Wireless Sensor Networks: Protocols, Optimization and Applications

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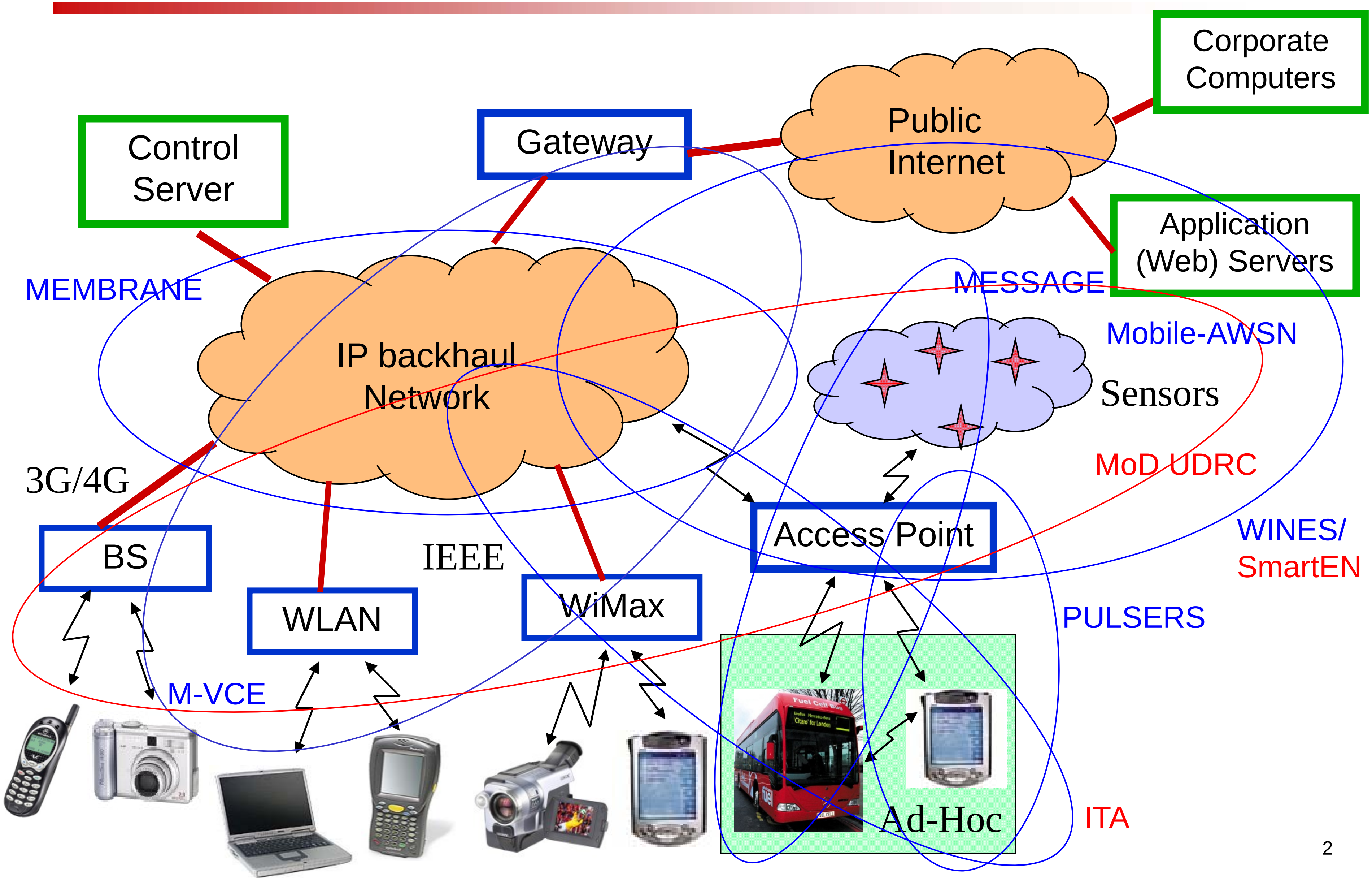
Current Wireless Communications and Sensor Research



Smart Infrastructure:
Wireless sensor network system for condition assessment and monitoring of infrastructure

UNIVERSITY OF CAMBRIDGE

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Aging Engineering Infrastructure

- **Water Supply and Sewer Systems**

  Thames Water
  - **31,000 km of pipelines**
  - **½ more than 100 yrs old, 1/3 more than 150 yrs old, ~30% leakage**

  Difficulties in implementing RTC with conventional technologies

- **Tunnels**

  London Underground (LUL)
  - **Tunnels 75 – 100 yrs old**
  - **Deterioration of linings**
  - **Minimal clearance to tunnel wall**
  - **Risks from 3rd party construction**

