Power Management in MANETs

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Introduction


Goal

- Power management is...
  - Increasingly important.
  - Wireless devices rely on battery power for all operations.
  - Savings allow for more capability in other areas, longer battery life, etc.

- Relatively unexplored
  - Many possible approaches
Power-saving Protocols for IEEE 802.11-based multi-hop ad hoc networks

- **Power-saving Techniques**
  - **Transmission power control**
    - Modulate transmission power based on need, per node.
  - **Power-aware routing**
    - Weight possible routes based on energy, rather than just delay. Either look at minimum power usage, or nodes with most remaining power. Both addressed in 2
  - **Low-power mode**
    - Implement power-saving states depending on node usage.
Network Assumptions

• Some recent works assume nodes are
  • Synchronized
    • Asynchronous operation poses other problems
      • Data transfer to 'sleeping' nodes
      • Neighbor discovery
        o worst case - relaying node asleep -> no route
  • Fully-connected
  • Aided by base station

• …None of these are desirable requirements
Other Approaches

- Use separate signaling channel to relay node state information
  - Power-Aware Multi-Access protocol with Signaling PA-MAS
- Include separate hardware that can receive wakeup signals
  - Remote Activated Switch - RAS
- Have some hosts serve as 'coordinators.'
  - chosen by remaining power, location in network; always on
- Use base stations to 'page' nodes when buffered packets are available
  - nodes wake periodically to check; can result in long delays when the network is heavily loaded
802.11 Power Saving

- Infrastructure-based network
  - Nodes have active and power saving states
  - Access Points
    - Relay packets, monitor node states (similar to paging from previous slide)
    - Periodically transmit beacon frames, which include Traffic Indication Maps (TIM) (lets nodes know there is traffic waiting)
  - Contention operation: nodes poll AP for buffered packets; contention-free: nodes wait for AP to poll
- Infrastructure-less networks
  - PS hosts wake periodically
  - ATIM (Announcement Traffic Indication Message) frames transmitted during ATIM window
  - Nodes contend to send beacons, ATIM frames
    - Beacons for synchronization, ATIM frames for traffic notification
802.11 Power Saving - ATIM Operation

Fig. 1. An example of unicasting in an ad hoc networks with PS hosts.
802.11 Power Saving - Problems

- Clock synchronization required for correct operation of ATIM traffic scheduling
- Neighbor discovery may be impeded by contention in beacon transmission
  - This can result in partitioning, making Synchronization even harder

- Proposed fixes:
  - More beacons (avoid situations arising from contention)
  - Overlapping awake intervals (without synchronization)
  - Wake-up prediction (beacons contain clock information - derive timing differences from this)
Solution?

- Three protocols proposed
  - Each node divides time into 'beacon intervals,' each of which includes an *active window*, *beacon window*, and *MTIM window*.
    - Active window: receiver powered on
    - Beacon window: beacon transmission
    - MTIM window: similar to ATIM frames
  - Outside of the active window, if a node has nothing to send, it goes to sleep
Time Division

- Notation: BI=beacon interval; AW=active window; BW=beacon window; MW>BW=MTIM window (lengths)

Fig. 2. Structure of a beacon interval: (a) active, beacon, and MTIM windows and (b) access procedure.
Protocol 1: Dominating-Awake-Interval

- Basic idea: Each host should stay awake for at least half of their beacon interval, guaranteeing some overlap with every other node.

- To satisfy the dominating-awake property,

\[
AW \geq BI / 2 + BW
\]

- Problem - beacons can be missed, depending on timing, if a node's BW happens to fall outside of another node's AW.

Fig. 4. An example where host B will always miss A’s beacons.
Protocol 1: Dominating-Awake-Interval

- Solution - Beacon intervals divided into 'odd' - MW and BW at start of AW - and 'even' - MW and BW at end of AW.

