Power Management

- The nodes are power-limited in two dimensions:
  1. small batteries
  2. power supplies cannot typically be reload

Several discussions presented have addressed different aspects of power management.
- This included
  - discussions on sensor placement
  - medium access control (MAC) layer protocols
  - moving nodes to reduce overall power consumption
  - intelligent routing
  - data broadcasting
Power Management

• redundant nodes are often deployed

Power Management

• distributed algorithms are designed so that only the minimum number of nodes required to complete a mission
• This type of algorithm may run on every node, or may run among nodes with special functions, for example, nodes responsible for providing localization beacons

Power Management

• In other networks,
  – nodes self-organize into a hierarchy of clusters to make communication
  – data broadcasting
Power Management

- cluster leadership must rotate to balance the processing and communication

Other solutions include designing algorithms and protocols that trade-off processing power and communication power to maximize the lifetime of the network.

- solution may even trade-off accuracy in data for power by, for example, reducing the number of bits/sample transmitted.

ADAPTIVE SENSING AND REPORTING IN ENERGY-CONSTRAINED SENSOR NETWORKS

Anh Tuan Hoang and Mehul Motani
Background Information

- Figure 1 shows a generic model for a cluster in a hierarchical cluster-based wireless sensor network.

- Nodes in each cluster monitor a particular geographical area
- report their measurements to the cluster head
- cluster head then may act on it or may aggregate and forward the data to the decision center.
Background Information

- nodes are deployed in remote areas
  - operate without battery recharges
  - replacements for long periods of time
  - while still providing acceptable QoS.

Problem

- Problem we consider in this section
  - how to provide acceptable QoS while maximizing the system lifetime.

Background Information

- System-level performance is the primary concern
- Existing literature in wireless sensor networks concentrates on system-level design and analysis.
Approach

• Here the approach is somewhat different.
• Focus on controlling a single node in a sensor network.
• Even though the final goal is to improve the system-level performance.

Background Information

• Increasing individual node lifetime is directly related to prolonging network lifetime.

• Dense sensor networks
  – Most communication occurs between nodes within close range.

Background Information

• Energy consumed in
  – Signal processing and electronics of the sensor node
  – Is comparable to the energy consumed by the transceiver.
Background Information

• Therefore, finding an appropriate trade-off between
  – energy used for communication
  – signal processing
  – electronics in the node is important.

Background Information

• Sensor networks will likely contain thousands of nodes
• Joint control of sensors may not be feasible
• Node-level control policies will ensure scalability.

Background Information

• Property of our node-level control approach is
  – when applied to all nodes in the sensor network
  – make the energy consumption in all the nodes statistically the same.
  – The energy consumption is uniform across the network
  – all nodes in the network will tend to die together.
Background Information

- This is a desirable property
  - in which the system performance degrades significantly when a certain number of nodes stop to operate, regardless of whether the rest of the network is still functioning.

Background Information

- Events of interest happen within the sensing region of a sensor node randomly

- Each event lasts for a random period of time during which it can be captured if the sensing unit of the node is active.

Background Information

- Events are considered missed if they disappear before being captured.

- If an event is captured
  - it is processed into data packets
  - buffered in the memory unit
Background Information

- Sensor node is only equipped with limited memory
- If all storage space is used up
  - Data packets generated from sensed events are lost
  - The corresponding events need to be recaptured.

Background Information

- The transceiver unit of the sensor node transmits data packets
  - To the cluster head at a fixed rate over a time-varying wireless channel.

Background Information

- Since the channel fluctuates in time
- Transmit power required to ensure reliable communication also varies with time.
Background Information

- When controlling a sensor node, we face the following trade-off.
  - Sensing and Transceiving units should be active as much as possible so that the event missed rate is minimized.

- On the other hand
  - Events occur randomly
  - periods when there are no events to sense
  - no data packets to transmit.