  Four of the UK's busiest road tunnels are among the 10 most dangerous in Europe (Blackwall Tunnel)

- **Bridges**

  Highway Agency/LUL/ Humber Bridge
  - **~150,000 bridges in UK**
  - **Critical links in road/rail infrastructure**
  - **Deterioration**
  - **Many structures below required strength**



Oxford Street

LUL tunnel

Blackwall Tunnel

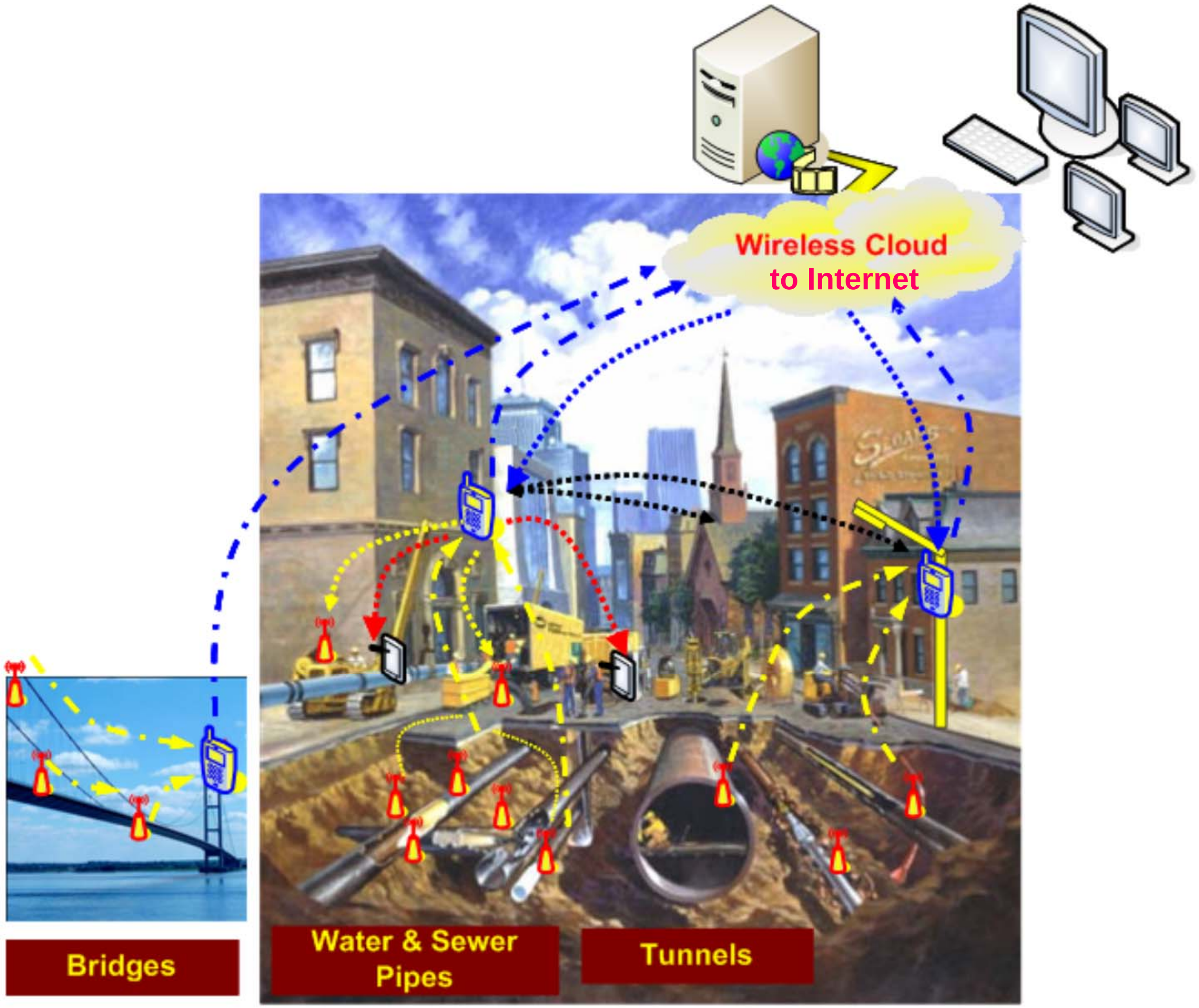
Collapsed Tunnel

The Humber Bridge

Generic/Pervasive Sensor Networks

<u>Major goal of this project:</u> Generic/Pervasive sensor networks

- Sharing of equipment for monitoring of multiple types of infrastructures
- Exploit common characteristics of different infrastructures to advance sensor network design