- Theorem 1: Dominating-awake-interval protocol guarantees, when $AW \geq BI / 2 + BW$, a PS host's entire beacon window always overlaps with any neighboring PS host's active window in every other beacon interval.

Fig. 3. Structures of odd and even intervals in the dominating-awake-interval protocol.
Protocol 2: Periodically-Fully-Awake-Interval

• Problem with Protocol 1 - requiring that nodes remain active at least half the time doesn't give much flexibility in energy saved.

• Solution - Introduce low-power (vs. fully-awake) intervals.
  • In low-power intervals, the active window is shortened to include only MW and BW.
  • Fully-awake intervals inserted periodically, every $p$ intervals
    • As long as $P>2$, more power saving than dominating-awake
    • …But time taken to discover new hosts increases on average
      • ->Better for less mobile environments
Protocol 2: Periodically-Fully-Awake-Interval

- Low-power intervals begin with $AW = BW + MW$; rest of interval spent in sleep state.
- Fully-awake intervals also begin with $BW$ and $MW$, but $AW = BI$; node is active for entire interval.
- *Theorem 2*: Periodically-fully-awake-interval protocol guarantees a PS host's beacon window overlaps with any neighboring PS host's fully-awake interval once every $p$ beacon intervals.

Fig. 5. An example of the periodically-fully-awake-interval protocol with fully-awake intervals arrive every $p = 4$ beacon intervals.
Protocol 3: Quorum-based

- Quorums used in distributed system design - sets of identities from which a node must obtain permission to transmit (in our case).
  - Used here to guarantee that a host's beacons can be heard during other hosts' active windows.
- $n$ - global parameter, where beacon intervals are divided into 'groups' of $n^2$

![Diagram of quorum-based protocol](image)

Fig. 6. Examples of the quorum-based protocol: (a) intersections of two PS hosts’ quorum intervals, (b) host A’s quorum intervals, and (c) host B’s quorum intervals.

- Each group forms an $n \times n$ matrix
  - Within the matrix, one row and one column are chosen – $(2n - 1)$ quorum intervals, $(n^2 - 2n + 1)$ non-quorum intervals
    - Quorum intervals: BW followed by MW; AW = BI (active throughout)
    - Non-quorum intervals: MW at start, with AW = MW (sleep)
Protocol 3: Quorum-based

- Theorem 3: Quorum-based protocol guarantees at a PS host always has at least two beacon windows that are fully covered by another PS host's active windows in every $n^2$ beacon intervals.

- Hosts only transmit or remain awake in $O(1/n)$ intervals ($O(2/n)$ combined).
  - As long as $n \geq 4$, total awake time is less than 50%
  - Again, this comes with the cost of greater latency in node discovery
## Summary of Protocols 1-3

Table 1
Characteristics of the proposed power-saving protocols

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Number of beacons</th>
<th>Active ratio</th>
<th>Neighbor sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominated-aware</td>
<td>1</td>
<td>$1/2 + BW/BI$</td>
<td>BI</td>
</tr>
<tr>
<td>Periodically-fully-aware</td>
<td>1</td>
<td>$1/p$</td>
<td>$p \times BI/2$</td>
</tr>
<tr>
<td>Quorum-based</td>
<td>$(2n - 1)/n^2$</td>
<td>$(2n - 1)/n^2$</td>
<td>$(n^2/4) \times BI$</td>
</tr>
</tbody>
</table>

- **Number of beacons** - beacons transmitted per beacon interval
- **Active ratio** - ratio of active vs. passive time
- **Neighbor sensitivity** - average time for PS host to learn of new neighbor

- **Notes:**
  - Quorum-based uses the least power transmitting beacons
  - Periodically-awake and Quorum-based use less energy overall depending on $p/n$
  - Dominated-awake is most sensitive to neighbor changes.
Unicast in Power-Sensitive Environments

- PS hosts are not always active - when can sending hosts transmit?
  - Beacon packets include node's clock, allowing other nodes to calculate time differences.
  - Sender attempts to align MTIM window with receiver's active window (pseudo-synchronization?)