- In those periods
  - sensing and transceiving units should be turned off
  - or idle

- For the same reason, when the wireless channel is in a deep fade
  - transceiving unit should be turned off (or idle).
Background Information

- The objective is to jointly control the
  - operating modes of the sensing
  - and transceiving components in the sensor
  node
- So that energy is conserved while
  guaranteeing the required event-missed
  rate.

Background Information

- While doing so, we assume that
  - the event arrival statistics
  - the buffer occupancy
  - the channel quality

  are available for us on which to base the
  control decisions.

Background Information

- The problem we are looking at is related to
  the central estimating officer sensor
  network (CEO) problem
Background Information

• The center controller (or CEO) receives noisy observations of a random source from a set of L observers over a rate-constrained link.
• The objective is to minimize the distortion of the CEO's estimate of the source subject to the rate constraints of the observers.

Central Estimating Officer in a sensor network

• It may be advantageous in many situations to monitor or observe the state of a system in a decentralized fashion.

• Sensor networks are used in a variety of applications where a centralized detector/estimator would not be
  – Feasible
  – too expensive
  – cannot achieve the space-time resolution
  – probability of detection required.
Central Estimating Officer in a sensor network

- In decentralized detection, sensor nodes forward their decisions to a decision fusion center which then computes a global decision on what the state of the system is.

Central Estimating Officer in a sensor network

- The CEO problem though similar to decentralized detection views the problem from an information theoretic perspective.

Central Estimating Officer in a sensor network

- A major difference from decentralized detection is that instead of making instantaneous decision about the state, it makes a sequence of decisions based on a set of successive observations.
Central Estimating Officer in a sensor network

- We may achieve less distortion by encoding
  - a block of observations
  - instead of single observations for the same rate

Central Estimating Officer in a sensor network

- The CEO of a firm (or the Central Estimating Officer in a sensor network) is interested in the output from a source

\[ \{X(t)\}_{t=1}^{\infty} \]

- which it cannot observe directly.

Central Estimating Officer in a sensor network

- Therefore employs a group of L agents who observe independently corrupted versions of

\[ \{X(t)\}_{t=1}^{\infty} \]

- and transmit their observations to the CEO under a finite sum rate constraint, R.
Markov decision processes

- Markov decision processes (MDPs) provide a mathematical framework for modeling decision-making in situations where outcomes are
  - partly random
  - partly under the control of the decision maker

Background Information

- MDP translate the sensor network system design problem
  - into a sensor node design problem
  - then formulate an optimization
- In which the sensing and transmitting components of the sensor node are jointly controlled to increase its lifetime.

Background Information

- MDP structure the above optimization problem as a
  - well-mannered Markov decision process
  - and use dynamic programming techniques to obtain the solution.
Network Architecture

• In a cluster-based network
  – sensor nodes are organized into clusters
  – each cluster is usually responsible for monitoring one specific geographical area.

Network Architecture

• We adopt the mixed model in which there are two different types of nodes.

Network Architecture

• Type I
  – These nodes are normal sensors whose main responsibility is to sense the surrounding environment to capture events of interest
  – equipped with very limited energy source.
  – transmit collected data directly to cluster heads that are Type II nodes.
Network Architecture

• Type II
  – The main functions of type II nodes are data gathering and/or relaying.
  – They aggregate the data collected in their corresponding clusters and relay them toward a decision center, where the data is interpreted and decisions are made.

Network Architecture

• type II nodes are less energy-constrained than type I nodes are.
• number of type II nodes is usually much less than that of type I nodes

Network Architecture

• There are several advantages of adopting a cluster-based architecture for wireless sensor networks.
  – sensor network consists of a very large number of nodes
  – organizing these nodes into clusters makes the control and management more scalable
  – cluster-based architecture makes it easier to carry out data compression and/or aggregation.
Network Architecture

• Data collected by nodes in the same cluster are usually strongly correlated.
• Therefore
  – nodes in the same cluster compress their data based on one another
  – for cluster heads to carry out data fusion/aggregation

Network Architecture

• Redundancy in collected data is removed before data leaves the cluster, it helps reduce network congestion and saves energy spent in relaying information.

