
A-Mac Parallel Multichannel Data Transfers

- Arbitration using signaling in preambles (like Dozer!)
- Selective scheduling of data-senders
- Use control, data (1), and data (2) channels

Sender 1

Receiver 1

Sender 2

Receiver 2
A-MAC Offers Modest Incast Performance

![Collision Domain](image)

<table>
<thead>
<tr>
<th>MAC</th>
<th>No. of Senders</th>
<th>Packet Delivery Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Avg</td>
</tr>
<tr>
<td>RI-MAC</td>
<td>1</td>
<td>99.9%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>97.5%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>95.6%</td>
</tr>
<tr>
<td></td>
<td>4 (Highlighted)</td>
<td>90.7%</td>
</tr>
<tr>
<td>A-MAC</td>
<td>1</td>
<td>99.9%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>99.3%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>99.3%</td>
</tr>
<tr>
<td></td>
<td>4 (Highlighted)</td>
<td>98.5%</td>
</tr>
</tbody>
</table>
A-MAC Network Wakeup

- Wakes up the network faster and more efficiently than LPL (Flash) flooding
A-MAC Works Well at Low Duty Cycles

\[ T_{probe} = 4,000 \, \text{ms} \]
\[ P_{avg} = 63 \, \mu\text{W} \]
\[ I_{avg} = 21 \, \mu\text{A} \]
\[ N = 59 \]
A-MAC Beats LPL/CTP Combinations

N = 59
T_{data} = 60 s
T_{probe} = 500 ms

<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>
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</table>
MAC LAYER TECHNIQUES – ARBITRATION USING CONTROLLED COLLISIONS
Collision Arbitration with StrawMan

- Multi-channel operation
  - Initial probe at pre-determined channel
  - Rest of communication at the other channel

Send Collision request

Reply longest length

Another request

StrawMan Performance

• Contiki + Tmote Sky
• RI-MAC
  – Version 1: Strawman + multi-channel operation
  – Version 2: random backoff (geometric distribution)
• Transmissions of COLLISION packets are synchronized
  – Receiver knows exactly when they occur
• Max COLLISION packets length is fixed
StrawMan: Goodput and Fairness

![Graph showing goodput and fairness](image)

- **Goodput**: Comparison of RI-MAC and RI-MAC + Strawman with varying data generation rates.
- **Fairness**: Comparison of Jain's Fairness index for RI-MAC and RI-MAC + Strawman with varying per-node data generation rates.
StrawMan: Reacting to Sudden Traffic Bursts

- 1-hop network with 8 nodes
  - Measuring the resulting goodput
  - Always contend

- Vary number of active contenders every 10s
StrawMan: Multi-hop Data Collection

- 82 nodes in the TWIST testbed
  - Multi-hop topologies (at least 4 hops)
  - Contiki Collect protocol

- Traffic patterns
  - No traffic (NT)
  - Periodic traffic (PT): 1 pkt every 5 minutes
  - Bursty traffic (BT):
    - Instantaneously generate 1 pkt on 8 randomly-selected nodes

<table>
<thead>
<tr>
<th></th>
<th>RI-MAC + Strawman</th>
<th>RI-MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>NT radio duty cycle (%)</td>
<td>0.34</td>
<td>0.40</td>
</tr>
<tr>
<td>PT radio duty cycle (%)</td>
<td>3.94</td>
<td>4.40</td>
</tr>
<tr>
<td>BT radio on-time (sec)</td>
<td>4.53</td>
<td>8.16</td>
</tr>
</tbody>
</table>
Networked Embedded Systems

MAC LAYER TECHNIQUES – DISTRIBUTED SCHEDULING
Hybrid Protocol Schemes

- **Dozer ultra low-power data gathering system**
  - Beacon based, 1-hop synchronized TDMA
  - Tree-based routing towards a sink
  - Optimized for ultra-low duty cycles
  - **0.167% duty-cycle, 0.032mA (@ 30sec beacons)**

- **Application is integrated with the protocol**
  - Dynamic adaptation
  - Back-off randomization for diversity
  - Jitter adaptation over multiple hops
  - Adaptive duty-cycle accounts for long-term loss of connectivity

