Wireless Sensor Network (WSN) Communications: Localization, MAC Protocols and Backend Applications

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Publications

- Journal papers
  1. M.O. Diaz and K.K. Leung, "Efficient data aggregation and transport in Wireless sensor networks", *Wiley Wireless Communications and Mobile Computing*, 2009.
  2. A. Bachir, M. Heusse, A. Duda, and K. K. Leung, "Preamble MAC Protocols with Persistent Receivers in Wireless Sensor Networks," *IEEE Trans. on Wireless Communications*, March 2009.
  3. A. Bachir, M. Dohler, T. Watteyne and K.K. Leung, "MAC Essentials for Wireless Sensor Networks," *IEEE Communications Surveys and Tutorials*, Second issue 2010.
- Conference papers
  1. Mario O. Díaz and K.K. Leung, "A test-based scheduling protocol (TBSP) for periodic data gathering in wireless sensor networks", 3rd International Workshop on Multiple Access Communications (MACOM), Barcelona, Spain, 13-14 September 2010.
  2. F. Theoleyre, A. Bachir, N. Chakchouk, A. Duda and K.K. Leung, "Energy Efficient Network Structure for Synchronous Preamble Sampling in Wireless Sensor Networks," IEEE ICC 2010, May 2010.
  3. Mario O. Díaz and Kin K. Leung, "Randomized scheduling algorithm for data aggregation in wireless sensor networks," IEEE European Wireless Conference, Lucca, Italy, April 2010.
  4. A. Bachir, F. Theoleyre, K.K. Leung and A. Duda, "Energy-Efficient Broadcasts in Wireless Sensor Networks with Multiple Virtual Channels," IEEE WCNC 2010, April 2010.
  5. P.Mazurkiewicz and K.K.Leung, "Performance of Angle-and-Range-Based Localization of Wireless Sensors", Pacific Rim Conference on Communications, Computers and Signal Processing, Canada, August 2009.
  6. Mario O. Díaz and Kin K. Leung, "Dynamic data aggregation and transport in wireless sensor networks," IEEE PIMRC, Cannes, France, September 2008.
  7. P.Mazurkiewicz and K.K.Leung, "Clique-Based Localization Algorithm for Sparse Networks of Wireless Sensors," Military CIS Conference, Poland, September 2008.
  8. P.Mazurkiewicz and K.K.Leung, "Clique-based Location Estimation Enhancement in GPS-free Localization for Wireless Sensors", ICCCN 2008, USA, August 2008.
  9. A.Magnani and K.K.Leung, "Self-Organized, Scalable GPS-Free Localization of Wireless Sensors", IEEE WCNC Conference, China, March 2007.

Research Topics Investigated

- Sensor localization
  - Devised distributed, efficient algorithms to determine sensor locations without help of GPS (e.g., London underground tunnels) by use of multiple antennas
  - Evaluated performance of proposed localization algorithms
  - Prototyped aspects of the proposed algorithms
- MAC protocols
  - Devised MAC protocols suitable for infrastructure monitoring
  - Combined MAC with data aggregation functions
  - Evaluated proposed protocols
- Backend applications
  - Developed software to visualize monitored data and control sensing operations remotely

Research Problem: Localization

- Scenario
  - Multi-hop sparse network of low-power sensors placed along a large structure, e.g. an underground tunnel.
  - A small fraction of all nodes: reference nodes, know their position by external means. Other nodes: unknown nodes, do not know their position.
  - All nodes have capability of performing the self-organizing, distributed localization algorithm which aims at determining the positions of all unknown nodes.
  - All nodes have specific hardware to measure some physical information that can be used for calculating the spatial correlations between nodes.
- Goals
  - Obtaining estimations of locations of unknown nodes by the means of ranging or angular measurements or gravity sensing.

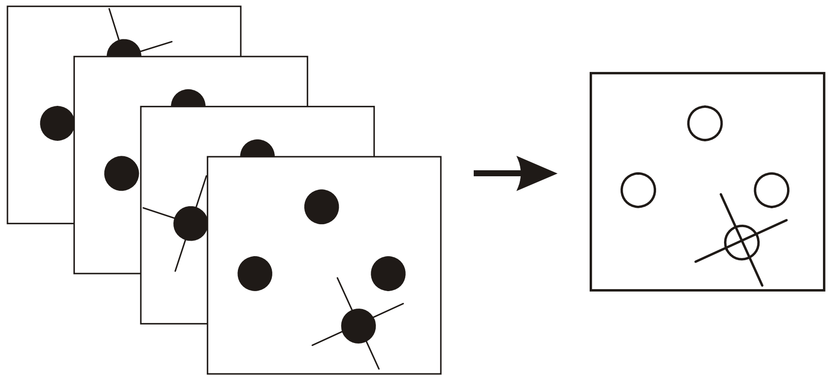
Rigidity: Uniquely identify sensor locations

- Rigidity Concept
  - Local capability of a distributed localization algorithm to find a unique location of every sensor node
  - Rigidity requirement is expressed in the minimum degree of node connectivity required by the algorithm to uniquely determine node locations
- Rigidity Requirements
  - Depend on the characteristics of the localization algorithm in use
  - Minimum Connectivity (MC) for rigidity for a specific algorithm
  - Greater connectivity than the minimum needed for good performance