- **Data analysis**
- **Device, network & service management**

Communications

Tiered structure and adaptive network topology
Scalable protocol design
Efficient, secure and robust

Sensors

Low-power, low-cost
Reliable performance

Advantages of Wireless

- Low-cost and fast deployment, especially in difficult-to-access areas
- Scalable: Enable dynamic system growth and extension
- Adaptive network configuration and operation in case of failure and unexpected events, resulting into improved reliability
- Take advantage of low-cost and low-power sensors

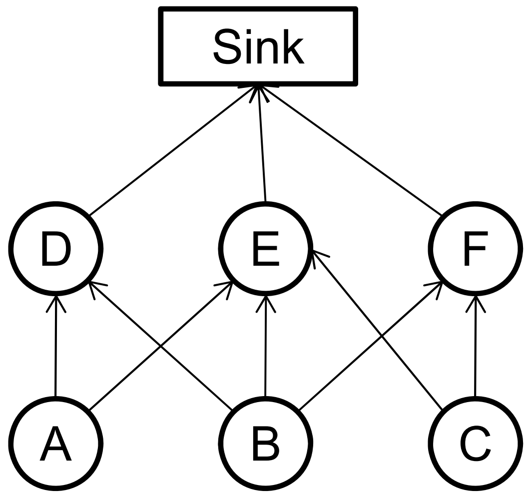
Two Small-scale Deployments as Proof-of-Concept

Research Challenges for Large-Scale Wireless Sensor Networks (WSN)

- **Scalability and adaptability**
  - Cross-layer protocol design
  - Protocols linking WSN and Internet for management and control
- **Efficiency**
  - Limited power supply
  - Harsh radio propagation environments
  - Tradeoffs between communication and computation
- **Security and reliability**
  - Distributed network architecture with no single point of failure
  - Protection measures against attacks and for privacy
  - Low-power public key cryptography
- **Testing and deployment in real operating infrastructures**
  - Not an easy task!
  - Asset owners have committed to provide assistance

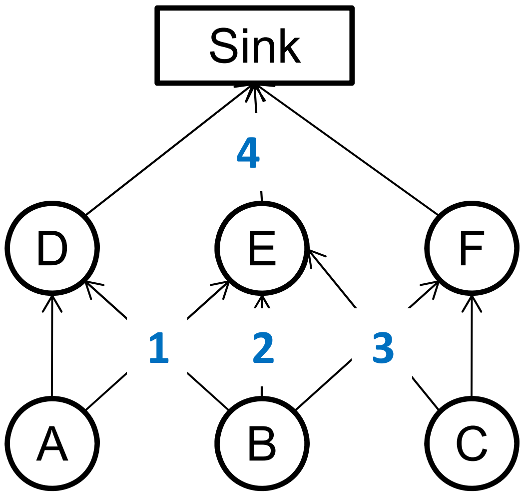
MAC Protocols: Monitoring Scenario

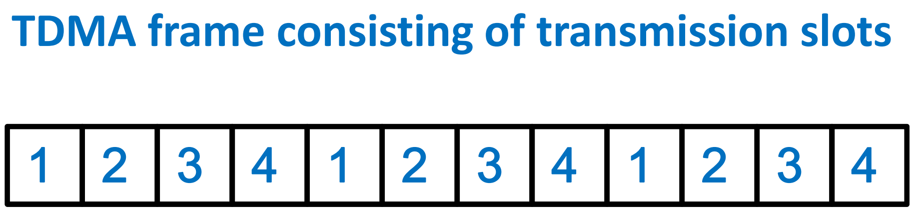
- Assumptions
  - A single data sink
  - Multi-hop network
  - Small batteries
  - Relatively slow-changing wireless links
  - Globally time synchronization
  - Event-triggered reporting of large volumes of data
- Application: large infrastructure
  - Fracture detection using acoustic emissions
    -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