- *Unicast* - MTIM -> ACK; receiver remains awake during interval, and sender contends to send buffered packets.
Simulations

- **ns-2**
  - 1000m x 1000m; transmission radius 250m (average route 3.2 hops); 802.11 MAC with added power saving protocol; AODV routing; 100s simulations; 95% confidence level

- **Modulate**
  - traffic load
  - mobility (speed)
  - beacon interval
  - number of hosts.

- **Measure**
  - neighbor discovery time
  - survival ratio
  - route establishment probability
  - route request/reply delay
A Note on Power Consumption

Table 4
Traffic-related parameters used in the simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unicast packet size</td>
<td>1024 bytes</td>
</tr>
<tr>
<td>Broadcast packet size</td>
<td>32 bytes</td>
</tr>
<tr>
<td>Beacon window size</td>
<td>4 ms</td>
</tr>
<tr>
<td>MTIM window size</td>
<td>16 ms</td>
</tr>
</tbody>
</table>

Table 3
Power consumption parameters used in the simulation

<table>
<thead>
<tr>
<th>State</th>
<th>Power Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unicast send</td>
<td>$454 + 1.9 \times L$ μJ/packet</td>
</tr>
<tr>
<td>Broadcast send</td>
<td>$266 + 1.9 \times L$ μJ/packet</td>
</tr>
<tr>
<td>Unicast receive</td>
<td>$356 + 0.5 \times L$ μJ/packet</td>
</tr>
<tr>
<td>Broadcast receive</td>
<td>$56 + 0.5 \times L$ μJ/packet</td>
</tr>
<tr>
<td>Idle</td>
<td>$843$ μJ/ms</td>
</tr>
<tr>
<td>Doze</td>
<td>$27$ μJ/ms</td>
</tr>
</tbody>
</table>

- $P_{base} + P_{byte} \times L$;
- where $P_{base} =$ base power consumption, $P_{byte} =$ power per byte, and $L$ is packet (frame) length.
Neighbor Discovery Time vs. Beacon Interval Length

- D: Dominating-aware; P(p): Periodically-fully-aware; Q(n): Quorum-based; AA: Always-aware

Fig. 7. Neighbor discovery time vs. beacon interval length (100 hosts, traffic load = 1 route/s, mobility = 5 m/s).
Fig. 9. Route request/reply delay vs. beacon interval length: (a) route request delay, and (b) route reply delay (100 hosts, traffic load = 1 route/s, moving speed = 5 m/s).
Route Establishment Probability vs. Beacon Interval

Fig. 10. Route establishment probability vs. beacon interval length (100 hosts, traffic load = 1 route/s, moving speed = 5 m/s).
Route Establishement Probability vs. Mobility

Fig. 13. Route establishment probability rate vs. mobility (beacon interval = 100 ms, 100 hosts, traffic load = 1 route/s).
Survival Ratio vs. Node Density

Other results
- Mobility has a negative impact on survival ratio - more retransmissions / route repair
- Increased traffic load leads to lower survival ratio
Variable-Range Transmission Power Control in Wireless Ad Hoc Networks

- Fundamental point - Constant-range transmission control is inefficient and should not be considered as a scalable solution.
  - As usual, there is a tradeoff - greater transmission range leads to fewer hops but more collisions.

  - At the physical layer, reducing transmission power increases the traffic capacity of the network.

  - There is a minimum bound on transmission power to avoid network partitions. At this lower bound, a fully connected tree can be constructed.
Considerations, Goal

- **Routing**
  - Higher transmission power gives shorter routes, and in some cases can provide route redundancy.
    - This also helps to minimize routing overhead.
  - Shortest-path (minimum number of hops) routes may not be the most energy efficient.
  - Force transmission range to its maximum at each link (and at MAC layer this can, again, lower throughput).