Network Architecture

• By organizing nodes into clusters and allowing
  – direct communication between sensor nodes
  – cluster heads, the total number of hops (on average) to the decision center is reduced,
  – reducing the average data-gathering latency.
Event Sensing and Data Routing

• We focus on event detecting applications in which the objective is to capture random events that happen within the coverage area of a sensor network.

Event Sensing and Data Routing

• Time is divided into slots of duration $\Gamma$.
  • time slot $i$ denotes the time interval $[\Gamma i, \Gamma (i + 1)]$

Event Sensing and Data Routing

• let $\Gamma = 1$
  
  • Assume that events happen in each time slot according to a Bernoulli distribution with probability $\lambda$
Event Sensing and Data Routing

• Suppose an event happens at time $t$ within time slot $i$, that is, $i \leq t < i + 1$

• The quantity $t - i$ is assumed to be uniformly distributed in $(0, I)$.

Event Sensing and Data Routing

• We also assume that the event exists in the sensing region for a period that is uniformly distributed in $(0, D]$ where $D$ is the maximum event lifetime.

Event Sensing and Data Routing

• The tasks of event sensing and data gathering are carried out using the following mechanism
Event Sensing and Data Routing

• Within each cluster, after detecting events and processing them into data packets, sensors send the data packets directly to the cluster head.

• We assume that there is a certain MAC scheme that allows reliable packet transmission (TDMA, CDMA).

Event Sensing and Data Routing

• We assume that there is no inter-cluster interference.
  – this can be achieved by assigning nonoverlapping frequency bands to adjacent clusters

Event Sensing and Data Routing

• Cluster heads carry out necessary data fusion/aggregation tasks and route the aggregated data to the decision center.
Event Sensing and Data Routing

- The performance metric of the sensor network is in terms of the event-missed rate and energy consumption.

- In many application, apart from the event-missed rate, data reporting latency is also an important performance factor.

Model of Sensor Nodes

- A generic model for a wireless sensor
Model of Sensor Nodes

- Each sensor consists of four main components:
- the sensing
  - analog to-digital conversion (sensing/ADC) unit
  - processing/storage unit
  - the transceiver
  - the power supply.

Model of Sensor Nodes

- Each operation of sensing, processing, buffering, and transmitting costs a certain amount of energy.

Model of Sensor Nodes

- We focus on controlling the sensing/ADC and transceiving units and assume that the operation of the processor/storage unit is determined by the corresponding nodes of the sensing/ADC and transceiving units.
Model of Sensor Nodes

• The sensing/ADC unit and the transceiving unit can support different operating modes, which correspond to different amounts of power consumed and work done.

Model of Sensor Nodes

• Assume that the sensing/ADC unit can operate in
  – active
  – off modes
• Transceiving unit can operate in
  – Active
  – Idle
  – off modes.

Operating Modes of Sensing/ADC Unit

• Active Mode of Sensor when the sensing unit is active
• the power consumed per time slot is $P_{sa}$
• In this mode, the sensing unit is able to capture all events happening within its sensing region.
Operating Modes of Sensing/ADC Unit

- If the sensing unit is turned off for more than one time slot, then when it wakes up there may be several events within its sensing region that have not been captured.

In that case,

- assume that the sensing/ADC unit can process multiple events simultaneously.

- If at least one event is captured within a time slot,
  - then A packets will be generated and added to the buffer.
Operating Modes of Sensing/ADC Unit

• assume that in the case when multiple events are processed within onetime slot,
• they can be represented using A packets.