In-network data aggregation

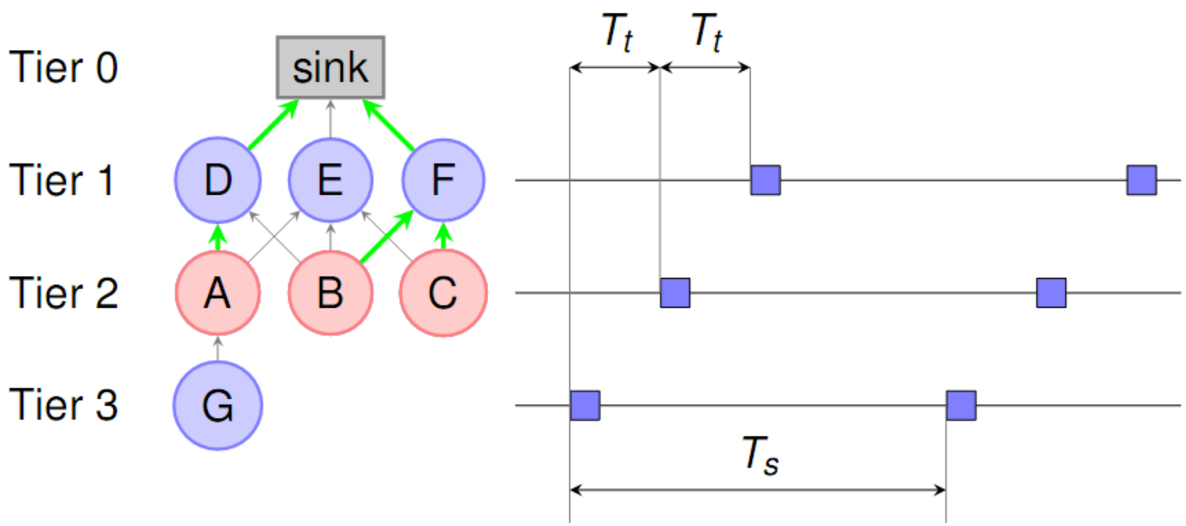
- Assuming that data from neighboring nodes is correlated, thus can be aggregated and compressed inside the network
- Every node generally executes the following steps
  - Receive data from its neighbors
  - Aggregate received data with its own data
  - Forward compressed data towards the sink
- We propose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





