Challenges in Multihop Wireless Networks

Catherine Rosenberg
Dept. of Electrical and Computer Engineering
University of Waterloo
Waterloo, Canada N2L 3G1

Joint Work with Aditya Karnik and Ravi Mazumdar
Wireless Networking

• Advent of wireless technologies has revolutionized communication
  – pervasive communication: on-demand, seamless connectivity between individuals and their environment (homes, offices, facilities, etc.)
  – ease of deployment
  – support of mobility

• Single hop wireless networks

<table>
<thead>
<tr>
<th>Service</th>
<th>Coverage</th>
<th>Data Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellular networks</td>
<td>voice and data</td>
<td>wide</td>
</tr>
<tr>
<td>Wireless LANs (hot-spots)</td>
<td>voice and data</td>
<td>small</td>
</tr>
<tr>
<td>Wireless PANs (personal devices)</td>
<td>data</td>
<td>very small</td>
</tr>
</tbody>
</table>

• Multi-hop wireless networks
  – provide wide coverage as well as high data rates by hopping over multiple short wireless links
Wireless Multihop Networks

- **Mesh networks** (e.g., IEEE 802.16 Broadband Wireless),
  - networking functionality is built into the network devices whereas user applications act as end users
  - network provides infrastructure for any-to-any communication
- **Ad hoc networks** (e.g., IEEE 802.11 ad hoc mode)
  - user devices not only act as application endpoints but also as routers
  - users themselves constitute the network with individual objectives
- Network devices need to be functionally sophisticated
Sensor networks present a totally different paradigm: networked sensors have one common goal.

Sensor objective is application-specific and collaborative.

Many-to-one (and possibly one-to-many) flow of data:
- In typical monitoring applications, data generated by sensors need to be gathered at a central station (sink) where it can be analyzed.

Miniature, sophisticated sensing hardware is being developed.
Networking Context

- Our work is in the context of two types of wireless networks
  - **Sensor networks**
    - distributed monitoring of signals of interest; e.g., chemical contaminants
    - medium to large scale network, i.e., few hundreds to thousand sensors
    - could be stand-alone or hierarchically embedded in bigger (metropolitan area) networks
    - one sink to which sensed data must be transported
  - **Community mesh networks**
    - medium size network providing connectivity to the Internet
    - network devices transport user data to a central gateway
- In this talk we highlight sensor networks and focus on traffic from the sensors to the sink
Challenges in Sensor Network Design

• **Limited frequency-resource**
  – spectrum may need to be shared with other applications

• **Shared communication medium (channel)**
  – medium access protocol is critical for performance

• **Constraints on transmission power**
  – limited battery energy, transmission regulations

• **Data relaying**
  – not all sensors will be able to communicate directly with the sink

• **Device failures**
  – necessitate self-organizing architecture

• **No real notion of link capacity**
  – interference makes it impossible to assign capacities to links unless strict transmission schedules are used
Design Issues in Sensor Networks

- Sensor network should be tailor-made to the application instead of generic
- Protocols can be jointly optimized rather than strict layering
  - inter-networking is not a major issue for sensor networks
  - cross-layer interactions have been seen to improve performance
- In spite of fervent research, some basic question remain unanswered
  - what is the achievable throughput of a given sensor network?
  - is maximum available power always better?
  - what is the best role of transmission power: going larger distances, or increasing data rates?
  - how should protocols be coupled, in particular routing and medium access?
  - what is a simple yet reasonable model for physical layer?
Approaches to understanding Sensor Network Design

• **Theoretical**
  - asymptotic analysis provide insights into performance as number of devices becomes large but not very useful for actual network engineering
  - for other tractable analysis, simplistic assumptions regarding the physical layer, wireless channel become necessary

• **Algorithmic**
  - distributed implementations for medium access, power control, etc.
  - usually limited by simplistic assumptions regarding physical layer, wireless channel
  - no real benchmark

• **Experimental**
  - design and deployment of real sensors in the field
  - addresses mostly hardware, miniaturization problems
  - can give only limited insights into optimal design
Optimal Configuration of Wireless Sensor Networks

• In our work we address two basic questions
  1. For a given placement of sensors and the sink what is the maximum achievable throughput of the network?
  2. How should the network parameters (i.e., the radio and link layer parameters at each sensor) be configured to achieve this maximum?

