Lecture #5

University of Essex

Wireless Sensor Networks

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Agenda

- Basics of Wireless Sensor Networks
- A TMDA-based Control Plane Algorithm
- Deployment and Power Assignment Problem in WSNs
- Summary, Q&A

Some materials courtesy to I.F. Akyildiz, etc's paper and slides "A Survey on Sensor Networks", IEEE Communications Magazine, August 2002.

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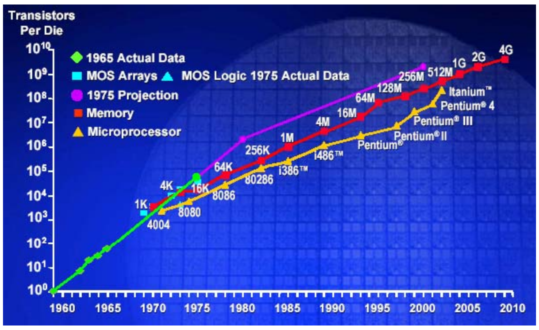
Faster, Smaller, Numerous

Moore's Law



- **Bell's Law**: New computer class every 10 years
  - mainframes (1960s)
  - minicomputers (1970s)
  - PC enabled by LAN (1980s)
  - Internet & Web browser (1990s)
  - Web services, e.g., MS .NET or the Grid (2000s), Smartphones (c. 2000)
  - Wireless Sensor Networks, (c. >2005): home and body area networks will form by 2010

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Wireless Sensor Networks: Features

- Recent advances in wireless communications and electronics have enabled the development of low-cost, low-power, multifunctional sensor nodes that are small in size and communicate in short distances.
- These tiny sensor nodes, which consist of sensing, data processing, and communicating components, leverage the idea of sensor networks.
- Sensor networks represent a significant improvement over traditional sensors.
- Sensor nodes are densely deployed either inside or close to the phenomenon.
- Random deployment in inaccessible terrains or disaster relief operations.
  - This also means that sensor network protocols and algorithms must possess self-organizing capabilities.
- Sensor nodes are fitted with an onboard processor.
  - Therefore certain data processing over raw data is carried out before transmission.

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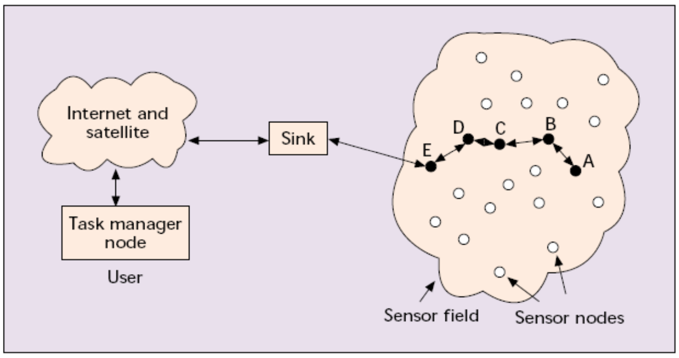
WSN Applications

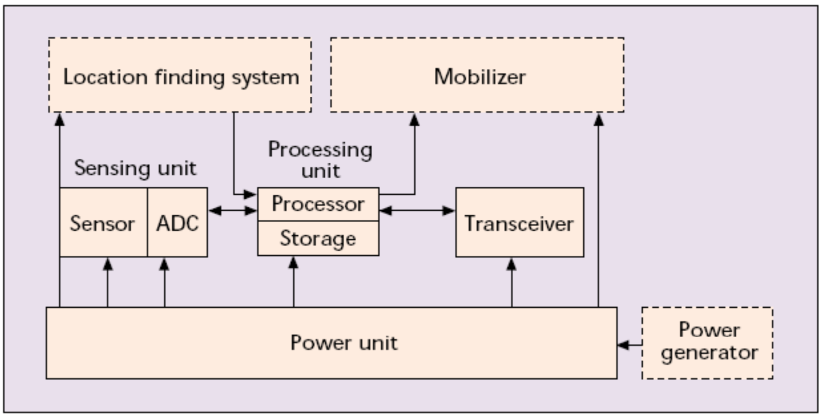
- A wide range of applications
- In *military*, for example, the rapid deployment, self-organization, and fault tolerance characteristics of sensor networks make them a very promising sensing technique for military command, control, communications, computing, intelligence, surveillance and targeting systems.
- In *health*, sensor nodes can also be deployed to monitor patients and assist disabled patients.
- Some other commercial applications include *managing inventory*, *monitoring product quality*, and *monitoring disaster areas*.

WSN Architecture

- The sensor nodes are usually scattered in a *sensor field.*
- Each of these scattered sensor nodes has the capabilities to collect data and route data back to the *sink* via multihop.
- The sink may communicate with the *task manager node* via Internet or satellite.



Architecture of a Sensor Node -1



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Architecture of a Sensor Node - 2

- A sensor node is made up of four basic components:
  - a sensing unit, usually composed of two subunits: sensors and analog-to-digital converters (ADCs).
  - a processing unit, which is generally associated with a small storage unit, manages the procedures that make the sensor node collaborate with the other nodes to carry out the assigned sensing tasks.
  - a transceiver unit: it connects the node to the network.
  - a power unit: might use solar cells.
- Or other additional application-dependent components such as:
  - A location finding system: for sensing or routing purpose
  - Mobilizer: to move sensor nodes
  - Power generator

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Factors Influencing the WSN Design

- The design of a WSN is influenced by many factors.
  - fault tolerance
  - Scalability
  - production costs
  - operating environment
  - sensor network topology
  - hardware constraints
  - transmission media
  - power consumption
- These factors can serve as a guideline to design a protocol or an algorithm for WSNs.
- In addition, these influencing factors can be used to compare different schemes.

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Fault Tolerance

- Why fails?
  - Lack of power,
  - physical damage,
  - or environmental interference
- The *reliability* $R_k(t)$ of a sensor node is modeled using the *Poisson distribution* to capture the probability of not having a failure within the time interval (0, *t*):

$$R_k(t) = \exp(-\lambda_k t)$$

- where λ_k and t are the failure rate of sensor node k and the time period, respectively.

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Scalability

- The number of sensor nodes deployed may be on the order of hundreds , thousands or even millions.
- The density can be calculated as

$$\mu(R) = (N\pi R^2)/A$$

  - *N* is the number of scattered sensor nodes in region A;
  - *R* is the radio transmission range.
- The number of nodes in a region can be used to indicate the node density.