Hardware capabilities	MC	Example
Single angle of arrival (AoA) /ranging (only one of two)	4	GPS, triangulation
Single AoA + ranging (both used)	3	DHL Algorithm
Two AoA's on $\perp$ planes + ranging	2	COBALT Algorithm
Two AoA's + range + gravity or magnetic north	1	COBALT Algorithm

COBALT: Clique-of-Nodes Based Localization Algorithm

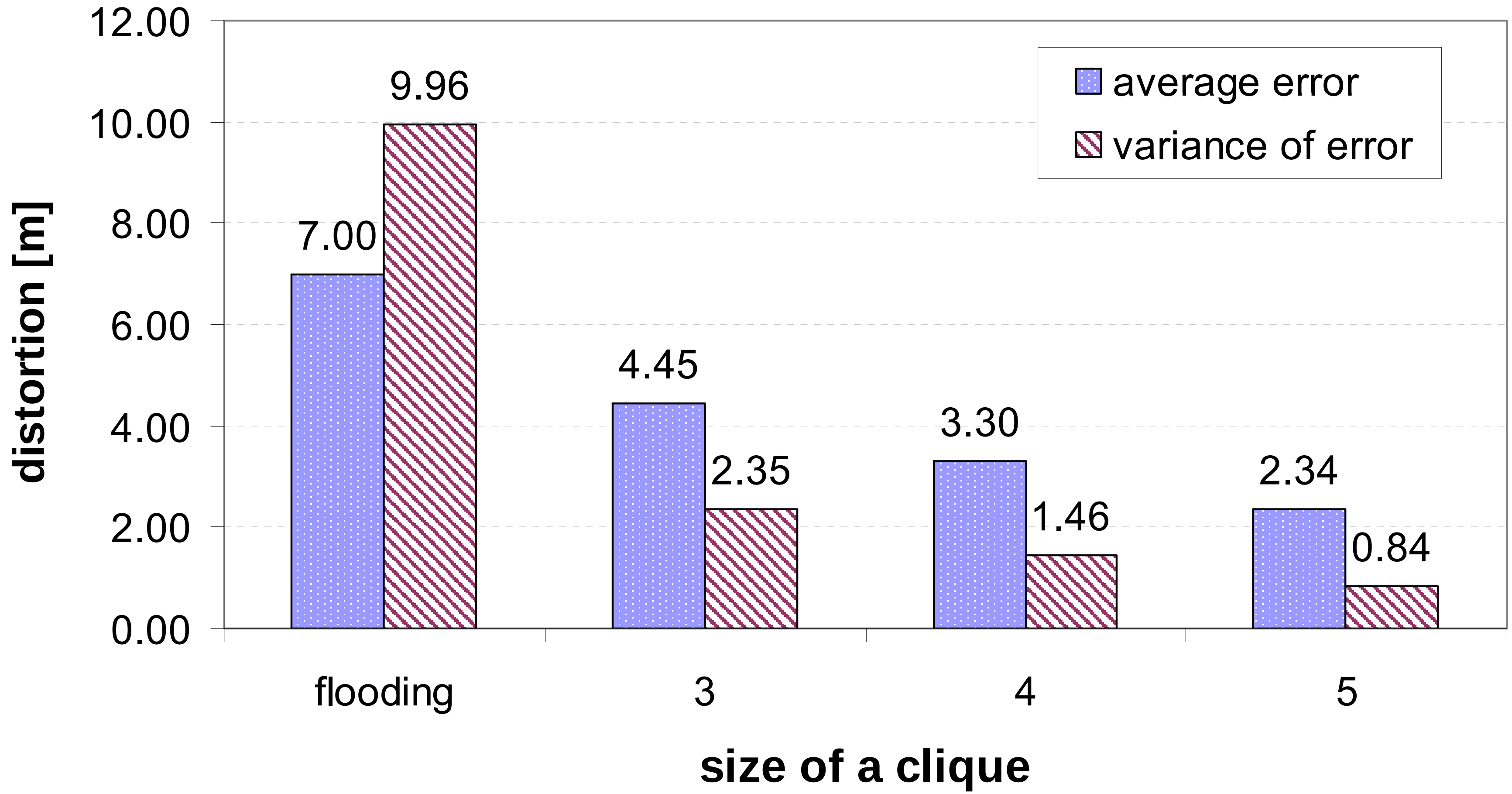
- Uses redundancy of groups of nodes (cliques) for eradicating location errors
- Require several location maps of a clique and merge them by MMSE
- Minimum connectivity: 1