• The higher the achievable network throughput, the higher will the temporal variations of the processes sensors can track be

• Objective of this work is to seek answers to both the questions and thereby
  1. determine what is achievable but not through asymptotic results
  2. derive (distributed) algorithms for optimally configuring sensor networks with arbitrary, fixed topologies using insights from the previous analysis
Informal Problem Statement

• $N$ sensors and a sink placed arbitrarily

• Each sensor generates data at an average rate of $\lambda$

• Transmission power $P$ and modulation-coding scheme $z$ are configurable radio parameters at each sensor
  – $P$ may need to be selected from specified discrete levels and $z$ from some small set of modulation-coding schemes

• How should transmission power and modulation scheme be selected at each sensor so as to maximize throughput, $\lambda$?

• The answer depends on routing and the channel access methodology
Physical Layer and Wireless Medium Issues

- Modeling physical layer and wireless channel is perhaps the biggest challenge for wireless network design.
- Aim of the physical layer is to transmit data successfully to the receiver over the communication channel.
- Owing to noise, communication cannot be error-free; hence success is specified in terms of acceptable (bit) error rate (BER).
- Data is physically transmitted using a modulation scheme. A modulation scheme $z$ provides a specific data transmission rate $c(z)$.
- To transmit data using $z$ (at $c(z)$) while maintaining a specified BER, the ratio of signal power to noise power at the receiver must be greater than some threshold $\gamma(z)$.
- The higher the rate provided by a modulation, the higher is the required $\gamma$.
- With higher transmission power $P$, a higher rate modulation can be employed.
Physical Layer and Wireless Medium Issues

• Wireless medium
  – is inherently broadcast: if two transmitters transmit on the same frequency band, a receiver of one can receive power from the second
  – has fading and shadowing in addition to signal attenuation (path loss)

• Hence the SINR requirement for transmission from \( i \) to \( j \) is specified as

\[
\left( \frac{d_{ij}}{d_0} \right)^{-\eta} F_{ij} P_i \geq \gamma(z)
\]

\[
N_0 + \sum_k \left( \frac{d_{kj}}{d_0} \right)^{-\eta} F_{kj} P_k
\]

– \( d_{ab} \) and \( F_{ab} \) denote the distance and the fading variables respectively between nodes \( a \) and \( b \), \( d_0 \) is near-field distance, \( \eta \) is path loss exponent

– sum in the denominator is over all simultaneously transmitting devices

• Thus unlike wired links, for transmission success not all wireless links can be active at the same time

• The set of links that can be active at the same time depends on the transmission power as well as the modulation scheme since \( \gamma \) depends on \( z \)
Physical Layer and Wireless Medium Issues

- A higher rate modulation can be potentially used on $L_1$ as compared to $L_2$
  - $R_1$ receives more power from $T_1$ than does $R_2$ owing to shorter length of $L_1$ (assuming no fading effects)

- If we impose that $T_2$ does not transmit when $T_1$ transmits
  - no interference at $R_1$ and indeed a higher rate modulation can be employed
  - however, $T_1$ and $T_2$ get to be active for a lesser amount of time

- Otherwise
  - interference at $R_1$ and a lower modulation must be used for robustness
  - however, $T_1$ and $T_2$ can be active for more time

- This trade-off is really what we need to understand in a multihop network setting
Physical Layer and Wireless Medium Issues

• Thus transmission power, modulation scheme and active times for each link in the network are interlinked

• If transmission power, modulation scheme and SINR requirement on each link are fixed, specification of which links cannot transmit simultaneously is given by conflicting set $D_l$ for each link $l$ ($D_l$ is a set of sets)
  - each set $D$ in $D_l$ is a minimal set of those links whose activation with $l$ violates the SINR requirement
  - at least one link from each $D$ must be silent for success on link $l$

• If each $D$ in $D_l$ is a singleton, conflicts among link transmissions can be represented by a contention graph $G$ vertices of which are links in the network
  - $(l, \hat{l})$ is an edge in $G$ if $\hat{l} \in D_l$ or vice versa

• Conflicting sets can be seen as specifying multiple contention graphs
  - for each link $l$, select one interferer $\hat{l}$ from each $D$ in its conflicting set
  - construct an undirected graph $G$ such that $(l, \hat{l})$ is an edge
Managing Access to the Wireless Medium

- How should access be managed?