Production costs

- Since sensor networks consist of a large number of sensor nodes, the *cost* of a single node is very important to justify the overall cost of the networks.
- The cost of a sensor node should be much *less than 1$* in order for the sensor network to be feasible.
- **Comparison:** The state-of-the-art technology allows a Bluetooth radio system to be less than US$10 [4]. Also, the price of a piconode is targeted to be less than US$1. The cost of a sensor node should be much less than US$1 in order for the sensor network to be feasible. The cost of a Bluetooth radio, which is known to be a low-cost device, is even 10 times more expensive than the targeted price for a sensor node.

Hardware constraints

- *Size*
  - matchbox-sized module
- consume extremely *low power*,
- operate in *high volumetric densities*,
- have *low production cost* and be *dispensable*,
- be *autonomous* and *operate unattended*,
- be *adaptive* to the environment.

Sensor network topology

- Deploying a high number of nodes densely requires careful handling of topology maintenance.
- Pre-deployment and deployment phase
  - Sensor nodes can be either *thrown in mass* or *placed one by one* in the sensor field.
- Post-deployment phase
  - Sensor network topologies are prone to *frequent changes* after deployment.
- Re-deployment of additional nodes phase
  - Addition of new nodes poses a need to *re-organize the network*.

Operating Environment

- Sensor nodes may be working
  - in busy intersections,
  - in the interior of a large machinery,
  - at the bottom of an ocean,
  - inside a twister,
  - in a battlefield beyond the enemy lines,
  - in a home or a large building.

Transmission media

- Sensor nodes are linked by a wireless medium.
- These links can be formed by radio, infrared, or optical media.
- Much of the current hardware for sensor nodes is based on RF circuit design.
- Industrial, scientific and medical (ISM) bands
  - offer license-free communication in most countries.
- Infrared
  - *license-free* and *robust to interference*
  - requirement of a *line of sight* between sender and receiver.
  - Infrared-based transceivers are cheaper and easier to build.
- Optical medium: in *Smart Dust* mote, which is an autonomous sensing, computing, and communication system.
- Both infrared and optical require a line of sight (LOS) between the sender and receiver.

Power consumption

- Sensor nodes are only equipped with limited power source(<0.5Ah, 1.2V).
- Node lifetime strongly dependent on battery lifetime.
  - In some application, replenishment of power resources might be impossible.
- In a multihop ad hoc sensor network, each node plays the dual role of data originator and data router.
- The malfunctioning of a few nodes can cause significant topological changes and might require rerouting of packets and reorganization of the network.
- Hence, power conservation and power management take on additional importance.

- The main task of a sensor node in a sensor field is to detect events, perform quick local data processing, and then transmit the data.
  - Power consumption can hence be divided into three domains: **sensing/acurating**, **communication**, and **data processing**.

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Communications via Radio

- Radio can mean differently:
  - Mote's radio is only a transceiver, and a lot of low-level processing takes place in the main CPU
  - While, typical 802.11b radios do everything up to MAC and link level encryption in the "radio"
- Energy per bit in radios is a strong function of desired communication performance and choice of modulation
  - Range and BER for given channel condition (noise, multipath and Doppler fading)
- Transmit, receive, idle, and sleep modes
  - E.g. WINS consumes only 1/6-th the power when MCU is asleep as opposed to active
  - Idle radio consumes almost as much power as radio in Rx mode
    - Radio needs to be completely shut off to save power as in sensor networks idle time dominates
    - MAC protocols that do not "listen" a lot

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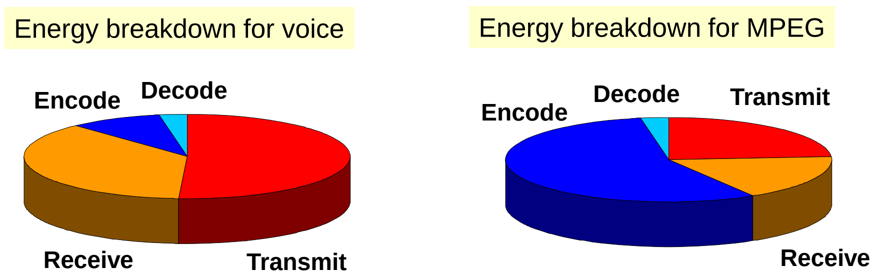
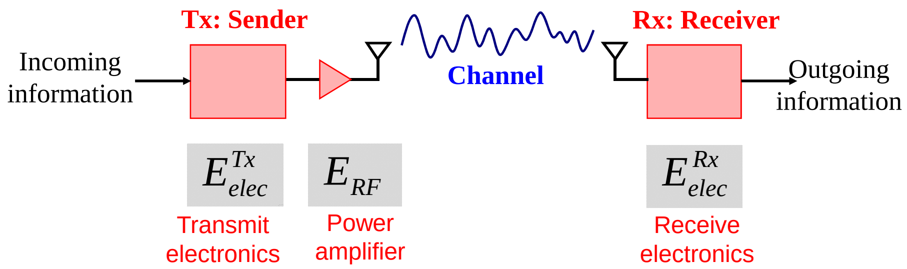
Energy Consumption: Computation vs. Communication



Radio: Lucent WaveLAN at 2 Mbps
Processor: StrongARM SA-1100 at 150 MIPS

- The relative impact of the communication subsystem on the system energy consumption will grow

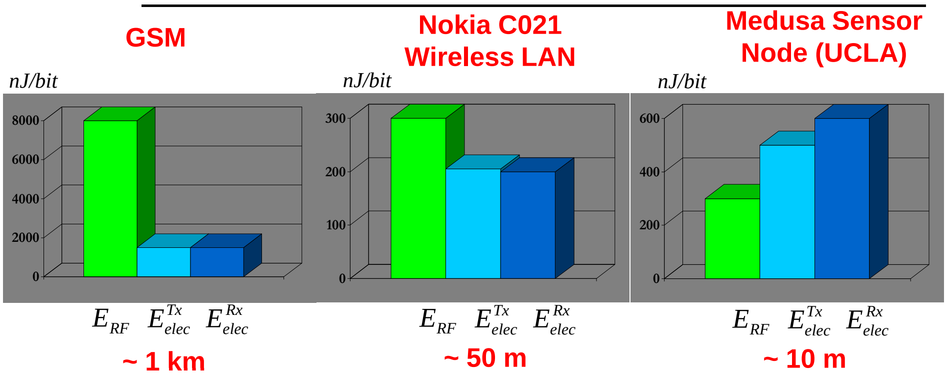
Energy in Radio



- Wireless communication subsystem consists of three components with substantially different characteristics
- Their relative importance depends on the **transmission range** of the radio