Operating Modes of Sensing/ADC Unit

• Assume that packets generated from processing all events that happen prior to or within time slot i are only added to the buffer at the end of time slot i

Operating Modes of Sensing/ADC Unit

• The buffer can stored up to B packets
• when there is no space left, packets dropped
• the corresponding events need to be recaptured.
Off Mode of Sensor

• When the sensing/ADC unit is off in a time slot, it consumes no power, that is, $P_{so}=0$.

• For example, it may happen that the event lifetime is long enough so that the sensing unit can be turned off and woken up some time later before the event disappears.

Off Mode of Sensor

• Another example is when the buffer is highly loaded, in which case, even if the sensing/ADC unit captures an event, the resulting packet will likely be dropped due to buffer overflow.

Off Mode of Sensor

• When the sensing component is in off mode, no sensing is carried out.
• Therefore, any event that happens and disappears during this period is missed.
Mode Transition Latency for Sensor

- Switching the sensing/ADC unit between active and off modes takes time.
- It is usually the case that the time needed to turn off some component is much less than what is required to turn it back on.

We assume that the time to turn the sensing/ADC unit off is equal to one time slot while the time needed to switch this component back on is $L_{so} = kr$ for some integer $k$.

During the transient period between active and off modes, we assume that the power consumed per time slot of the sensing/ADC unit is $\frac{P_{sa} + P_{so}}{2}$. 
Operating Modes of Transceiving Unit

- When considering the operation of the transceiver, we mainly focus on controlling the transmission of data packets out of the buffer.

We assume there is a separate channel to exchange control and channel information. The transceiver circuit can be in one of the three possible modes:
- active, idle, and off.

Active Mode of Transceiver

- When the transmitter is in active mode, packets are transmitted out of the buffer at the maximum rate of r packets per time slot.
- The power cost when transmitting at rate r depends on the condition of the wireless channel.
Active Mode of Transceiver

- The channel is represented by a stationary and K-state Markov chain.
- We assume that the channel remains in the same state during each time slot.
- Let $G$ and $\Gamma$ denote the instantaneous channel state and fading gain, respectively.

$G$ is an integer with $1 \leq G \leq K$ and $\Gamma$ is a positive real number.

When the channel is in state $G = k$, $0 \leq k < K$,
- the fading gain is $\Gamma = \gamma_k$, $\gamma_k > 0$

The K-state Markov channel model is completely described by its stationary distribution of each channel state $k$, denoted by $p_G(k)$, and the probability of transiting from state $k$ into state $j$ after each time slot, that is, $P_G(k, j)$, $0 \leq k, j < K$. 
Active Mode of Transceiver

• Let $P_{ta}$ be the power consumed in the active mode when the channel gain is unity.
• When the channel gain is $\gamma$, the actual power needed to transmit at rate $r$ is $P_{ta}/\gamma$.

Active Mode of Transceiver

• When the transmitter is active, apart from the transmission power, there is also power consumed in the electronics, denoted by $P_{tc}$.

Idle and Off Modes of Transceiver

• The transceiver can also operate in idle and off modes. In both of these modes, no data are transmitted out of the buffer.
• The main purpose of operating in these modes is to save power when there is no urgent need to transmit data, that is, when the buffer is lightly loaded, or when the channel conditions are not good, that is, the channel is in a deep fade.
Idle and Off Modes of Transceiver

- The power consumed by the transceiver in its idle and off modes are $P_{ti}$ and $P_{to}$, respectively.
- We assume $P_{ti} = P_{ic}$ and $P_{to} = 0$.

Mode Transition Latency for Transceiver

- We assume that, for the transceiver unit, mode transitions must either originate from or terminate at the active mode.
- In other words, transitions are not allowed between idle and off modes.