<table>
<thead>
<tr>
<th>Scheduled</th>
<th>Random Access</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explicit non-conflicting schedules</td>
<td>Randomized channel access</td>
</tr>
<tr>
<td>Synchronization needed</td>
<td>Synchronization not needed</td>
</tr>
<tr>
<td>Possible to assign to each link a capacity</td>
<td>No notion of link capacity</td>
</tr>
<tr>
<td>Per link capacity constraints on flows</td>
<td>Aggregate stability constraints</td>
</tr>
<tr>
<td>Centralized, complex</td>
<td>Distributed, robust</td>
</tr>
<tr>
<td>Implementable in small-medium scale networks</td>
<td>Even for large scale networks</td>
</tr>
<tr>
<td>Superior performance</td>
<td>Much inferior to scheduled</td>
</tr>
<tr>
<td>Useful for analytical results</td>
<td>Analysis is typically intractable</td>
</tr>
</tbody>
</table>

- Since we seek a capacity result we consider centrally computed non-conflicting link transmission schedules
Scheduled Sensor Networks

- A transmission schedule specifies the start time \(t_{ls}\) and end time \(t_{lf}\) of transmission for each link \(l\)
  - schedules are constructed over \([0, 1]\) by assigning a (connected) segment of time to each link

- A non-conflicting transmission schedules is a transmission schedule in which each link achieves the specified SINR threshold for the entire duration of its transmission

- Conflicting sets determine the set of non-conflicting transmission schedules

- Given the transmission power \(P_l\) and modulation scheme \(z_l\) for each link, and a non-conflicting transmission schedule, capacity of link \(l\) is \(c_l(z_l)(t_{lf} - t_{ls})\)
Constructing Non-conflicting Schedules

• For simplicity consider one contention graph, $G$, specified by conflicting sets

• A clique in $G$ is a set of links in which any two cannot transmit simultaneously

• Given $G$, a non-conflicting schedule assigning transmission time $\left(t_l^f - t_l^s\right) = \delta_l$ to link $l = 1, \ldots, L$ can be constructed if and only if a multiple bin packing problem has a feasible solution

• If $G$ is perfect, the above is equivalent to maximal weighted clique having weight at most 1
Problem Formulation

- Radio parameters, routing and scheduling are intricately related

- For fixed radio parameters
  - a link activation schedule results in certain traffic capacity for each link; this dictates which links must be used in order to maximize $\lambda$
  - a given routing scheme specifies flow on each link and hence dictates a link activation schedule

- Thus to maximize the network throughput, the radio parameters, routing and scheduling must be jointly optimized

- We assume that a sensor can configure its radio parameters separately for each of its out-going links
Throughput Optimization: Problem Formulation

- $\mathcal{R}_i$ denotes the set of routes for sensor $i$ to the sink, $\phi^r_i$ the fraction of traffic of $i$ routed on $r \in \mathcal{R}_i$, $r_o$ source sensor of route $r$

- $\theta$ denotes a non-conflicting schedule and $\Theta(.)$ set of non-conflicting schedules

\[
\begin{align*}
\text{max } & \lambda \\
\lambda \sum_{r \in \mathcal{R}_i} \phi^r_{r_o} & \leq c_i(z_l)(t^f_l - t^s_l) & l = 1, \ldots, L \\
\sum_{r \in \mathcal{R}_i} \phi^r_i & = 1 & i = 1, \ldots, N \\
\phi^r_i & \geq 0 & r \in \mathcal{R}_i, i = 1, \ldots, N \\
\lambda & \geq 0, \theta \in \Theta(z, P), z \in \mathcal{Z}(P), P \in \mathcal{P}
\end{align*}
\]

- Link capacity constraint: data flow on link $l$ cannot exceed its capacity
- Routing constraint: data flows sent by sensor $i$ over routes in $\mathcal{R}_i$ must equal $\lambda$
- The remaining are feasibility constraints on schedules, modulations and powers
- An optimal solution exists under certain technical conditions
Throughput Optimization: Results

• Determining optimal throughput is NP-hard

• Optimal throughput is related to the maximal weighted clique problem in the contention graphs specified by conflicting sets
  – weight of a vertex is the total flow carried by that link
  – to maximize throughput, clique weights need to be minimized by arranging data flows

• We obtain explicit analytical results for
  – regular topologies
    * sensors placed according to pre-determined regular patterns; e.g., grid
  – simplified interference structure
    * conflicting sets are represented by one contention graph with a simple structure; two links $l$ and $\hat{l}$ are connected if transmitter of $\hat{l}$ is within a certain region around the receiver of $l$
    * can be used to obtain bounds on the throughput in the SINR model
Sensors on a Grid

- Sensors placed on a unit grid with sink in the bottom left corner; $N \times N$ grid has 1 sink and $n = N^2 - 1$ sensors

- All sensors use same transmission power $P$ yielding maximum transmission range $R(P)$

- Modulation-coding scheme is such that each link (of length $L \leq R(P)$) has the same basic data rate (assume normalized to 1)
  - no advantage of higher received power on shorter links

- Simplified Interference Models: one contention graph such that
  - Interference range model (IR): links $l$ and $\hat{l}$ are connected if transmitter of $\hat{l}$ is within $R_I(P) = \beta R(P)$ of the receiver of $l$ ($\beta \geq 1$)
  - Two-circle model (TC): links $l$ and $\hat{l}$ are connected if transmitter of $\hat{l}$ is within $R_I(P) = \beta r$ of the receiver of $l$ where $r(\leq R(P))$ denotes the length of $l$ ($\beta \geq 1$)
Sensors on a Grid: Interference Models

Interference-range Model

Two-circle Model
Sensors on a Grid

Figure 1: Example of $3 \times 3$ grid and contention graph for links used in the routing. IR model. $\beta = 2$ and $R(P) = 1$.