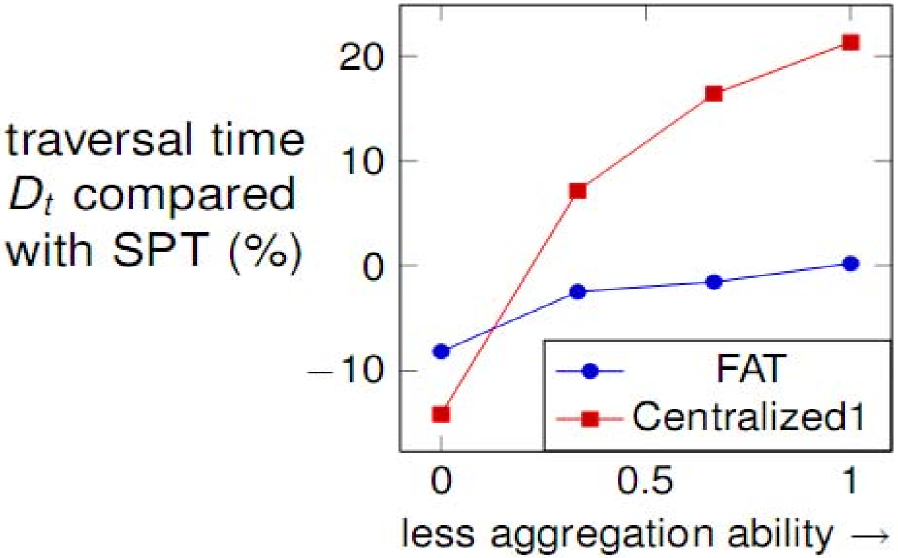
Fast Aggregation Tree (FAT) Protocol

- 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



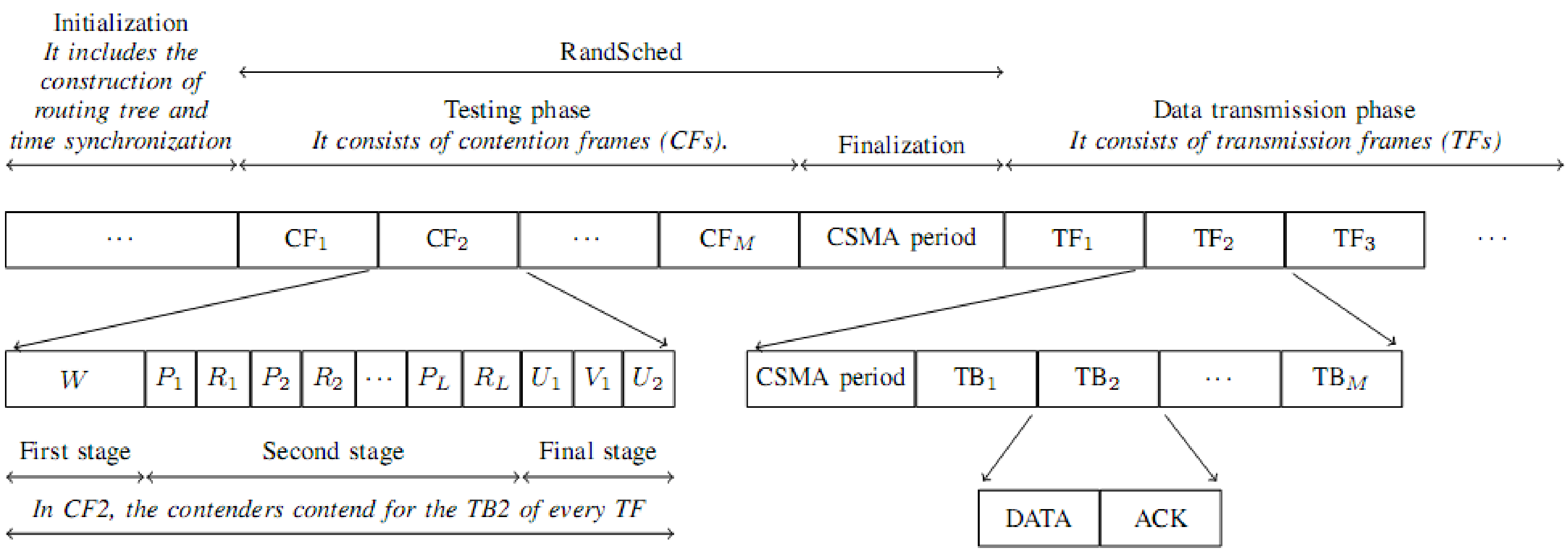
Two MAC Protocols: RandSched and TBSP

- 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 infeasible
    - 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)

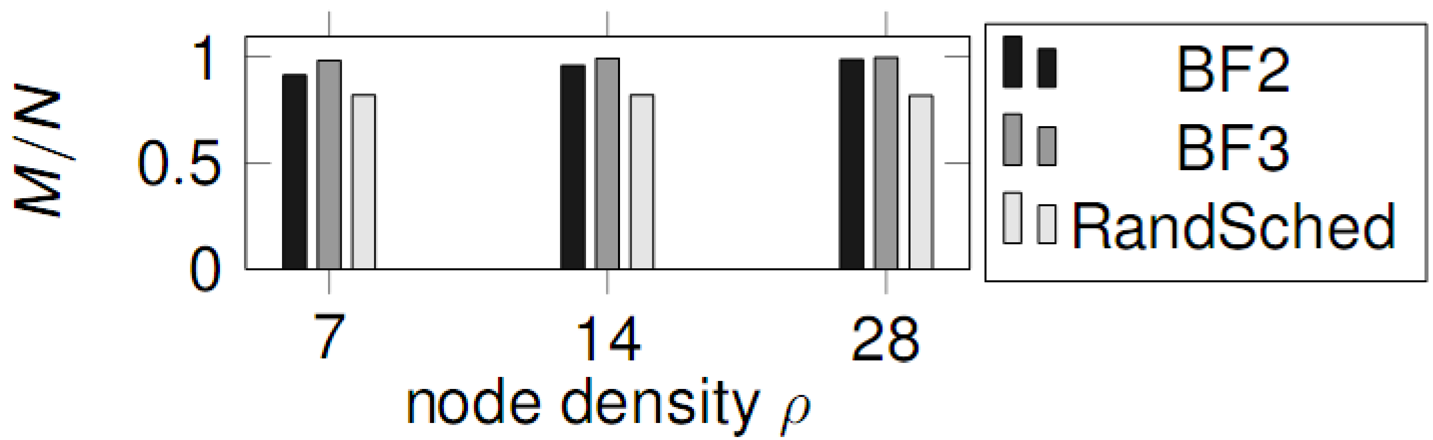
RandSched: Scheduling for data aggregation

- 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

Optimal Resource Allocation for Battery Limited Wireless Sensor Networks

Yun Hou (Imperial College)
Kin K. Leung (Imperial College)
Tom LaPorta (PSU)

ITA Project (Sponsored by U.S. Army & U.K. MoD)

Background

NUM:
Max ∑U(x)
x= resources

Wired networks
Max U over (Rate)

→

Wireless networks
Max U over (Rate, Power)

↓

Wireless single radio networks
Max over (Rate, Power, Per-node Airtime)
Because: Multiple flows served by the same node share the airtime [1]

This new work:

Battery limited scenarios, how long a flow can be active is related to transmission power

- Flow duration added into as another optimization variable
- Max U over (rate, power, airtime, flow-duration)

[1] Yun Hou, Kin K. Leung and Archan Misra, "Enhancing Congestion Control with Adaptive Per-Node Airtime Allocation for Wireless Sensor Networks," Proc. of IEEE PIMRC 2009, September 13-16, Tokyo, Japan.

Motivation

- Sensor networks – battery limited
- Current NUM objective function

$$U_f = U(X_f)$$

Utility as a function of flow rate only

- But:

  Large flow rates → high transmission power → battery runs out quickly!!