Dozer System

• Tree based routing towards data sink
  – No energy wastage due to multiple paths
  – Current strategy: SPT

• TDMA based link scheduling
  – Each node has two independent schedules
  – No global time synchronization

• The parent initiates each TDMA round with a beacon
  – Enables integration of disconnected nodes
  – Children tune in to their parent’s schedule
Dozer System

• Parent decides on its children data upload times
  – Each interval is divided into upload slots of equal length
  – Upon connecting each child gets its own slot
  – Data transmissions are always ack’ed

• No traditional MAC layer
  – Transmissions happen at exactly predetermined point in time
  – Collisions are explicitly accepted
  – Random jitter resolves schedule collisions

Clock drift, queuing, bootstrap, etc.

![Diagram showing data transfer and jitter over time]
Dozer Scheduled Data Transfers

parent

child 1

child 2

time
Graceful Degradation & Effective Retries

- Configurable beacon synchronization timeouts
  - Typically 3-5 retries

- Adaptive scanning activity
  - Reduction on intermittent loss of connectivity
  - Energy savings on bootstrapping and longer network failures
Low-Power System Design

MAC LAYER TECHNIQUES – CONSTRUCTIVE INTERFERENCE
Wireless Interference

• Spatially close wireless stations transmit signals at the same time and with the same frequency

• Destructive interference
  – Interference generally reduces the probability that a receiver correctly detects the information

• Constructive interference
  – A receiver detects with high probability the superposition of the signals generated by multiple transmitters

Stations A, B, and C transmit signals to a common receiver R
IEEE 802.15.4 Uses DSSS Modulation
IEEE 802.15.4 Modulation

• 1 Byte is divided into 2x 4-Bit Symbols

• Each Symbol is mapped to a pseudo-random noise (PN) sequence with 32 chips (2 MChips/sec)

• Offset-Quadrature Phase Shift Keying (O-QPSK) with half-sine chip shaping (equivalent to MSK modulation)

• PN sequences introduce randomization and redundancy
IEEE 802.15.4 Modulation Scheme

- IEEE 802.15.4: standard for 2,450 MHz wireless radios
- A 3-step process converts binary data to a baseband signal

- In-phase and quadrature-phase components of the baseband signal determine the phase of the transmitted RF signal
Half-Sine O-QPSK Modulation: Example

- Data rate: $1/T_c$ chip/s = 2 Mchip/s = 62.5 ksymbol/s = 250 kbps
- The information carried by each chip generates a complete phase change of the RF signal every 0.5 µs
Synchronous Transmissions

- Multiple nodes transmit **same packet** at **same time**

- R receives packet with high probability if $\Delta \leq 0.5 \mu s$

- Property exploited also in A-MAC [Dutta et al., SenSys ’10]
Synchronized Transmission with Backcast

• A link-layer frame exchange in which:
  – A single radio PROBE frame transmission
  – Triggers zero or more *identical* ACK frames
  – Transmitted with tight timing tolerance
  – So there is minimum inter-symbol interference
  – And ACKs collide *non-destructively* at the receiver

A-MAC’s Contention Mechanism

Sender

Receiver

Sender

Listen  P  A  D  P-CW  BO

Listen  P  A  D  P-CW  D

↑  ↓  ↓  ↓  ↑

↑  ↑  ↑  ↑  ↓

Backcast

frame collision
ALL-TO-ALL NETWORK FLOODING: GLOSSY
Increasing Reliability: Glossy Floods

• Main objectives
  – Fast and reliable flooding of messages
  – Accurate global time synchronization
  – Hide complexity of multi-hop networks

• Challenge in multi-hop wireless networks
  – Uncoordinated transmissions, packet loss, retransmission delays

• Glossy: Flooding architecture for wireless sensor networks
  – Fastest possible propagation, by design
  – Highly reliable (> 99.99 %)
  – Requires no network state information
  – Efficient also in dense networks
  – Time synchronization at no additional cost

Glossy: Key Techniques

- Temporally decouple network flooding from application tasks

- Exploit synchronous transmissions for fast network flooding
Synchronous Transmissions

- Multiple nodes transmit **same packet at same time**

- \( R \) receives packet with high probability if \( \Delta \leq 0.5 \mu s \)

- Property exploited also in A-MAC [Dutta et al., SenSys ’10]
Challenges for Efficient Flooding

How to relay packets **efficiently** and **reliably**?