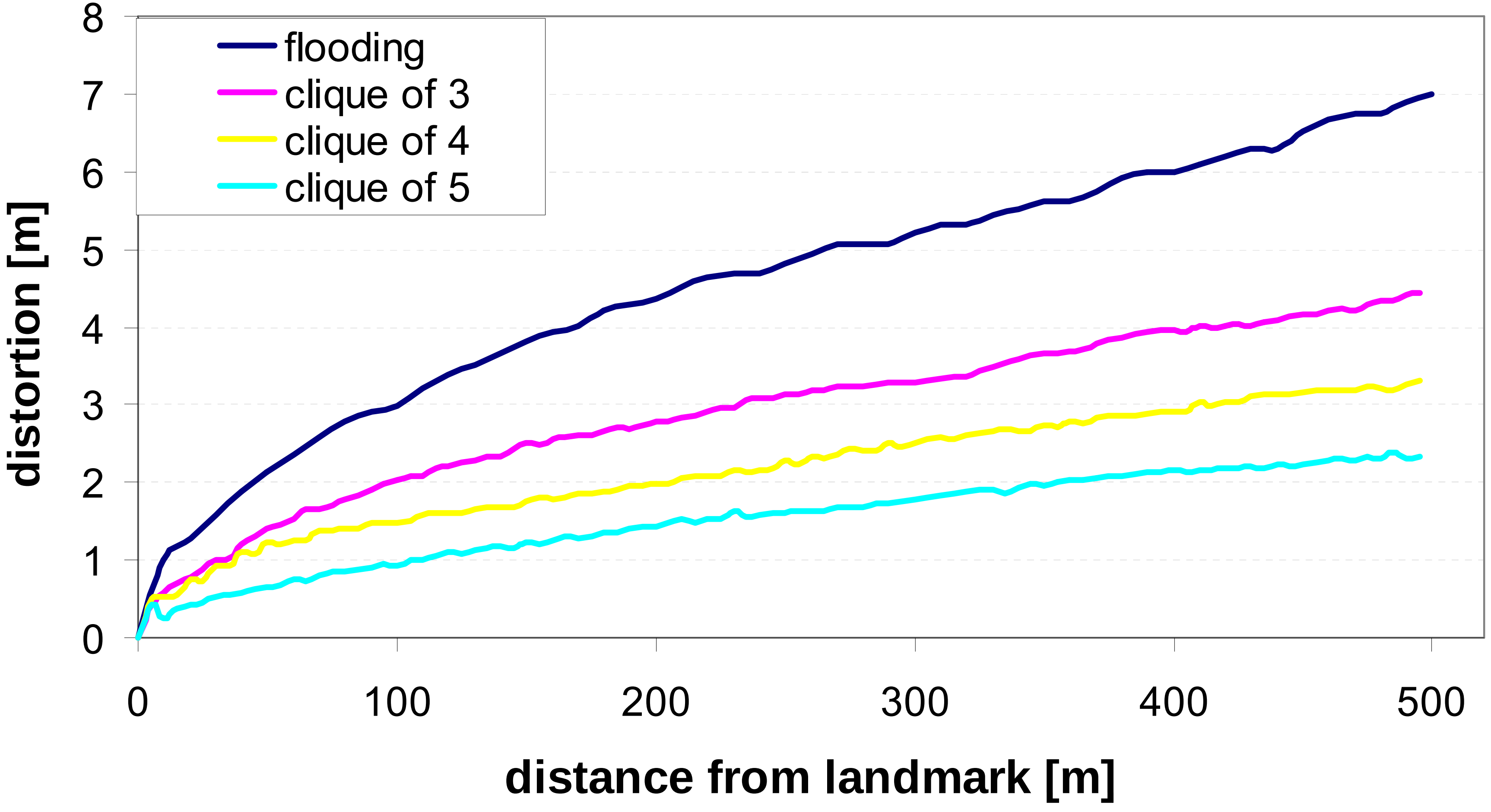
- Applicable for sensor networks with rich capabilities. The following capabilities are required for each sensor node:
  - 3-D antenna array for 2π-range azimuth and π-range elevation measurements
  - Ranging measurement, e.g., ToA or TDoA
  - Accelerometer (for earth gravity direction)

COBALT Performance: Simulation results

- Setting: 500 m of tunnel, average hop distance 10m



COBALT Performance (Cont'd)

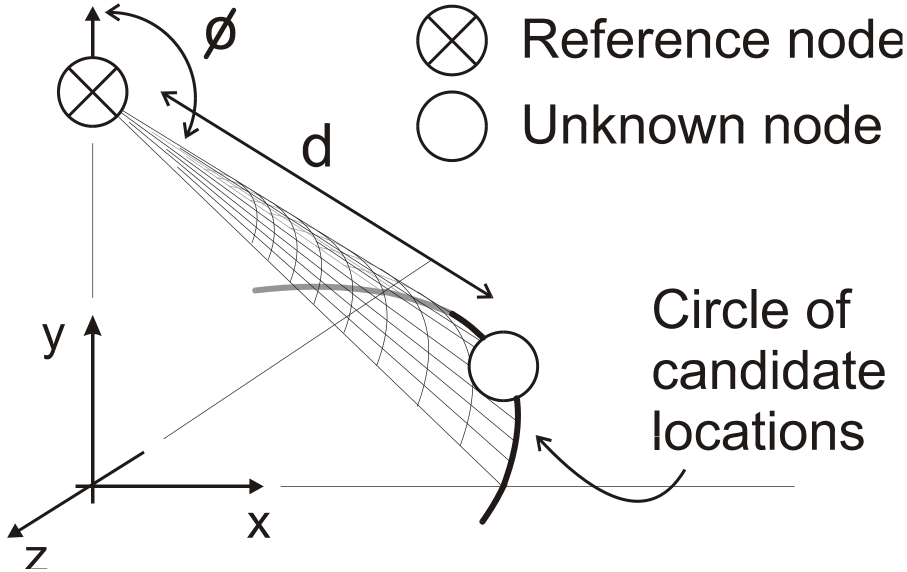


Depleted Hardware Requirement Localization (DHL) Algorithm

- Antenna array is reduced to linear antenna array
  - In particular, as little as 2-element array

- Minimum connectivity: 3

- Compromise between
  - COBALT hardware requirements and
  - Trilateration/triangulation connectivity requirement