- We introduce:

■ A new utility to consider both flow rate and duration

$$\max U(X_f \cdot \tau_f) \longrightarrow \text{Flow duration}$$

■ A new energy constraint

$$\text{s.t. } P_n \cdot \tau_f \leq E_n \longrightarrow \text{Residual energy}$$

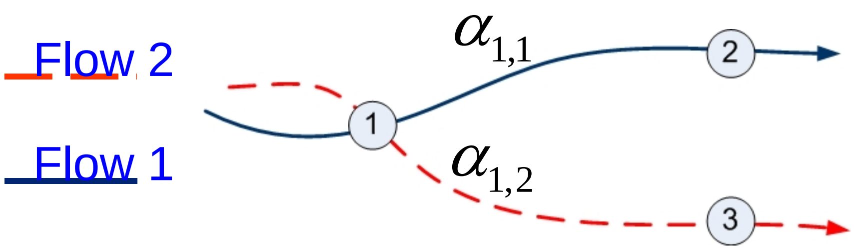
System settings

Single-radio Sensor:

A node can transmit for one flow at a time

Multiple flows going through the same node

⇒ **Flows are scheduled one by one**



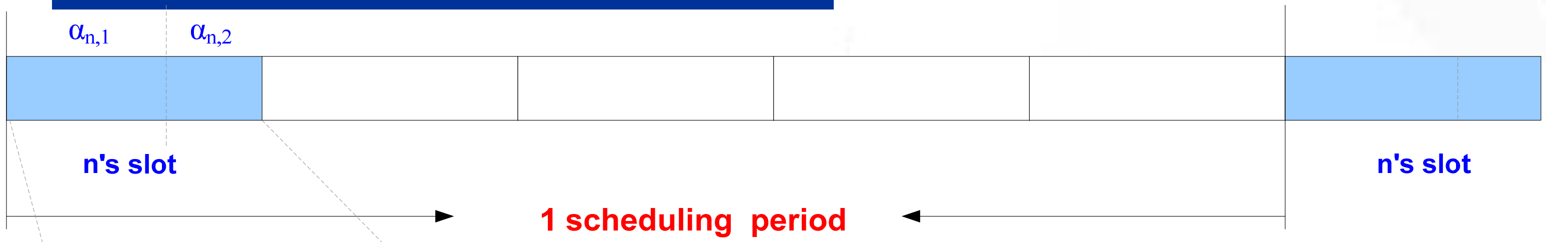
(n, f) link originated from node n on flow f

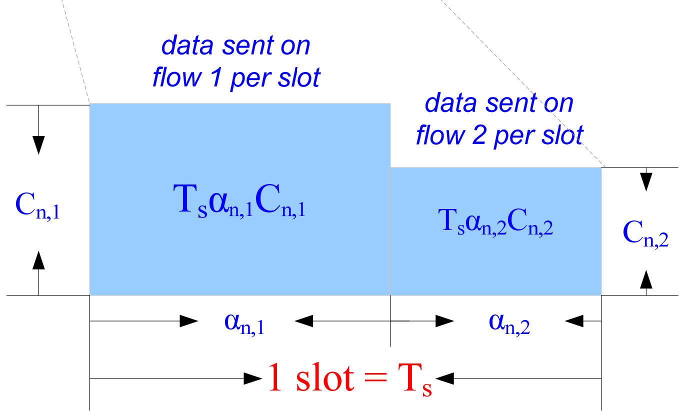
$\alpha_{n,f}$ airtime fraction of flow f on node n

All flows "share" the air-time of the node

$$\sum_{f:\, n\in Path(f)} \alpha_{n,f} = 1$$

System settings





Periodic scheduling, 1 slot per node throughout the period

A node divides its slot to transmit all flows using the same **power**, then

Total number of slots a node can transmit:

$$E_n / (P_n \cdot T_s)$$ → New constraints

Capacity $C_{n,f}$ for various flows at a same node are different

Amount of data (n, f) can send in one slot

$$T_s \cdot \alpha_{n,f} \cdot C_{n,f}$$

P_n transmission power of node n

T_s length of one time slot

τ_f number of time slots that flow f lasts

E_n residual energy of node n

Problem formulation

Two Constraints:

Flow rate and duration are determined by the minimum values along the path

$$X_f \le \min_{n \in Path(f)} \{\alpha_{n,f} C_{n,f}\} \quad \text{and} \quad \tau_f \le \min_{n \in path(f)} \{E_n / (P_n \cdot T_s)\} \quad \forall f$$

rate constraint *duration constraint*

They are equivalent to:

$$X_f \le \alpha_{n,f} C_{n,f} \quad \text{and} \quad \tau_f \le E_n / (P_n \cdot T_s) \quad \forall f \text{ and } n \in path(f)$$