Courtesy to M. Srivastava's slides for Mobicom02 tutorial

Energy Consumption Examples



- The RF energy increases with transmission range
- The electronics energy for transmit and receive are typically comparable

Courtesy to M. Srivastava's slides for Mobicom02 tutorial

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Simulation Tools

- Sensor Network-level Simulation Tools
  - Ns-2 enhancements by ISI
  - Ns-2 based SensorSim/SensorViz by UCLA
  - C++-based LECSim by UCLA
  - PARSEC-based NESLsim by UCLA
- Node-level Simulation Tools
  - MILAN by USC for WINS and µAMPS
  - ToS-Sim for Motes
- Processor-level Simulation Tools
  - JoulesTrack by MIT

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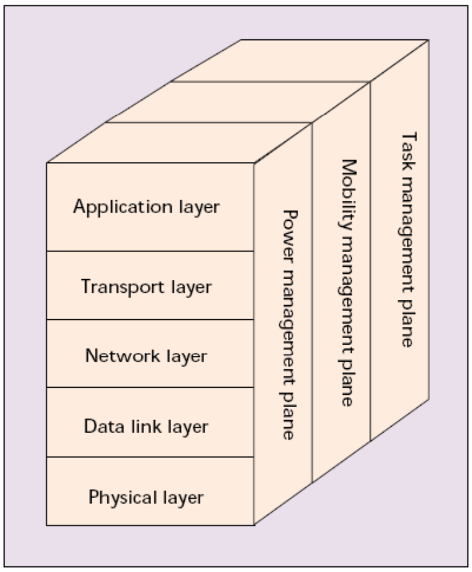
Protocol Stack



- Used by the sink and sensor nodes

Protocol Layers

- The **physical layer** addresses the needs of simple but robust modulation, transmission, and receiving techniques.
- Since the environment is noisy and sensor nodes can be mobile, the medium access control (**MAC**) protocol must be power-aware and able to minimize collision with neighbors' broadcasts.
- The **network layer** takes care of routing the data supplied by the transport layer.
- The **transport layer** helps to maintain the flow of data if the sensor networks application requires it.
- Depending on the sensing tasks, different types of application software can be built and used on the **application layer**.

Management Planes

- These management planes make sensor nodes work together in *a power efficient way*, route data in a *mobile* sensor network, and *share resources* between sensor nodes.
- Power management plane
  - manages how a sensor node uses its power.
  - For example, the sensor node may turn off its receiver after receiving a message.
  - When the power level of the sensor node is low, the sensor node broadcasts to its neighbors that it is low in power and *cannot participate in routing messages*.
- Mobility management plane
  - *detects* and *registers* the *movement* of sensor nodes
  - So a route back to the user is always maintained
  - the sensor nodes can keep track of who are their neighbor sensor nodes.
- Task management plane
  - *Balances* and *schedules* the *sensing tasks* given to a specific region.
  - Not all sensor nodes in that region are required to perform the sensing task at the same time.

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Physical Layer

- Frequency selection, carrier frequency generation, signal detection, modulation, and data encryption.
- 915 MHz ISM band has been widely suggested for sensor networks.
- signal propagation effects
  - the minimum output power required to transmit a signal over a distance d is proportional to d^n, where 2<= n < 4.
  - The exponent n is closer to four for low-lying antennae and near-ground channels, as is typical in sensor network communication.
  - *multihop communication* in a sensor network can effectively overcome shadowing and path loss effects, if the node density is high enough.
- Modulation schemes: Simple and low-power modulation schemes.
  - The modulation scheme can be either baseband, as in UWB, or passband.
- Strategies to overcome signal propagation effects
- Hardware design

Open research issues

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Data Link Layer

- The data link layer is responsible for the multiplexing of data stream, data frame detection, medium access and error control
- It ensures reliable point-to-point and point-to-multipoint connections in a communication network.
- Media Access Control – two goals:
  - Creation of the network infrastructure
  - Fairly and efficiently share communication resources between sensor nodes

Why existing MAC protocol can't be used?

- The primary goal of the existing MAC protocol is the provision of high QoS and bandwidth efficiency.
- In a *cellular system*, the base stations form a wired backbone.
  - A mobile node is only a single hop away from the nearest base station.
  - infrastructure- based: base station doing network-wide synchronization
  - Power-awareness is not a big deal:
    - base stations have unlimited power supply and
    - the mobile user can replenish exhausted batteries in the handset.
- *Mobile ad hoc network* (MANET), a close peer to WSNs
  - MAC in a MANET:
  - forming the network infrastructure and
  - maintaining it in the face of mobility.
  - Hence, the primary goal is the provision of high QoS under mobile conditions.
  - Battery can be replaced by the user, and hence power consumption is only of secondary importance.

Why existing MAC protocol can't be used?

- In contrast to these two systems, the sensor network may have a much larger number of nodes. The transmission power (~0 dBm) and radio range of a sensor node is much less than those of MANET.
- Topology changes are more frequent in a sensor network due to both node mobility and failure.
- The mobility rate can also be expected to be much lower than in the MANET.
- In essence, the primary importance of power conservation to prolong network lifetime in a sensor network means that none of the existing MANET MAC protocols can be directly used.

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MAC for WSNs

- MAC protocol for sensor network must have built-in
  - power conservation,
  - mobility management
  - failure recovery strategies
- How to achieve energy efficiency:
  - A variant of TDMA,
  - random medium access such as CSMA
  - constant listening times
  - adaptive rate control schemes.
- Some MAC protocols for WSNs to follow

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Network layer

- The networking layer of sensor networks is usually designed according to the following principles:
  - *Power efficiency* is always an important consideration.
  - Sensor networks are mostly *data centric*.
  - *Data aggregation* is useful only when it does not hinder the collaborative effort of the sensor nodes.
  - An ideal sensor network has *attribute-based addressing* and *location awareness*.