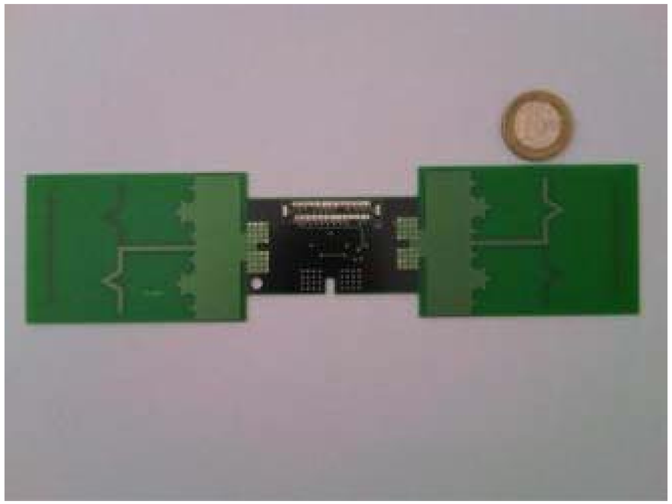
Summary of Contributions on Localization

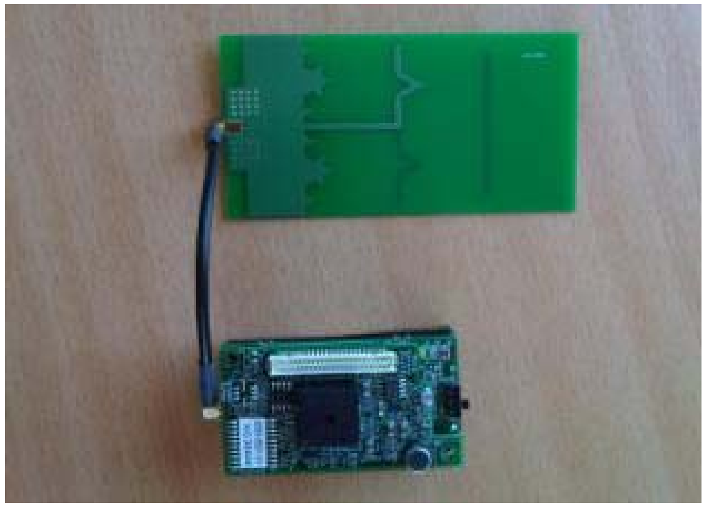
- Three algorithms proposed & studied
  - Error-eradicating COBALT algorithm (Clique-Of-nodes BAsed LocalizaTion) by use of redundancy available in groups of nodes (called cliques). Applicable for high redundancy of spatial measurements.
  - Using rich spatial information: Two angles + range + gravity direction – no network topological requirements. Always rigid: It works whenever the network is connected. Requires a complex antenna array.
  - DHL algorithm (Depleted Hardware Localization) uses simple, linear antenna array and ranging

Hardware Required	MC	Example
Single AoA /ranging (only one of these)	4	GPS, triangulation
Single AoA + ranging (both used)	3	DHL Algorithm
Two AoA on ⊥ planes (AoA) + ranging	2	COBALT Algorithm
Two AoA's + range + gravity or magnetic north	1	COBALT Algorithm

Prototyping of Localization Algorithm

- Prototyping partner: SignalGeneriX (Cyprus)
  - SignalGeneriX designed and produced the array of directional antennas for MicaZ
  - Imperial contributed by antenna measurements in the tunnel environment (Aldwych London Underground tunnel in August 2009)
  - Below: prototypes of 2 directional antennas (left picture), sensor node board connected to 1 directional antenna (right picture)





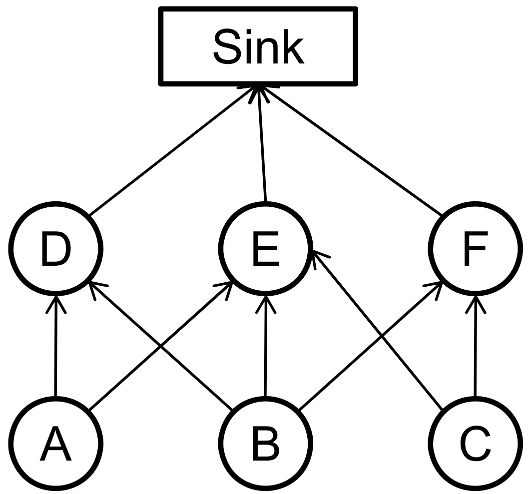
Localization demonstration with SignalGeneriX

- Demonstration objectives
  - Show newly designed and manufactured hardware
    - Directional antennas
    - MicaZ add-on for interfacing the antennas with MicaZ node
  - Use algorithm suitable for the hardware capability
    - AoA method is used
    - Simple form of error correction based on MMSE is performed
- Demonstration scenario
  - Three reference nodes with known positions
  - One node with unknown position

Demo works!