The final formulation:

$$\max_{X,P,\alpha,\tau} \sum_f U_f = \sum_f \log\left[T_s \left(X_f \cdot \tau_f\right)\right]$$

proportional fair among flows

total amount of data transmitted on flow *f*

$$s.t. \quad X_f \le \alpha_{n,f} \cdot C_{n,f} \quad \forall f \text{ and } n \in path(f)$$

$$\text{and} \quad \tau_f \cdot P_n \le E_n / T_s$$

Concavity/convexity analysis

To show: objective function is concave and constraints are convex

Objective function: $\max_{X,P,\alpha,\tau} \sum_f U_f = \sum_f \log\left[T_s\left(X_f \cdot \tau_f\right)\right]$

$$\sum_f \log T_s + \sum_f \log X_f + \sum_f \log \tau_f$$

⇒ concave

Constraints: $s.t.\ X_f \le \alpha_{n,f} C_{n,f}$ and $\tau_f \cdot P_n \le E_n / T_s \quad \forall f$ and $n \in path(f)$

Proved in ACITA 09

⇓

convex

Geometric programming

$\tau_f^{'} = \log \tau_f \quad P_n^{'} = \log P_n$

⇓

$e^{\tau_f^{'} + P_n^{'}} - E_n / T_s \le 0$

⇒ convex

The algorithm (Ts = 1)

Forwarding nodes:

1. update the shadow prices for flow rate and duration

$$\lambda_{n,f}(t+1) = \left[\lambda_{n,f}(t) - \gamma_{\lambda}\left(\alpha_{n,f}C_{n,f}(t) - X_f(t)\right)\right]^{+} \quad \text{and} \quad \mu_{n,f}(t+1) = \left[\mu_{n,f}(t) - \gamma_{\mu}\cdot\left(E_n - \tau_f(t)P_n(t)\right)\right]^{+}$$

2. update the transmission power

$$P_n(t+1) = P_n(t) + \gamma_P\left(\frac{1}{P_n(t)}\sum_{f\in Flow(n)}\lambda_{n,f}(t)\alpha_{n,f} - \sum_{e\neq n} M_e(t) - \sum_{f\in Flow(n)}\mu_{n,f}(t)\tau_f(t)\right)$$

2. update the airtime fractions

$$\alpha_{n,f}(t+1) = \left[\alpha_{n,f}(t) - \gamma\left(\alpha_{n,f}(t) - \eta_{n,f}(t)\Big/\sum_{e\in F_n}\eta_{n,e}(t)\right)\right]^{+}$$

Source nodes:

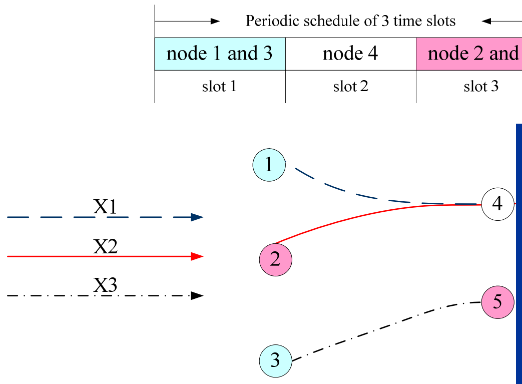
1. Update the flow rate

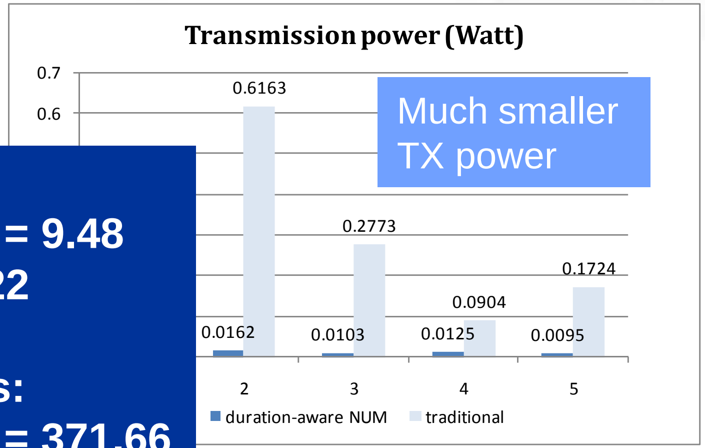
$$X_f(t+1) = \frac{1}{\sum_{n\in Path(f)}\lambda_{n,f}(t+1)}$$