  - Suggests modulating transmission range to control network topology.

- **Goal:**
  - *Given the tradeoffs mentioned, is it possible to put together a set of protocols that can scale transmission range based on network conditions?*
Physical Connectivity

- Nodes represented by set $V = \{x_1, x_2, \ldots, x_n\}$
- Edges represented by set $E = \{\{x_i, x_j\}\}$
- Weight of edge $|e| = |x_i - x_j|$
- Power level $P$, $P_{\text{min}} \leq P \leq P_{\text{max}}$
  - Connectivity exists when transmitting power $P_i$ at node $x_i$ provides signal level $S_j > S_0$ at destination $x_j$
  - Decay: function of transmitted power $- \tilde{S}_j \sim \frac{P_i}{|x_i - x_j|^\alpha}$, $2 \leq \alpha \leq 4$
Common-Range Transmission

• Definitions:
  • Connectivity $k(M)$ of graph $M$ is the minimum number of vertices needed to disconnect $M$
    - Measure of link redundancy
  • Minimum common transmission range $R_{com}^{min}$ is the minimum value of $R_{com}$ that maintains a connected graph (fully connected)
    - permits construction of a spanning tree.

Fig. 1. Transmission range and graph connectivity: (a) illustrates a fully connected network where all nodes are reachable in one hop (e.g., $k_v \gg 1$), (b) illustrates a connected network, (c) illustrates the case where at least one node is disconnected forming network partitions, and (d) illustrates a minimum spanning tree that uses variable-range transmission with node $x_r$ as root of the tree.
Common-Range Transmission

- From the Gupta and Kumar papers,
  \[ R_{com}^{\text{min}} > (1 + \epsilon) \sqrt{\frac{A \ln n}{\pi n}}; \epsilon > 0. \]
  - where \( A = \) area, \( n = \) node count.

- Traffic capacity of a network, where \( L = \) average source-destination distance and \( W = \) the maximum throughput of transmissions (note inversely proportional to \( R \)).

- Requirement: no other transmissions within \((1 + \Delta)R\) of transmitter.

- Combining these,
  \[ \lambda(R_{com}^{\text{min}}) \leq \frac{16 \sqrt{A} W}{\sqrt{\pi \Delta^2 L} \sqrt{n \ln n}}. \]
Variable-Range Transmission

- $\psi(|e|) = |e|^{\alpha}$. weight of each link - minimum transmission range usable

- Assume that there is some unique route for every pair with average hop distance $\overline{R}$.
  - This can be compared to $R_{min}^{com}$ in the common-range case

- Average range in the minimum spanning tree: $\overline{R}_{MST} = \frac{M(x_1, x_2, \ldots, x_n)}{n-1}$
  - Weight of minimum spanning tree: $M(x_1, x_2, \ldots, x_n) = \min_{e \in E} \sum_{e} \psi(|e|)$

  - Edge-weighting function $\psi(|e|) = |e|^{\alpha}$. leads to $\overline{R}_{MST} \sim c(\alpha, d) \frac{n^{(d-\alpha)/d}}{n-1}; \ 0 < \alpha < d.$
  - $\alpha$: power attenuation factor, $d$: dimension of space
Comparison

- Ultimately, at least in the 2-dimensional case, it can be shown that average transmission power in the variable-range case is less than the minimum in the common-range case for 'large' n. (intuitively, it makes sense that this would be so)

Fig. 10. Disadvantages of common-range transmissions.
Capacity Analysis

For R to hear T, need $|T - R| \leq a$; for R' to hear T', need $|T' - R'| \leq b$.

Analysis of this situation regarding minimum distance between the two transmissions is difficult given that each node (and, in the more general case, all nodes) use differing transmission powers.

- Proportional to $a$ when T transmits, $b$ when T' transmits.