- Avoid aggressive, uncoordinated broadcasts

- Typical approach:
  Coordinate packet transmissions
  - CF [Zhu et al., NSDI 2010]
  - RBP [Stann et al., SenSys 2006]
  - Maintain topology-dependent state
Glossy Flooding Architecture

• **All** receiving nodes relay packets **synchronously**
  – Simple, but radically different solution
  – No explicit routing
  – No topology-dependent state

• Key Glossy mechanisms
  – Start execution at the same time
  – Compensate for hardware variations
  – Ensure deterministic execution timing
Glossy Example Flood Propagation
Glossy Example Flood Propagation
Glossy Example Flood Propagation
Glossy Example Flood Propagation

Initiator

 Receivers
Glossy Fast Packet Propagation Details

When Glossy starts:

- Turn on radio

Example

Timeline

Initiator

Receivers

radio off
idle listening
Tx request
Glossy Fast Packet Propagation Details

Initiator:

- Set relay counter $c = 0$
- Transmit packet

Example

Timeline

- Initiator
- Receivers
- Radio off
- Idle listening
- Tx request
- $c = 0$
Glossy Fast Packet Propagation Details

At packet reception:

- Increment relay counter $c$
- Transmit synchronously

Example

Timeline

- radio off
- idle listening
- $Tx$ request

$T = 0 \quad T = 1$
Glossy Fast Packet Propagation Details

At packet reception:

- Increment relay counter $c$
- Transmit synchronously

Example

Timeline
Glossy Fast Packet Propagation Details

Stop and turn off radio when:

- Already transmitted $N$ times

Example

Timeline ($N = 2$)
Glossy Fast Packet Propagation Details

- $T_{slot}$ is constant by design
- Local estimates of $T_{slot}$
  - Received relay counter $c$

\{ Reference time $t_{ref}$ \}

- $t_{ref}$ provides synchronized time

Example

Timeline ($N = 2$)

- Initiator
- Receivers

- Radio off
- Idle listening
- Tx request

$t_{ref}$ $T_{slot}$
Propagation in Glossy

- A **relay counter** $c$ is set to 0 at the first transmission.
- A node increments $c$ before relaying the packet.

(In this example a node transmits at most twice)
Time synchronization in Glossy

- Estimate the **relay length** during propagation
- Compute a common **reference time**

![Diagram of time synchronization with relay nodes and propagation time](image)
Glossy: Main Evaluation Findings

- A few ms to flood packets to hundreds of nodes
- Reliability > 99.99% in most scenarios
- Synchronization error < 1 µs even after 8 hops
Evaluation of Glossy on FlockLab

- Multi-modal monitoring at network scale
- Flooding protocol (Glossy)
  - Packet transmissions overlap
- Power
  - Find current consumption for each state
  - Expected behavior?
- Activity
  - Packet exchange
Today’s Hot Researcher & Paper

• David Culler
  – Faculty at UC Berkeley

• (Distributed) systems background
  – Many well-known systems implementations
  – Founder of TinyOS initiative
  – Drove first large-scale WSN applications (habitat monitoring)

• Now focusing on sustainable energy use (buildings)

J Hill, R Szewczyk, A Woo, S Hollar, D Culler, K Pister: System architecture directions for networked sensors. ACM SIGOPS operating systems review 34 (5), 93-104
Recap of Today

• Networked Embedded Systems focus on cross-layer solutions
  – No strict division across interfaces (like OSI model)

• (Temporal) Co-ordination helps a lot

• Most protocols employ a mix of stochastic elements (contention) and schedule based elements

• State-of-the-Art protocols allow reliable communication at very little energy cost