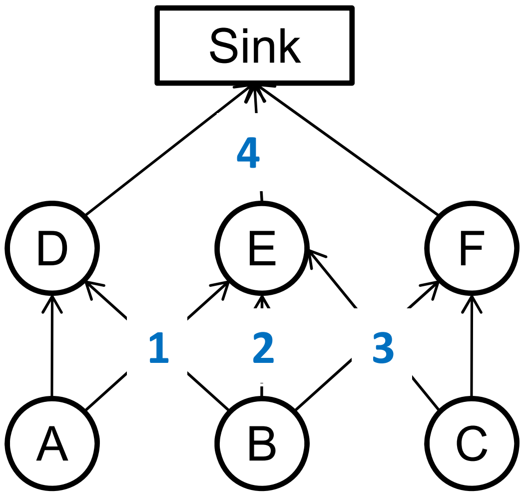
MAC Protocols: Monitoring Scenario

- Assumptions
  - A single data sink
  - Multi-hop network
  - Small batteries
  - Relatively slow-changing wireless links
  - Globally time synchronization
  - Event-triggered reporting of large volumes of data
- Application: large infrastructure
  - Fracture detection using acoustic emissions
    - Wires of the main cable from suspension bridge over the Humber
    - Concrete and steel bridges and tunnels
  - Vibration monitoring in tunnels and bridges

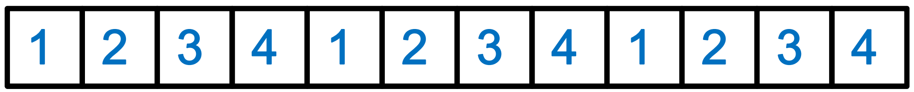


In-network data aggregation

- Assuming that data from neighboring nodes is correlated, thus can be aggregated and compressed inside the network
- Every node generally executes the following steps
  - Receive data from its neighbors
  - Aggregate received data with its own data
  - Forward compressed data towards the sink
- We propose two protocols. Their respective goals are deciding:
  - The route followed by the packets to be aggregated, which is a tree
  - The schedule for the packet transmissions

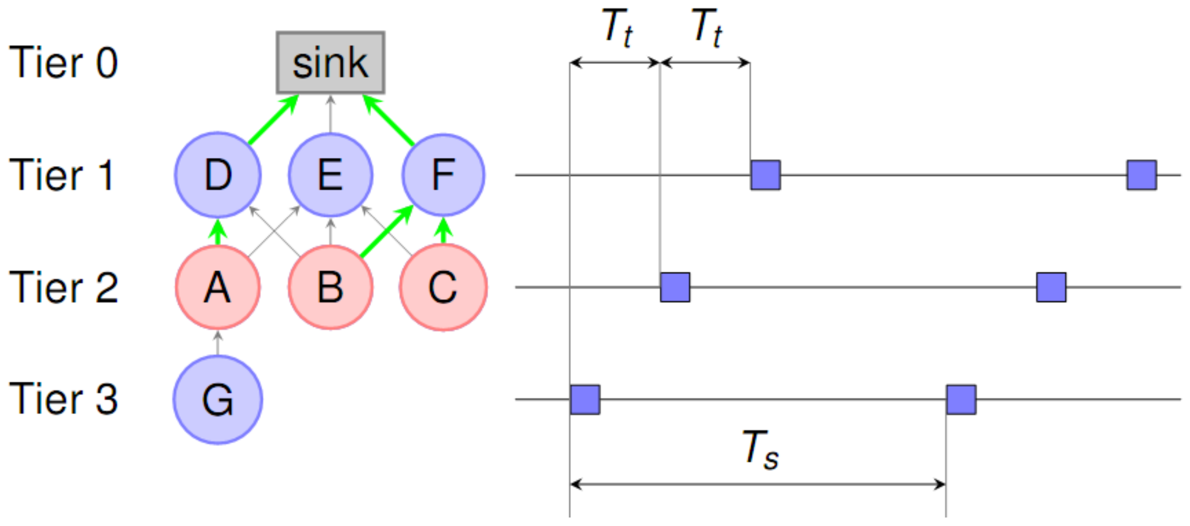


TDMA frame consisting of transmission slots



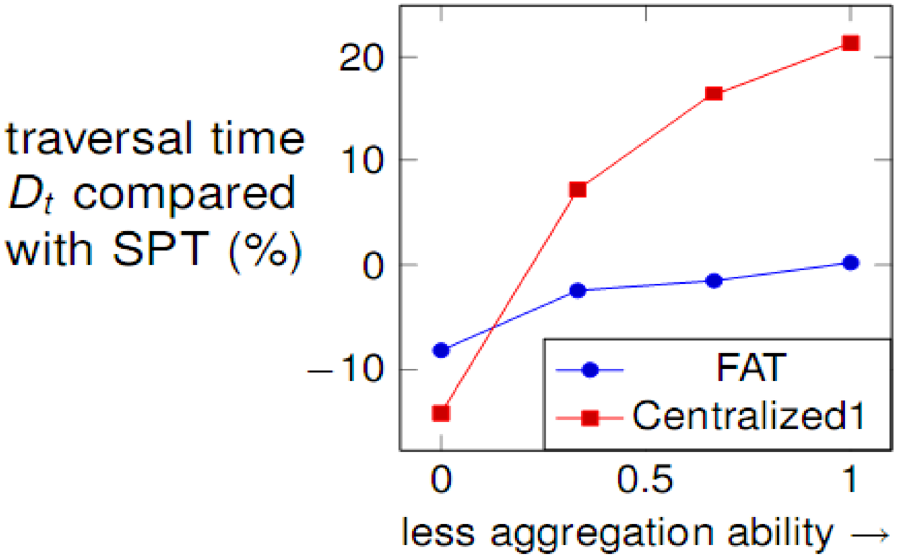
Fast Aggregation Tree (FAT) Protocol

- Goal of FAT
  - Quickly construct a data aggregation tree in a duty-cycled network
- Functioning
  - Radio transceivers of sensor nodes are turned on periodically with period T_s.
  - There is an offset of the schedules of nodes in different tiers
- Key advantage
  - Time to construct the tree is divided by the number of tiers
  - Therefore, nodes can sleep for longer periods and save energy