Mode Transition Latency for Transceiver

- Similar to the case of the sensing/ADC unit, we assume that the powers consumed when transiting between active and idle modes is $(P_{ic} + P_{ti})/2$ and between active and off modes is $(P_{ic} + P_{to})/2$. 
Mode Transition Latency for Transceiver

- Similar to the case of sensing/ADC unit, we assume that the time delay for switching the transceiving unit from active mode to either idle or off mode is equal to one time slot.
- The latency for switching the transceiving unit from idle and off modes back to active mode are denoted by $L_{ti}$ and $L_{to}$.

Discrete-Time Adaptive Power Management

- At the beginning of each time slot, given that the knowledge of the event process, the buffer occupancy and the channel conditions are available, we have to make a control decision on the operating modes of the sensing/ADC unit and the transmitting unit.

- While doing so, we face the trade-off between conserving energy, so that the system lifetime can be increased, and providing good quality of service, in terms of event-missed rate.
- Here, increasing lifetime is equivalent to reducing the time-averaged power consumed.
Discrete-Time Adaptive Power Management

In order to take both of the factors into account, we formulate the following optimization problem:

At the beginning of each time slot, select the operating modes of the sensing/ADC and transmitting units so that the weighted sum of the average power consumed and event-missed rate is minimized.

Markov Decision Process

We structure the above optimization problem as a Markov decision process.

This involves defining the system states, the set of valid control actions for each system state, the cost associated with taking a particular control action in a given system state, the dynamics of the system state given a control action, and finally the objective function over which the optimization will be carried out.

System States

- $G_i$ is the channel state during time slot $i$, $0 \leq G_i < K$.
- $B_i$ is the number of data packets in the buffer at the beginning of time slot $i$, $0 \leq B_i \leq B$.
System States

• $S_i$ is the state of the sensing/ADC unit at the beginning of time slot $i$. Apart from two states active and off; the sensing component can also be in one of the transitional states $TR(k)$, $k = 1, 2, \ldots (L_{so} - 1)$. The sensing unit is in state $TR(k)$ when it is in the process of transitioning from the off state to the active state, and there are $k$ time slots remaining before the active state is assumed.

System States

• $T_i$ is the state of the transceiving unit at the beginning of time slot $i$. Similar to the case of the sensing unit, the possible states of the transceiving unit are active, idle, off, and $TR(k)$, $k = 1, 2, \ldots (L_{so} - 1)$.

System States

• $C_i$ is the number of consecutive time slots (until the end of time slot $i - 1$) during which the sensing/ADC unit has been effectively off.

By saying the sensing/ADC unit is effectively off during a particular time slot, we mean that no event is successfully captured during that time slot.
System States

The first scenario is when the sensing/ADC unit is actually turned off and no processing is done.

The second scenario is when the sensing/ADC unit is active, however, the buffer is full so that processed data are lost and corresponding events need to be recaptured.

System States

$C_i$ is important in estimating how many events currently exist in the system and require processing.

As the maximum lifetime of an event is $D$ time slots, we only need to consider $0 \leq C_i \leq D$.

The system state at time slot $i$ is $X_i = (G_i, B_i, Si, T_i, C_i)$.

Control Actions

- At the beginning of time slot $i$, given knowledge of the event process and the system state $X_i$.
- We need to decide whether to leave each component of the system in the same operating mode or to transition to another mode.
Control Actions

- Note that the set of possible control actions depends on the current system state.
- Let \( U(x) \) denote the set of all possible control actions when the system is in state \( x \).
- Figure 6.3 depicts the state diagram of the operation of the sensing/ADC and the transceiving units.

System Dynamics

- The channel dynamics do not depend on control actions.
- Given a particular control action, it is straightforward to determine the dynamics of these variables.
Instead, we concentrate on characterizing $B_{i+1}$, $C_{i+1}$, assuming that $B_i$, $S_i$, $T_i$, $C_i$ and $S_{i+1}$, $T_{i+1}$ are already known. Let

\[ S = \mathbb{1}(S_i = \text{active} \text{ and } S_{i+1} = \text{active}) \]

\[ T = \mathbb{1}(T_i = \text{active} \text{ and } T_{i+1} = \text{active}) \]

where $1(e)$ is the indicator function for the event $e$. $S = 1$ means that the sensing/ADC unit is active during time slot $i$. $S = 0$ means that the sensing/ADC unit is effectively off during this time slot.