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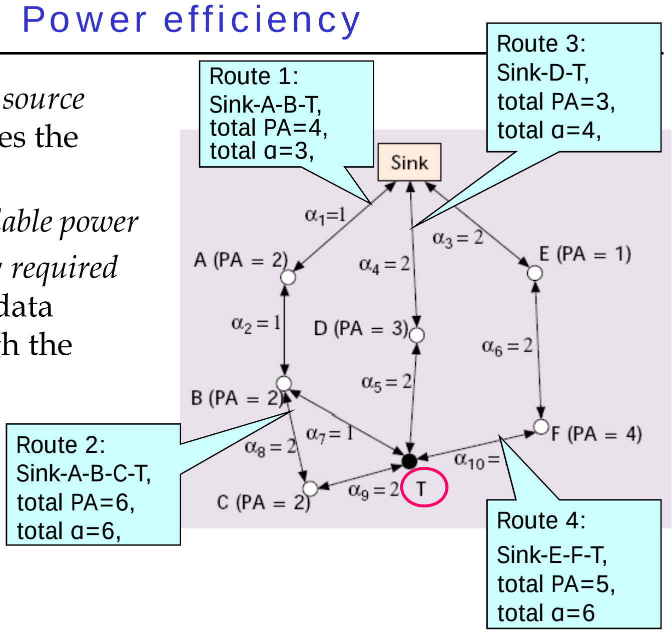
Power efficiency

- Node T is the *source node* that senses the phenomena.
- PA is the *available power*
- α is the *energy required* to transmit a data packet through the related link.



Power efficiency

- Maximum available power (PA) route
  - Select Route 2
- Minimum energy (ME) route
  - Select Route 1 (if α the same then ME=MH)
- Minimum hop (MH) route
  - Select Route 3 (if α the same then MH=ME)
- Maximum minimum PA node route
  - Select Route 3
  - Preclude the risk of using up a sensor node with low PA.

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Data-centric Routing

- *Interest dissemination* is performed to assign the sensing tasks to the sensor nodes.
- Two approaches used for interest dissemination:
  - Sinks broadcast the interest
  - Sensor nodes broadcast an advertisement for the available data and wait for a request from the interested sinks.
- *Requires attribute-based naming*
  - Querying an attribute of the phenomenon, rather than querying an individual node.
  - Eg: "the areas where the temperature is over 70°F" is a more common query than "the temperature read by a certain node"

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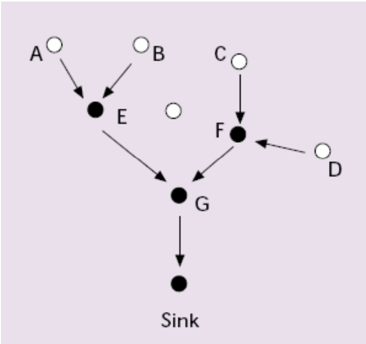
Data aggregation

- A technique used to solve the implosion and overlap problems in data-centric routing.
- Data coming from multiple sensor nodes with the same attribute of phenomenon are aggregated.
- Data aggregation can be perceived as a set of automated methods of combining the data the comes from many sensor nodes into a set of meaningful information.
  - With this respect, data aggregation is Known as *data fusion*.
- Sensor network is usually perceived as a *reverse multicast tree*.



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Transport layer

- The transport layer is needed when the system is planned to be *accessed through Internet* or other external networks.
- Few scheme related to the transport layer of a sensor network has been proposed in literature.
  - Hardware constraints such as limited power and memory.
  - Acknowledgments are too costly.

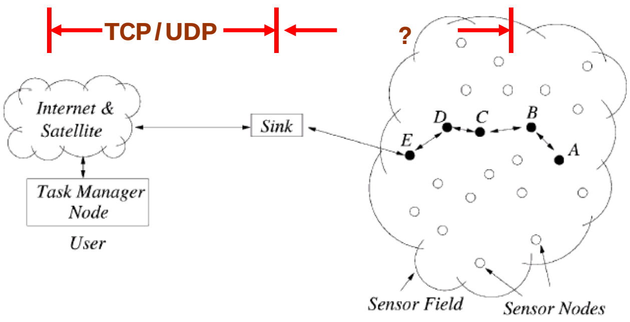

Fig. 2. Sensor nodes scattered in a sensor field

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Application layer

- Potential application layer protocols for sensor networks remains a largely unexplored region.
- Task assignment and data advertisement protocol (TADAP)
  - Users send their interest to a sensor node, a subset of the nodes or whole network.
  - This interest may be about a certain *attribute* of the phenomenon or a *triggering event*.
  - Another approach is the *advertisement of available data* in which the sensor nodes advertise the available data to the users
- Sensor query and data dissemination protocol (SQDDP)
  - SQDDP provides user applications with interfaces to *issue queries*, *respond to queries* and *collect incoming replies*.
  - attribute-based or location-based naming
    - the locations of the nodes that sense temperature higher than 70 ^{0}C
    - Temperatures read by the nodes in region A
  - Sensor query and tasking language (SQTL) is proposed.

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Agenda

- Overview of Wireless Sensor Networks
- A Nimble and Adaptive TDMA Control Phase Algorithm for Cluster-based WSNs
- Deployment and Power Assignment Problem in WSNs
- Summary, Q&A

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CSMA vs TDMA

- Medium Access Control (MAC) protocol plays a critical role in the performance of wireless sensor networks.
- While CSMA/CA as led by IEEE 802.11 being the mainstream technique for wireless network MAC, it is not inherently immune to the retransmission caused by collision, and overhearing and this retransmission consumes much sensor energy.
- In contrast to the random access protocols, the scheduling based MAC protocols such as TMDA bear inherent immunity to these factors.
- This paper considers cluster-based sensor networks where the cluster head in a cluster serves naturally as a base station to carry out cluster-level time slot scheduling.

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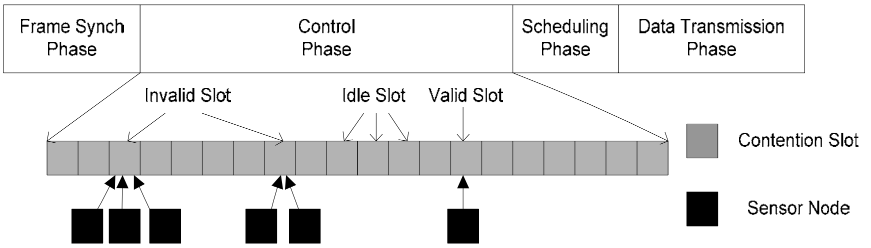
TDMA-based MAC

- TDMA-based MAC in wireless networks typically involves the following four phases:
  - frame synchronization phase,
  - control phase,
  - scheduling phase and
  - data transmission phase.