FAT Performance

- FAT's tiered architecture restricts possible parents, not optimal
- Traversal time is the time to transmit data, a measure of the quality of the aggregation tree
- SPT is the shortest path tree
- The algorithm Centralized1 is only good for high aggregation ability
- FAT is relatively good across all degrees of aggregation ability



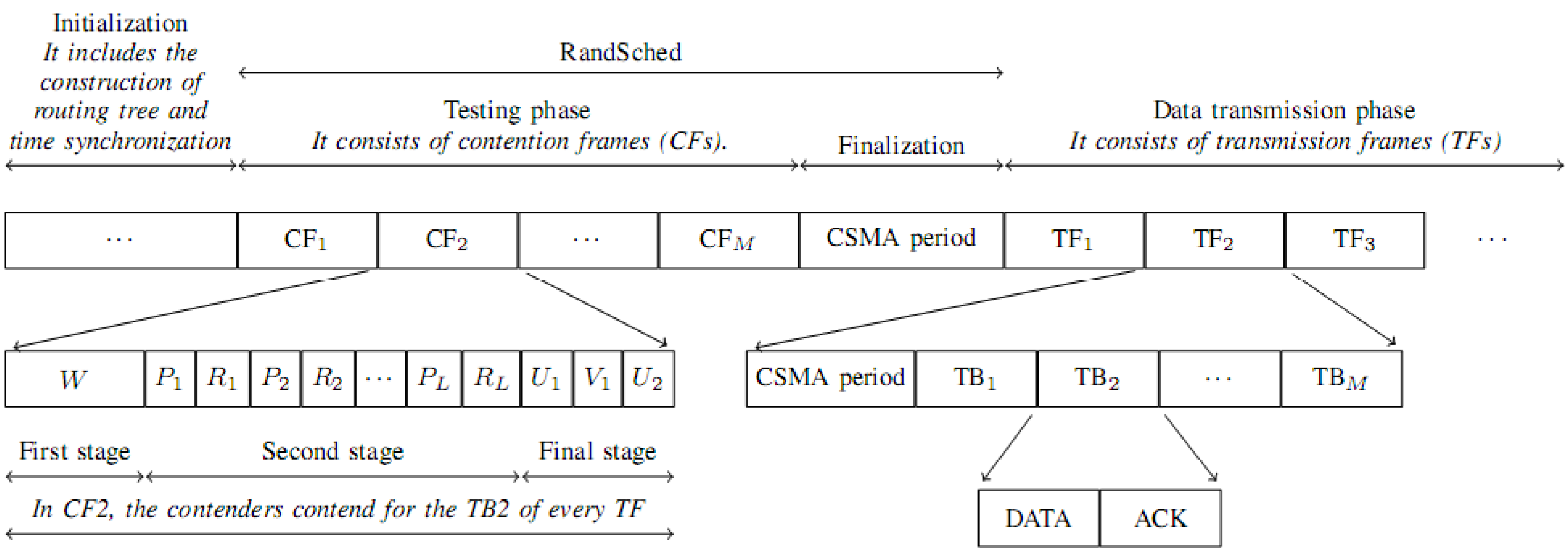
Two MAC Protocols: RandSched and TBSP

- Problems of the existing scheduling algorithms
  - Some of them are centralized
  - The obtained schedule may be infeasible
    - The *k*-hop interference model fails occasionally
    - The joint interference from multiple nodes may be unfeasible
    - Our simulation results are in the table below
    - BF*k* neglects the interference caused more than *k* hops away

	Fraction of unduly scheduled nodes		
ρ	BF2	BF3	RandSched
7	0.0796	$\approx 10^{-4}$	0 (theoretical)
14	0.0321	$< 10^{-4}$	0 (theoretical)
28	0.0098	$< 10^{-4}$	0 (theoretical)

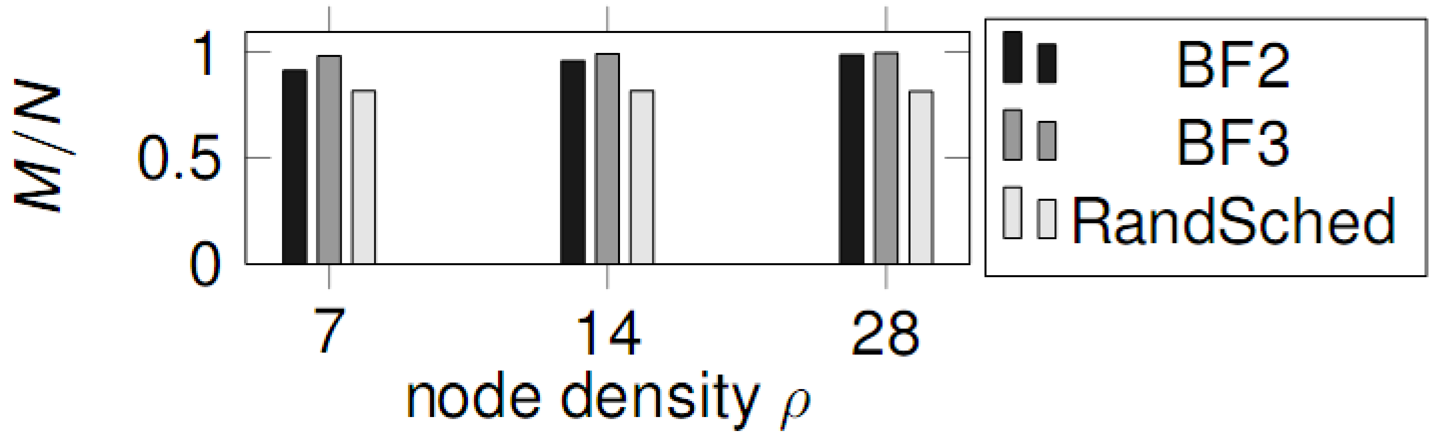
RandSched: Scheduling for data aggregation