Similarly, variable $T$ indicates whether or not the transceiving unit is active during time slot $i$. 
System Dynamics

• Now let

\[
L = \begin{cases} 
B - \max(0, B_i - r) & \text{if } T = 1 \\
B - B_i & \text{otherwise}
\end{cases}
\]

• then \(L\) is the space left in the buffer during time slot \(i\).

System Dynamics

• During time slot \(i\) the sensing/ADC unit will successfully process incoming events if it is in the active mode and there is enough space left in the buffer to store data resulting from event processing.

System Dynamics

• Therefore,

\[
C_{i+1} = 1(S = 0 \text{ or } L < A) \times \min(C_i + 1, D)
\]

• At the beginning of time slot \(i\), the sensing/ADC unit has been effectively off for \(C_i\) time slots.
### System Dynamics

- Given that events happen in each time slot according to an i.i.d.

\[
W(\lambda, C_i) = 1 - \prod_{j=0}^{C_i} (\lambda P_{mf}(C_i - j) + 1 - \lambda)
\]

- Bernoulli process with probability \( s \), we can write down the probability of having at least one event to process in time slot \( i \) as

\[
P_m(t) = \begin{cases} 
1 - 0.5 & \text{if } t \geq D + 1 \\
\frac{t - 0.5}{D} & \text{if } 1 \leq t \leq D \\
0 & \text{if } t \leq 0
\end{cases}
\]

- \( P_m(t) \) is the probability that an event happening in time slot \( a \) disappearing before the beginning of time slot \( a + t \).
System Dynamics

• Now the buffer occupancy at the beginning of time slot $i + 1$ can be written as

$$B_{i+1} = \begin{cases} B - L & \text{if } C > 1 \\ B - L + E & \text{otherwise} \end{cases}$$

• where $E = A$ with probability $W(\lambda, C_i)$ and $E = 0$ with probability $1 - W(\lambda, C_i)$.

Numerical Results and Discussions

• In this section, we study the performance of the adaptive control policies obtained by solving the Markov Decision Process (MDP) formulated in Section 6.2.3. In particular, we look at the following adaptive policies:

Fully Adaptive

• The operating modes of both sensing and transmitting units are adapted to the channel and buffer conditions.
Fully Adaptive

- The sensing/ADC unit supports active and off modes while the transmitting unit can operate in active, idle, and off modes.
- It is expected that this scheme will perform best over all adaptive policies being considered.

No Off Mode for Sensor

- The transmitting unit is adaptive to the buffer and channel states.
- The sensing unit is always active.
- Our purpose of looking at this scheme is to determine whether it is essential to have a sensing component that can adapt to the system conditions.

No Off Modes for Sensor and Transmitter

- The sensing and transmitting units only support two modes, that is, active and idle.
- By comparing the performance of this scheme to that of the fully adaptive scheme, we can determine the importance of allowing the sensing and transmitting components to turn off when the system work load is low.
Numerical Results and Discussions

- The policies described above are obtained by solving the optimization problem formulated in the previous section.
- Different adaptive schemes are obtained by defining the cost function in different ways.
- For example, to prohibit the off mode, we simply set the cost of going from active to off mode to be very large.

Numerical Results and Discussions

- The channel is modeled as a two-state Markov channel (sometimes called the Gilbert–Elliot channel) shown in Figure 6.4.

![State diagram of two-state Markov channel.](image)
Numerical Results and Discussions

- The channel can be either in a good or bad state and will transition between the states with the probabilities shown in the state diagram.
- The channel gain in the bad state is $\gamma_0 = 0.2$ and in the good state is $\gamma_1 = 1$. 