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Main objective

- Much work on scheduling, but less on the control phase.
- The scheduling phase utilizes the result of the control phase, mainly the number of successful nodes requesting data transmission, to perform time slot allocation.

- The main work for control phase is to decide its own length in terms of time slots.
- This length, when contention is utilized, is also termed as *contention window* (CW).

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Polling

- A commonly used mechanism in control phase is polling, a scheduling-based approach.
- Polling reserves a slot for each sensor regardless the sensor's data transmission request.
- Polling guarantees no collision at a cost of longer control phase length, which as a result leads to longer packet delay time and low channel utilization (refer to the later analysis for details).
- Improvement to polling has been proposed which adopts random access [7], [8], mainly using CSMA since it is the most influential contention protocol in practice.
- However, many of these literatures on wireless sensor networks utilize CSMA directly, not focusing on how to find a proper backoff window size as the length of TDMA control phase.

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Backoff Window Size – Current Literature

- Various researches have been carried out on backoff window size [9]~[12].
- Sift [9] sets the backoff window size to a constant while leaving nodes to select the probability of successful transmission in different slots. If no node transmits data in the first slot, every node increases its successful transmission probability for the next slot.
- Y. Xiao [11] introduces the priority into smaller-sized backoff windows. These researches have indicated that a mechanism that dynamic detects and estimates the number of active nodes usually performs better than otherwise.
- Cali [10] establishes the relation of the number of active stations and the idle period.
- Bianchi [12][13] proposes the relation of the number of contention nodes and the collision probability using Kalman and ARMA filter.
- The results of these works are all presented in average and expectation.

Shortcomings of the Current Literature

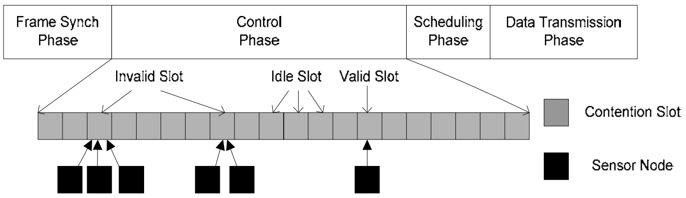
- However, although research [13] uses Kalman and ARMA to get much more accurate results, the information needed for this calculation is massive and the computation is complex.
- Furthermore, these researches all assume that the number of nodes making request is fixed, namely, all nodes always have data ready to be transmitted (i.e. saturation conditions).
- These assumptions are not realistic in the real functioning of wireless sensor networks.
- An algorithm called NACPA is proposed in this paper, aiming to calculating the control phase length (i.e., the number of contention nodes) in a much simpler manner and without the above assumptions.

NACPA Features

- This is achieved via a combination of experimental method and the re-use of the information obtainable from an existing hardware (AGC: Automatic Gain Control).
- Moreover, this paper, for the first time to the best of our knowledge, proposes to calculate the number of contention node (denoted as *N*) from the contention slot's point of view rather than contention node's perspective.
- This design methodology contributes significantly to the simplification of the contention node estimation process and the control phase algorithm itself, as to be demonstrated in the paper.

Fundamentals

- Sensor nodes contend for contention slots (CS) in the control phase.
- The length of a CS can typically accommodate a data transmission request (DTR) from a sensor.
- When a sensor has data to transmit, it randomly selects a CS to send DTR to base station (i.e., the cluster head in cluster-based sensor networks as is the case of this paper), as illustrated in the figure below.
- These sensors that successfully obtain a CS are able to be scheduled a data transmission slot in data transmission phase.
- The failure ones retransmit their DTR in the next round.



Problem Re-investigation

- Given:
  - N: the number of contention nodes, and
  - M: the number of CS (Contention Slot) in a round
- There is:
  - the higher the probability of a CS being a valid slot (i.e., being selected by only one sensor) is,
  - the more sensors are that get their DTR received without collision, i.e., the higher the total number of valid slots becomes, and consequently the more r (the success rate of nodes getting their DTR received by the cluster head) and u (the control phase utilization) become.
- Therefore, the problem of maximizing r and u is converted to a problem of maximizing the probability of a CS being a valid slot by tuning M.
- Theorem 1 below shows there exist such a maximum of the probability of a CS being a valid slot and the value of this maximum is highly coupled with the values of M and N.

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Theorem 1

- Theorem 1: the probability of a CS being a valid slot is maximized when M=N.
- Proof: Given a CS, let $p(x)$ be the probability of this CS being selected by x sensor nodes simultaneously. $p(x)$ is calculated by:

$$p(x) = C_N^x \left(\frac{1}{M}\right)^x \left(1-\frac{1}{M}\right)^{N-x} \qquad (1)$$

When x=0, $p(x)$ is the probability of a CS being idle; when x=1, $p(x)$ is the probability of a CS being a valid slot; when x>1 (and with ceiling N), $p(x)$ is the probability of a CS being an invalid one. NACPA is interested in how to tune M so as to obtain a maximum p(1). Since M is a variable in Equation , p(1) is denoted as $p(M)$ and derived from as follow:

$$p(M) = N\frac{1}{M}\left(1-\frac{1}{M}\right)^{N-1}$$

In order to get the maximum of $p(M)$, the derivative of $p(M)$ is calculated:

$$\frac{dp(M)}{dM} = N(N-M)\left(1-\frac{1}{M}\right)^{N-2}\frac{1}{M^3}$$

Set Equation =0, we have M=N. This means, when M=N, the probability of CS being used successfully is the maximal. □

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Problem Conversion

- The target of NACPA is to, at the end of round *i*, calculate the contention window size of next round, i.e., M_{i+1}.
- Theorem 1 proves that when $M=N$ the probability of a CS being a valid slot is maximized. Then the problem of calculating M_{i+1} is converted into the calculation of N_{i+1}.
- However, it is practically impossible to know N_{i+1} because round (i+1)-th has not occurred yet. A commonly used technique is to use N_i to replace N_{i+1} [10].
- So NACPA utilizes the result of *i*th round to decide the contention window size of the (i+1)-th round.
- An improvement is to use the results of all *i* rounds to calculate the contention window of the (i+1)-th round, such as in the work by Bianchi [13] where Kalman filter is utilized for this purpose. A similar approach can be integrated into our work.
- However the focus of this paper is how to estimate a more accurate *N* for one round with a significantly reduced computation complexity.
- For presentation simplicity and without ambiguity this paper uses *N* to denote N_i.