- Distributed scheduling protocol
- Initialization phase
- Testing phase
  - In CF*i* it is decided which nodes gain access to TF*i*
  - A node only gains a transmission slot if it has been proved that it can tolerate other nodes' interference
- Data transmission phase



Properties of RandSched

- Medium overhead, but scale well because RandSched is a distributed protocol
  - 12 slots per Contention Frame (CF) are sufficient to decide the transmitters of a certain slot
  - This number of slots is independent of node density and network size
- Shorter schedule than BF*k* → lower latency and higher throughput (See figure below)
  - M is the number of slots of the schedule
  - N is the number of nodes in the network



Test Based Scheduling Protocol (TBSP)

- Differences with RandSched
  - Only supports uncompressed traffic (no data aggregation)
  - It is adaptive (it enables parts of the schedule to be recomputed without affecting other nodes' schedules)
- Targeted applications
  - Periodic data gathering with slowly-varying traffic
  - Latency of 15 TDMA frames to acquire a slot can be tolerated
- Advantage of TBSP over comparable protocols
  - Lower energy consumption (no need to monitor other nodes' schedules)
  - Lower probability of dismissing a neighbor as unreachable

Conclusions on MAC Protocols

- FAT constructs an aggregation tree in a duty-cycled environment quickly
- RandSched produces a TDMA schedule for data aggregation reliably
- TBSP adapts a TDMA schedule for uncompressed traffic with little power consumption
  - Uncompressed traffic is necessary in a preliminary data-collecting stage in order to determine how data can be compressed