Fig. 2. (a) Protocol model of interference. (b) Disks of unknown radii around the receivers are disjoint.
Capacity Analysis

- Standard deviation decreases as n increases
- With this approximation in mind,

\[ \lambda(\bar{R}_{MST}) \leq \frac{16\sqrt{AW}}{\pi \Delta^2 L} ; \quad n \to \infty. \]

- Shouldn't this depend on n?
  - Maybe not: greater node density results in shorter average transmission ranges, greater possible MAC throughput.

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**TABLE 1**

Mean Value and Standard Deviation of the Weight of Edges in a MST versus Number of Nodes

<table>
<thead>
<tr>
<th>number of nodes</th>
<th>mean value [meters]</th>
<th>standard deviation [meters]</th>
</tr>
</thead>
<tbody>
<tr>
<td>200x200 network</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>54.26</td>
<td>14.10</td>
</tr>
<tr>
<td>100</td>
<td>17.81</td>
<td>0.83</td>
</tr>
<tr>
<td>1000</td>
<td>5.92</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Network Connectivity

- What is the effect of all of this on routing?
- Basis: Some ideal on-demand common-range protocol
- In general, as transmission power is decreased, routing overhead increases (more hops -> more route upkeep)
  - Tradeoff: this may offset gains at the MAC layer through lower transmission power
The Effect of Mobility

- $h$ represents the overlapping regions of node transmission areas.
- Ideally, with variable range transmission, this is close to 0. With node mobility, this results in almost constant route repairs.
- Result: Small $h$ only feasible in static networks.
- Ultimately, route maintenance messages become more prevalent as transmission radius decreases.

Fig. 3. Routing in MANET-type ad hoc networks. (a) Route discovery. (b) Route maintenance. (c) Overlapping region between two adjacent nodes. (d) Overlapping region between two nodes out of range requiring a third node to establish a route.
Route Discovery

- In the 'assumed' reactive routing protocol, routes are discovered by broadcast with radius $R$, area $A = \pi R^2$.
- There is some inherent waste in this operation from the perspective of area coverage - the next hop of the broadcast occupies some of the same space as the previous hop.
  - Calculation $\Rightarrow 0.68A$
- Even more space is wasted when overlapping with other broadcasts on other paths is taken into account.
- The total number of broadcast messages required given transmission radius $R$ and network area $A_T$ is found to be

$$Q(R) \sim \frac{A_T}{(1 - 0.68)A} = \frac{A_T}{(1 - 0.68)\pi R^2}.$$  
- Note reliance on $1/R^2$: by decreasing the radius, overhead may skyrocket.
Capacity and Signaling Overhead

• What is the effect of routing overhead on observed throughput?

\[ \lambda(R, t) = \lambda(R, t) - CJ(R, t). \]

• Optimal R is found to be

\[ R_{opt} = \frac{8C\Delta^2 L^2 n v \arccos\left(\frac{3}{4}\right)}{AW(48 \arccos\left(\frac{3}{4}\right) - 9\sqrt{7})} . \]

• Note that this assumes the use of some existing fixed-range-based routing protocol; the ideal variable-range protocol could be specified that the minimum range is used per link.

• This can lead to average link duration of 0!
Numerical Results

- Physical Connectivity

- Unfortunately, this does not include edge effects (assumption - nodes all have roughly the same number of neighbors).

Fig. 4. Transmission range in wireless ad hoc networks.
Numerical Results

- Network Connectivity

Fig. 6. Route discovery in wireless ad hoc networks.

Fig. 7. Route maintenance and available capacity.
Simulations

- ns-2
  - 1500m x 300m; 50 nodes; DSR; Random waypoint

- Broadcasting may not be usable in a variable-range transmission routing protocol.

Fig. 8. Signaling load in MANET protocols.

Fig. 9. Network partitions in MANET protocols.
Conclusion

- Information presented here is a work in progress - there seems to be a lot of potential, but not much as far as actual implementation. Variable-range transmission may be a good next step, but will require changes to other network layers as well.
Questions?