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Analysis on *N*

- *N* is composed of two parts: the number of success nodes and the number of failure node, i.e.:

$$N = m_S + \sum_{i=1}^{m_F} n_i$$

- where m_S is the number of valid CS's (i.e. the number of successful sensor nodes), m_F is the number of invalid CS's, and n_i is the number of contention nodes on *i*-th invalid CS.
- Note that this calculation is carried out from the slot's point of view rather than node's perspective.
- Now the problem is how to get *N* - the total number of nodes making DTR in a given round.

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Further Analysis on *N*

- Using the signal from AGC (Automatic Gain Control) circuit in the wireless communication radio interface, a cluster head can detect if a slot is idle, used by only one sensor, or there is a collision. Namely,
  - *m*S and *m*F can be obtained.
- However AGC hardware cannot tell how many nodes leading to the collisions in an invalid CS. This paper proposes to utilize a probability-based mechanism to estimate $\sum_{i=1}^{m_F} n_i$ since sensors randomly select contention slots.
- To find out the most probable number of contention nodes causing a collision on a given CS. And this probability-based estimation is across all CS's in the control phase. We denote this most probable number of contention nodes as *N*c. Then, the equation in the previous slide is converted into:

$$N = m_S + m_F N_c$$

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Theorem 2

- Theorem 2: Given *N* and *M*, there exist one and only one *x* where *x*>1 such that *p*(*x*) is maximized.
  - Its physical implication is: when collision occurs on one CS, there is only one most probable number of nodes (i.e. *N*c) that have selected this CS simultaneously.
- Proof: refer to the published paper.

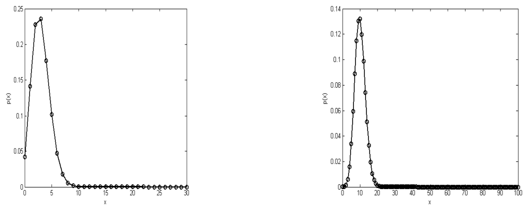

Fig. 2

- Fig. 2 on *p*(*x*) illustrates that when *x*>1, each graph has only one maximum (i.e. when *x*=*N*c), as proved in Theorem 2.

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Calculation of Nc*

- Expectation E(x) is used to compute the *average* most probable number of contention nodes, denoted as Nc*.

$$N = m_S + m_F \times N_c^* \qquad N_c^* = \mathrm{E}(x) = \sum_i x_i p(x_i \mid x_i > 1)$$

- Now let's consider the behaviour of E(x) under N=M.
  - Recalculate $p(x)$
- When N=n, we denote $p(x)$ as $p1(x)$ and $p2(x)$ respectively for N=n and N=n+1. there is: when N is much larger than 1, $p1(x)$ is very close to $p2(x)$.

Table 1 $p(x)$ **under different** N **(**N=M**)**

	x=1	2	3	4
N=5	0.4096	0.2048	0.0512	0.0064
8	0.3927	0.1963	0.0561	0.0100
10	0.3874	0.1937	0.0574	0.0112
11	0.3855	0.1928	0.0578	0.0116
30	0.3741	0.1871	0.0602	0.0140
80	0.3702	0.1851	0.0609	0.0148

Nc*=E(x)=2, when N=5, and 10;
Nc*=E(x)=2.3, when N=11, 30 and 80.

$$N_c^* = \mathrm{E}(x) = \begin{cases} 2, \text{ when } M = N \le 10 \\ 2.3, \text{ when } M = N > 10 \end{cases}$$

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M<N

- When M<N, NACPA sets M to Mmax where Mmax is the maximum size of a content window allowed by the system.

$$N_c^* = \mathrm{E}(x) = \begin{cases} 2, \text{ when } M = N \le 10 \\ 2.3, \text{ when } M = N > 10 \\ \sum_i x_i p(x_i \mid x_i > 1,\ p(x_i) > \zeta), \text{ when } M \ne N \end{cases}$$

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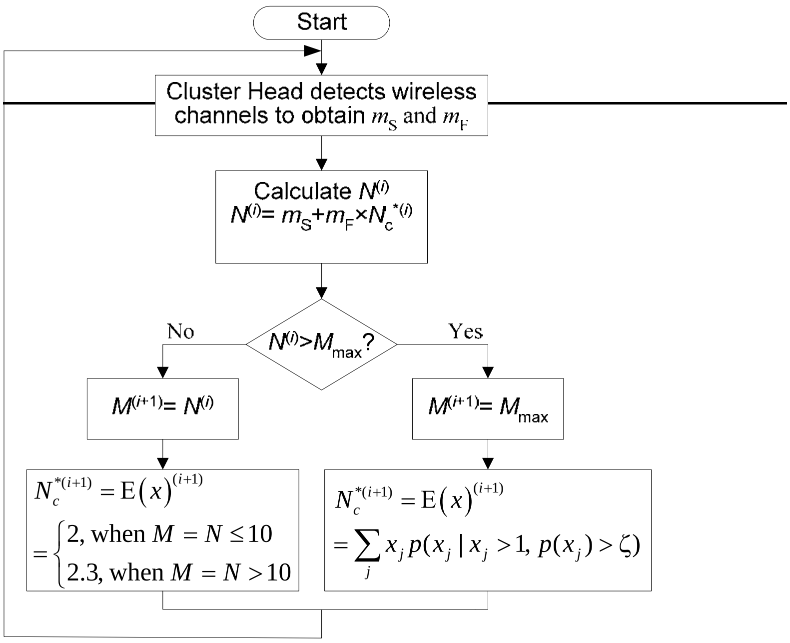

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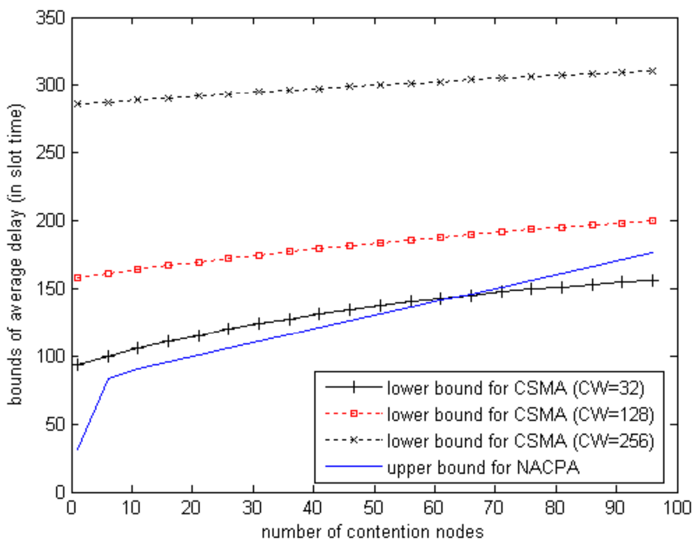
Analytical Evaluation: Bounds of Average Delay