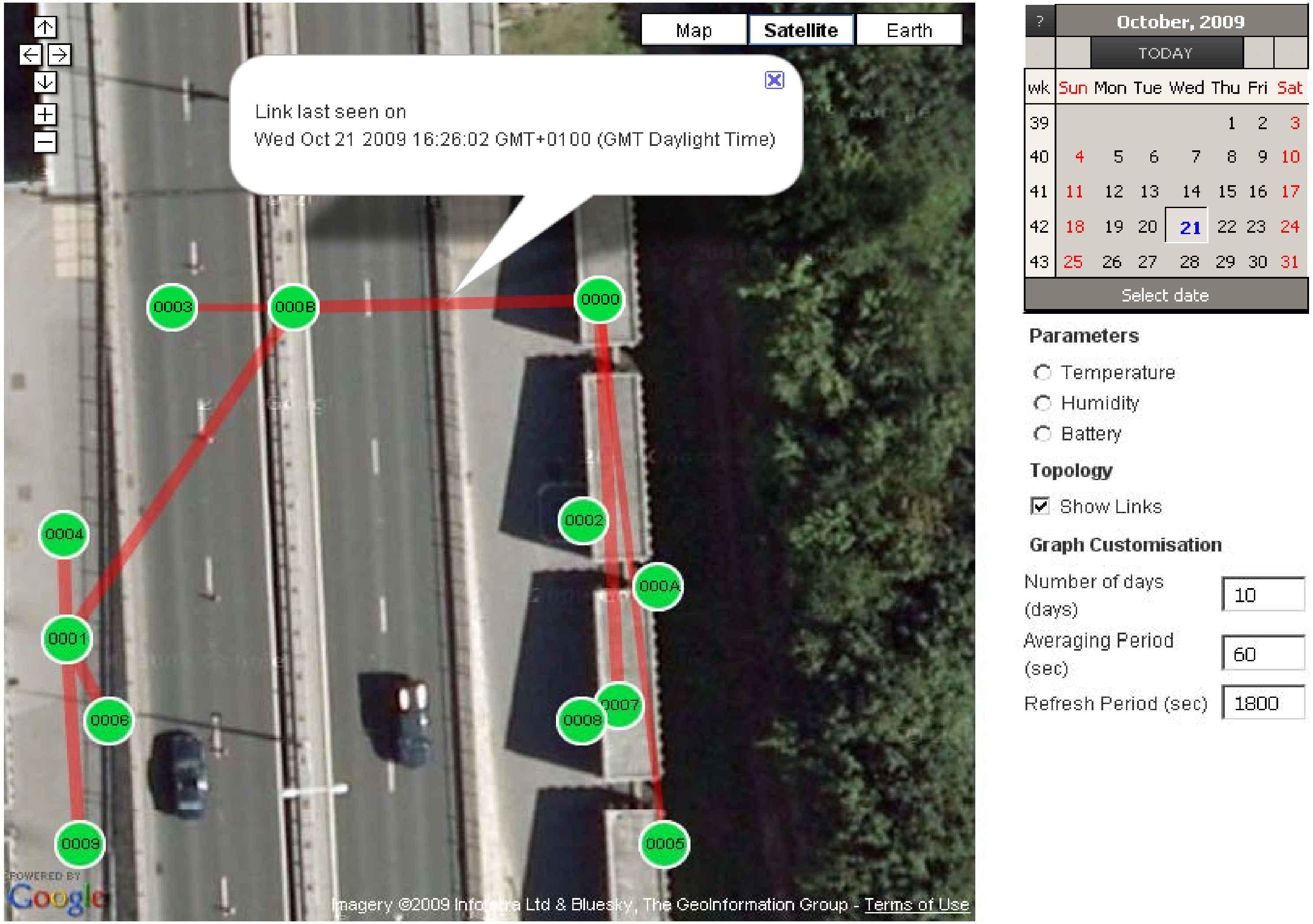
WINES: Smart Infrastructure

Backend Application

Web application architecture

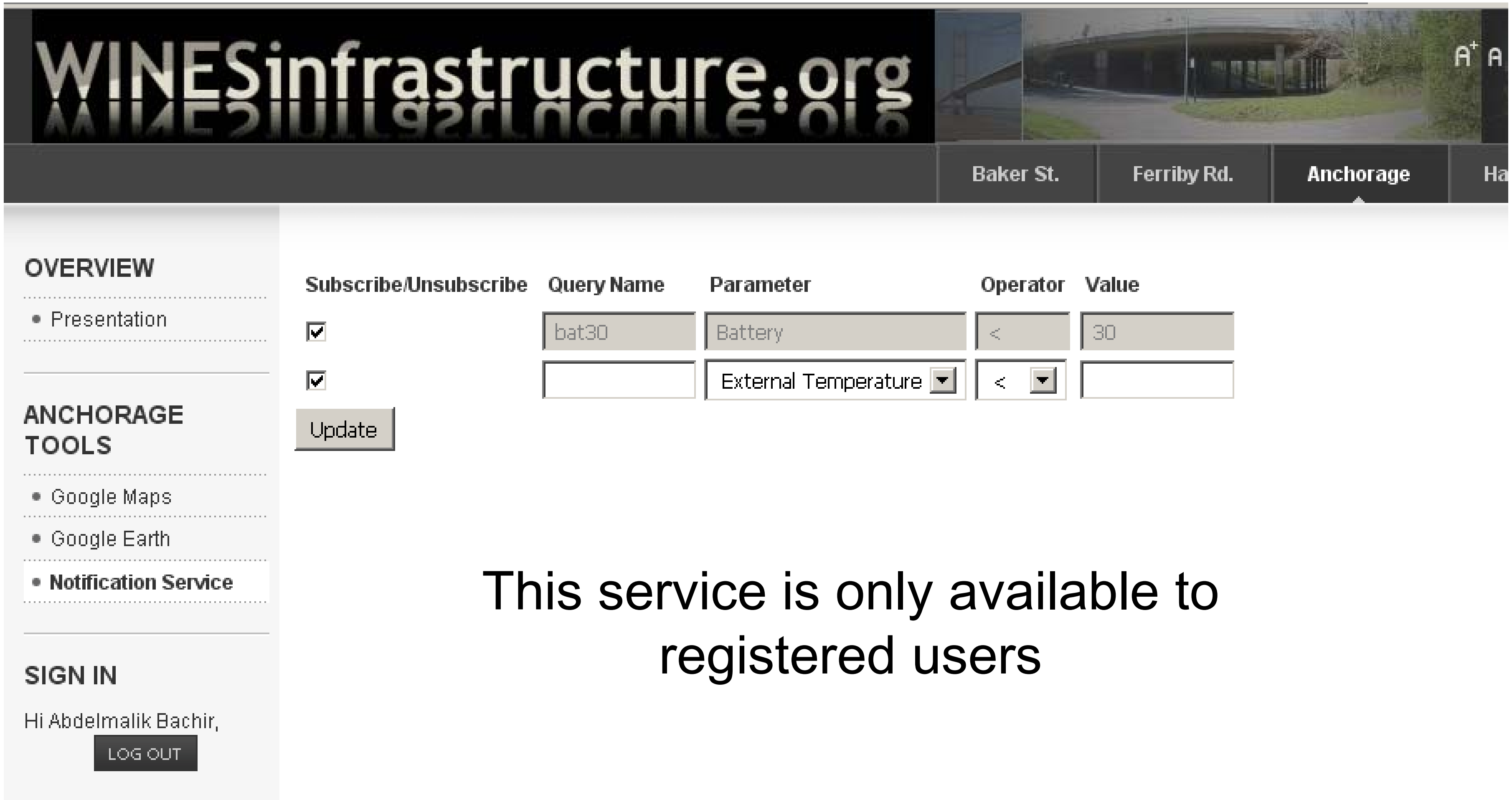
- Horizontal menu
  - WSN deployments
- Vertical menu
  - operations for the selected deployment
    - Google Maps
    - Google Earth
    - Notification
- Login screen
  - only users with a passphrase can register
  - only registered users can use notification service

Google Maps - Example



Google Earth - Example

Notification service - Example



This service is only available to registered users

Notification Service

- a javascript dynamic webpage for each deployment
  - Accessible only for authorized users
- a set of input boxes for users
  - To set simple queries
  - Specify parameter operator value
    - e.g. External temperature > 15
- an ergonomic interface for add/deleting queries
  - Just check or uncheck tick-boxes
  - Previous queries are in grayed input boxes to avoid unintentional modification