2. Update the flow duration

$$\tau_f(t+1) = \frac{1}{\sum_{n\in Path(f)}\mu_{n,f}(t+1)P_n(t+1)}$$

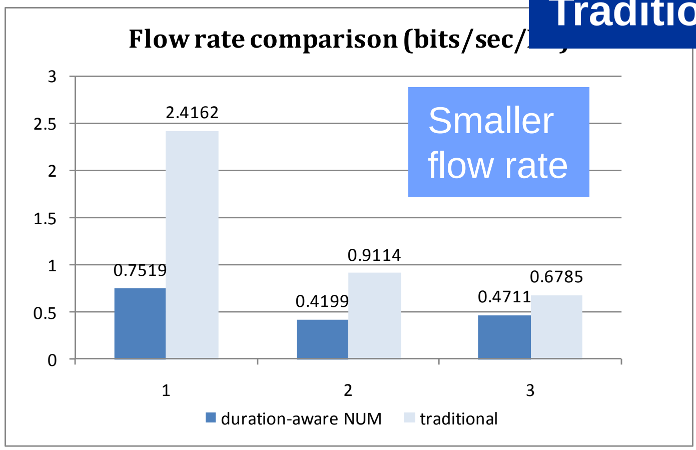
Numerical results

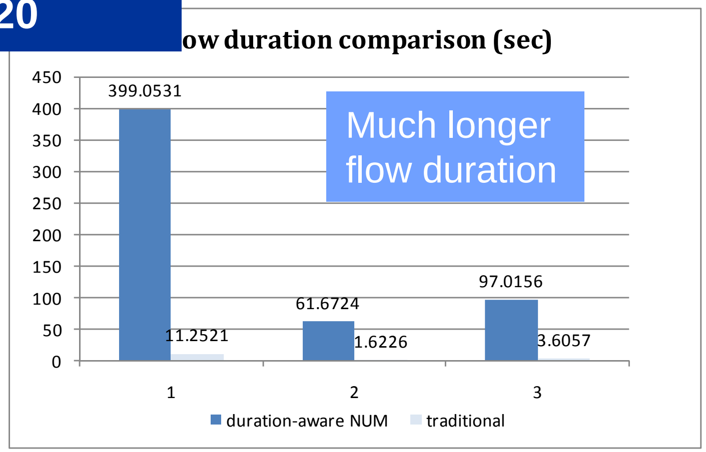


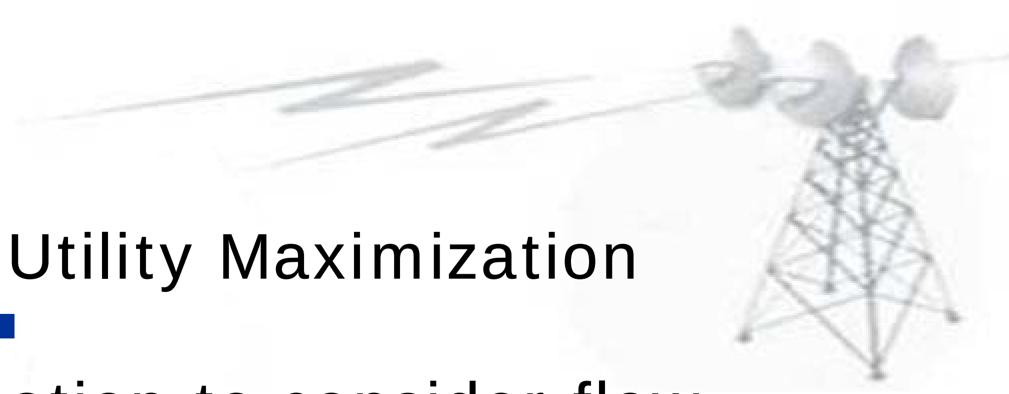


Utility:
Duration-aware = 9.48
Traditional = 1.22

Transmitted bits:
Duration-aware = 371.66
Traditional = 31.20







Conclusion on Network Utility Maximization

- A new resource allocation to consider flow duration together with flow rate
- The problem is formulated with four variables (rate, power, airtime-fraction, duration)
- Concavity of the problem has been proved and a distributed algorithm has been developed
- Simulation results show
  - When total amount of data is to be maximized, the new NUM framework gives the optimal solution
  - When energy is limited, the new NUM tends to give very small power allocation to prolong flow duration

WSN issues for future research

- Combine continuous and discrete distributed optimization
  - Continuous: NUM, rates, power, air time, flow duration, etc.
  - Discrete: transmission schedule (MAC), routing, data-aggregation path, etc.
- Network coding
  - How to take advantage of network coding for efficient data transfer and aggregation?
  - Physical-layer network coding possible?
- Transport protocols
  - Simple transport protocol for reliability and in-network data aggregation
- ....

Thank you