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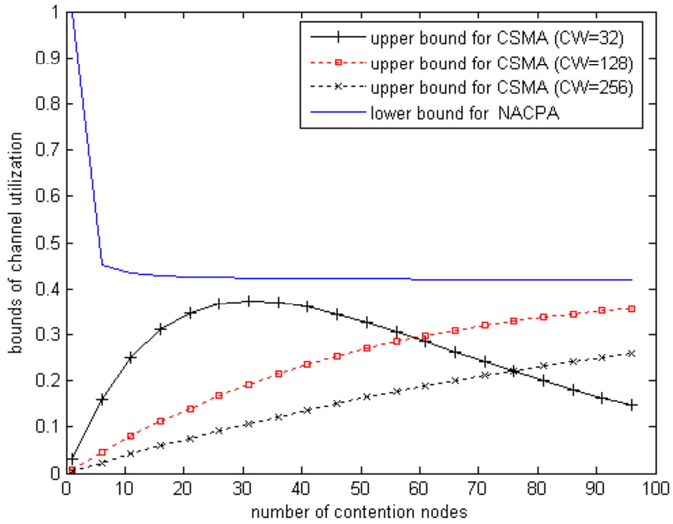
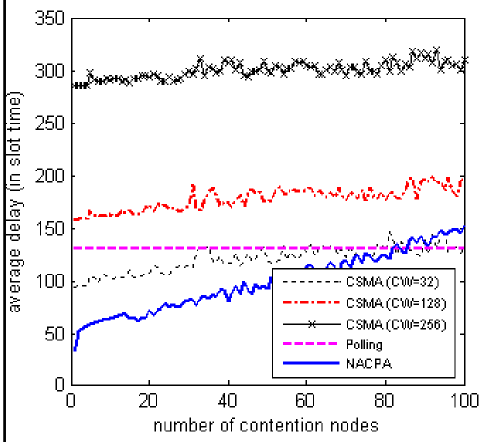
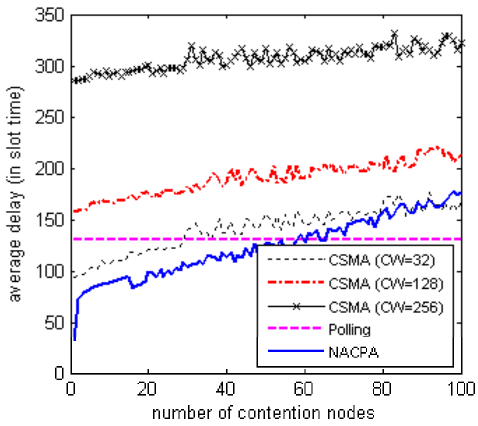
Analytical Evaluation: Bounds of Channel Utilization



Simulation Results: Average Delay



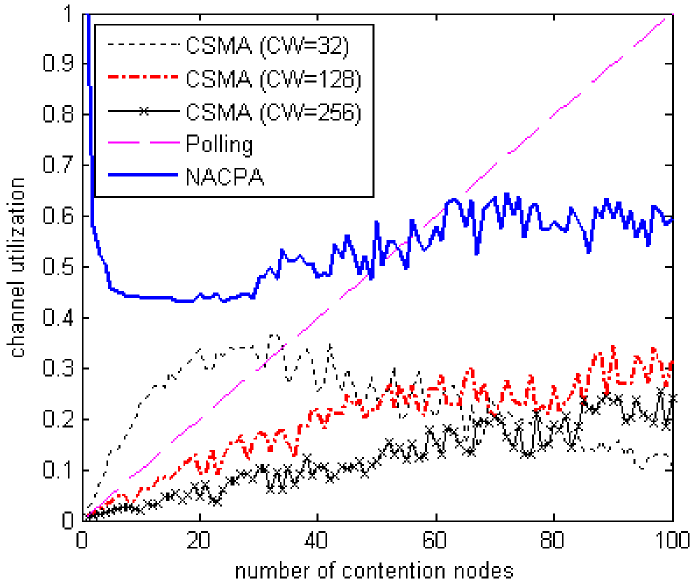
Q=125 bytes



Q=250 bytes

- payload in the data transmission phase: Q

Simulation Result: Channel Utilization



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Conclusions

- A dynamic and adaptive algorithm called NACPA to control the control phase of TDMA-based MAC in sensor networks.
- NACPA firstly proves that the best performance is achieved when contention window size is set equal to the number of contention nodes in one round. Then, by taking advantage of the AGC hardware feature, NACPA proposes a more accurate way to calculate the number of contention nodes in one round and discards the non-practical assumptions of a fixed number of contention nodes.
- By further analyzing the features of contention probability against the number of contention nodes, NACPA significantly reduces its computation complexity making it feasible for resource-constrained sensor networks. The analytical evaluation and simulation results both showed its effectiveness and efficiency in comparison with two typical MAC algorithms: polling and CSMA.

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Agenda

- Overview of Wireless Sensor Networks
- A Nimble and Adaptive TDMA Control Phase Algorithm for Cluster-based WSNs
- Deployment and Power Assignment Problem in WSNs
- Summary, Q&A

Objectives

- Deployment: to find the initial location of a sensor
- Power assignment: to specify the initial transmission power of a sensor
- In order to maximize two (conflicting) objectives: **coverage** & **lifetime**
- Challenge: how to achieve these two goals simultaneously (and may subject to some constraints)?
- Solution: using modern evolutionary algorithms and meta-heuristic.
- Offline, provide guidance to WSN designers

System Model

- Consider a 2-D static WSN formed by:
  - a rectangular sensing area *A*,
  - a number of homogeneous sensors N and
  - a static sink *H* with unlimited energy, placed at the center of A.
  - The sensors are responsible to monitor and periodically report an event of interest to *H*.
- We assume a perfect medium access control and adopt the simple path loss communication mode (square distance-based).
- Residual Energy:

$$E_i(t) = E_i(t-1) - ((r_i(t)+1) \times P_i \times amp)$$

- A is composed of rectangular grids of identical dimensions centered at (x', y') and we adopted a "binary" sensing model. A grid at (x', y') is covered, denoted by g(x', y') = 1, if it falls within a sensor's sensing range Rs, otherwise g(x', y') = 0.
- We consider unit-size grids, which are several times smaller than Rs, for a more accurate placement

Problem formulation

Given:

- A: 2-D plane of area size x × y
- N: number of sensors to be deployed in A.
- E: initial power supply, the same for all sensors.
- Rs: sensing range, the same for all sensors.