- The problem is to find power $P$, a routing scheme, and a link activation schedule to maximize throughput $\lambda$.
- $\lambda(P)$ is upper bounded by $\frac{1}{N^2 - 1}$.
- $\lambda(P)$ can be obtained in a closed form; e.g., for either interference model, for $\beta = 2$, (i) $R(P) = 1$, $\lambda(P) = \frac{1}{2N^2 - 10}$ (ii) $\lambda(P_{\text{max}}) = \frac{1}{N^2 - 1}$.
Figure 2: $6 \times 6$ grid of 35 sensors, $\beta = 2$ and $P$ is such that $R(P) = 1$

- For $R(P) = 1$, IR and TC models yield the same results
- Only two sensors can transmit to sink - leads to traffic bottleneck
- Optimal routing spreads out the traffic, two branches feed the traffic into the sink
Sensors on a Grid: IR model, Optimal Routing

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{grid.png}
\caption{6 x 6 grid of 35 sensors, $\beta = 2$ and $P$ is such that $R(P) = 2$}
\end{figure}

- $R(P) = 2$
- Optimal routing is such that
  - traffic from sensors within $\beta R(P)$ from sink is routed using shortest path
  - traffic outside this region flows in two branches deviating away from each other and finally getting fed into the region through the border sensors
Sensors on a Grid: IR model, Optimal Routing

Figure 4: 6 × 6 grid of 35 sensors, $\beta = 2$ and $P$ is such that $R(P) = 5$

- When $R(P) > \frac{N}{\beta}$ the shortest path routing region becomes as large as the network
Sensors on a Grid: IR model, Throughput

Figure 5: $\lambda(P)$ vs $R(P)$. $N = 6$

- $\lambda$ is maximized by using $P_{\text{max}}$
- Increase in power is not always optimal; higher power does not necessarily increase the reach but always increases interference range
- If power available is below a threshold, determined by $N$ and $\beta$, it is optimal to use lower than the available one; e.g., $N = 10$, $\beta = 2$, unless $R(P) \geq 8$, it is optimal to use $R(P) = 2$

Figure 6: $\lambda(P)$ vs $R(P)$. $N = 10$
Sensors on a Grid: TC model, Optimal Routing

Figure 7: $6 \times 6$ grid of 35 sensors, $\beta = 2$ and $P$ is such that $R(P) = 2$

- When $R(P) = 2$, the optimal routing is such that
  - traffic from sensors within $\beta R(P)$ gets trisected to reach the sink; routing is not shortest path
  - traffic outside this region flows in two branches deviating away from each other and finally getting fed into the region through the border sensors
Sensors on a Grid: TC model, Optimal Routing

Figure 8: $6 \times 6$ grid of 35 sensors, $\beta = 2$ and $P$ is such that $R(P) = 4$

- When $R(P) > \frac{N}{\beta}$, traffic is collected along rows and columns, and hauled to the sink using long links.
Sensors on a Grid: TC model, Throughput

Figure 9: $\lambda(P)$ vs $R(P)$. $N = 6$

- $\lambda$ is maximized by using $P_{\text{max}}$
- Increase in power increases the throughput
Perspective on Routing

- Routing pattern is a complex balance of longer and shorter links

- In IR model
  - longer links are favored since interference is determined by the range not transmission distance
  - some links are necessarily short to feed traffic into the border sensors
  - at higher power, routing is extremely simple

- In TC model
  - smaller links are used to gather data at a point from which longer links go to the sink
  - longer links reduce spatial reuse but can be used to haul large traffic directly to the sink
  - combination of short and long links reduces clique weights
**Summary**

- Determining maximum throughput of a sensor network is a computationally hard problem
- Radio parameters, routing and scheduling are intricately related
- In the case of grid topology and simplified interference structure
  - maximum throughput can be found in a closed form
  - **maximum throughput and optimal schedule** is determined by the maximum weighted clique problem in the contention graph
  - **optimal routing** can be explicitly found; can be extended for other regular topologies
- **Further studies**
  - what is an optimal routing with multiple modulation schemes? with SINR interference model?
  - are these results, in particular optimal routing, useful in random access networks?