The **design variables** set (X) is composed by:

- Lj : the location of sensor j.
- Pj : the transmission power level of sensor j.

Objectives: Maximize coverage Cv(X) and lifetime L(X).

The network **coverage** Cv(X) is defined as the percentage of the covered grids over the total grids of A and is evaluated as follows:

$$Cv(X) = [\sum_{x'=0}^{x} \sum_{y'=0}^{y} g(x', y')]/x \times y$$

The network **lifetime** is defined as the time that the first sensor dies.

Proposed Algorithm

Input: • network parameters (A, N, E, R_s);
- m : population size and number of subproblems;
- T: neighborhood size;
- uniform spread of weights $\lambda^1, ..., \lambda^m$;
- the maximum number of generations, gen_{max};

Output: • the external population, $EP = \{X^*\}$.

Step 0-Setup: Set $EP := \emptyset$; $gen := 0$; $IP := \emptyset$;

Step 1-Decomposition: Initialize m subproblems, i.e. $\max g^i(Y^i|\lambda^i)$, for $i = 1, ..., m$.

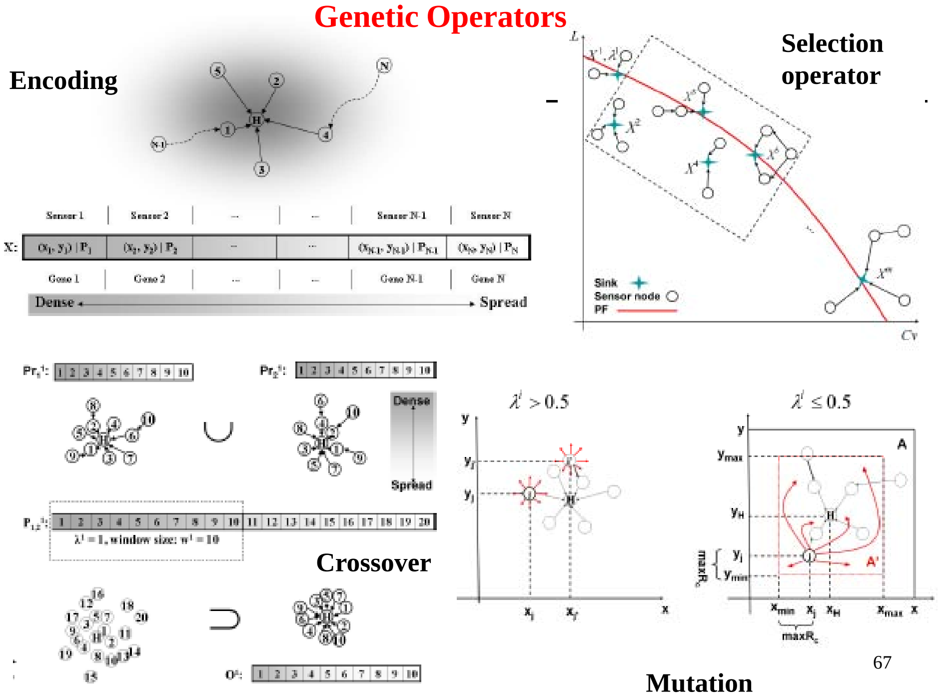
Step 2-Initialization: Randomly generate an initial internal population $IP = \{Y^1, \cdots, Y^m\}$;

Step 3: **For** each subproblem $i = 1$ to m **do**

- **Step 3.1-Genetic Operators:** Generate a new solution O^i by using selection, crossover and mutation operators.
- **Step 3.2-Improvement:** Apply a problem specific repair/improvement heuristic on O^i to produce X^i.
- **Step 3.3-Update Populations:** Update IP, EP and the T closest neighbors of subproblem i with X^i.

Step 4-Stopping criterion: If stopping criterion is satisfied, i.e. $gen = gen_{max}$, then stop and output EP, otherwise $gen = gen + 1$, go to **Step 3**.

Genetic Operators



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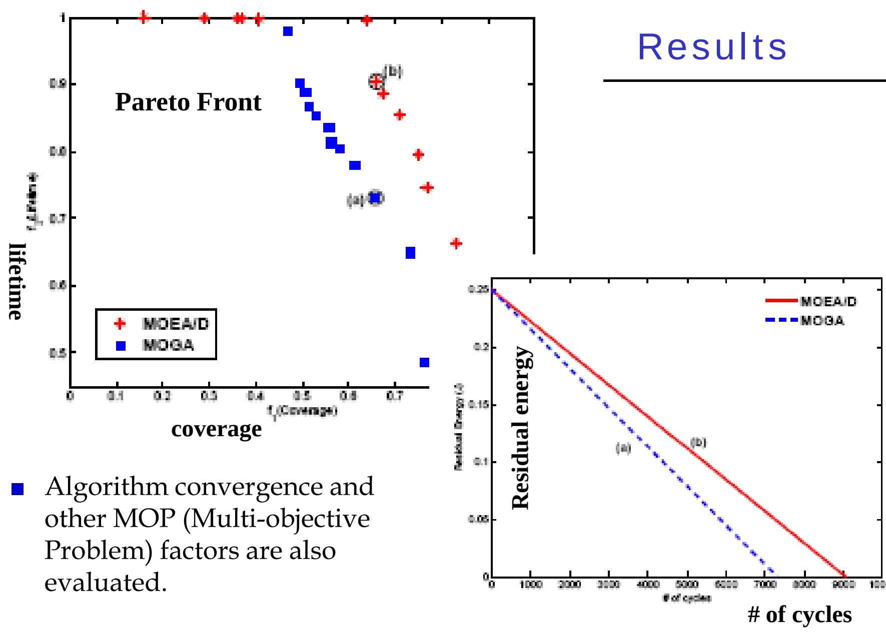
Results



- Algorithm convergence and other MOP (Multi-objective Problem) factors are also evaluated.

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References for more details

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