TARA: Topology-Aware Resource Adaptation to Alleviate Congestion in Sensor Networks

Presented by Smith & Klein
ODU-CS895 Mobile Computing

Background[1]

- Application: Remote Sensors (vs cell phones, e.g.)
- Sensor net nodes unaware of topology characteristics
- Congestion arises from standard, 2-state implementation
  - Dormant State
    - Conserves energy (lengthens net lifetime)
    - Characterized by low traffic volume
    - Limited number nodes (routing path) concurrently active
  - Crisis State
    - High traffic volume
    - More data coming in than nodes can handle = congestion
    - Data loss may occur (dropped packets) → loss of "fidelity"

[1]Note: Includes intro & related work sections

Background (continued)

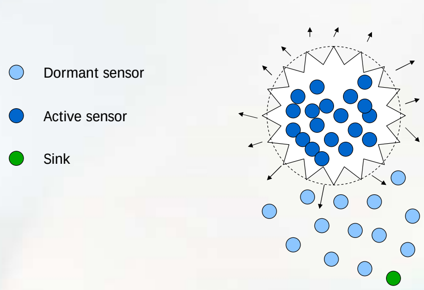
- Traditional traffic control methods are unacceptable
- Most address capacity (traffic control)
  - CODA, congestion detection/avoidance
  - Proportional bandwidth allocation
  - Limit source rate
  - Flow control
- Some ~address fidelity (via traffic control)
  - Event-to-Sink Reliable Transport protocol (ESRT)
  - Prioritized medium access control (MAC)
- Ideal: Balance fidelity & capacity
  - Reducing source traffic → critical information lost
  - Problem occurs from topology-unaware aspect
  - Awareness is hard problem
    - Need end-to-end network knowledge
    - Need local picture, too

Congestion in Sensor Networks

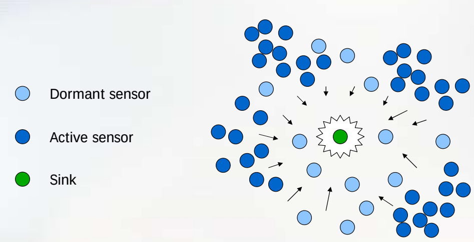
- Congestion = incoming data > transmission capacity
- 3 Typical hot spot scenarios:
  1. Source Hot Spot
  2. Sink Hot Spot
  3. Intersection Hot Spot
     - Merging traffic
     - Crossing traffic
- Sensor nets are dynamic
  - Deployment strategies can mitigate source & sink hot spots
  - Intersection hot spots need ad hoc solutions

Consider the examples on the following slides

Scenario 1: Source Hot Spot

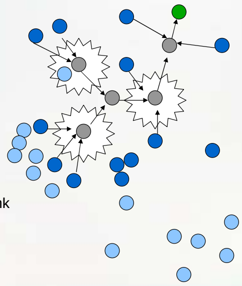


Scenario 2: Sink Hot Spot



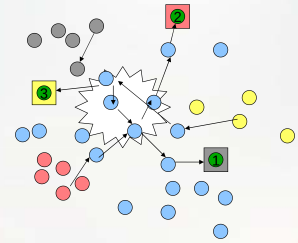
Scenario 3a: Intersection Hot Spot (Merging Traffic)

- Dormant sensor
- Active sensor
- Sink
- Sensor on route to sink



Scenario 3b: Intersection Hot Spot (Crossing Traffic)

- Path/dormant sensors
- Sinks (1, 2, 3)
- Sensors: source #1
- Sensors: source #2
- Sensors: source #3

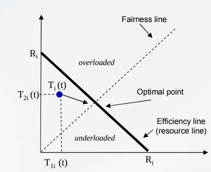


Traffic Control vs Resource Control

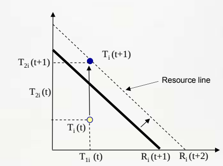
- **Traffic Control**
  - **Lots of research in this area**
  - **Assumes fixed resource provisioning**
  - **AQM used in wired networks**
  - **Resource utilization and fairness (balancing data volume with resource availability for optimal result)**
  - **Not as practical in sensor nets because of sensor net lifecycle is dynamic (varies with input, battery life, interference, etc)**
- **Resource Control**
  - **Goal is fidelity management (get key data through)**
  - **Bring extra resources on line when they're needed**
  - **Few efforts geared toward this aspect**

Effective resource control requires topology awareness – which ones to turn on/off to maintain optimal performance

Frameworks of traffic control and resource control



(a) Traffic control



(b) Resource control

- Optimal efficiency occurs when

$$T_{1i}(t) + T_{2i}(t) = R_i$$

- This is when traffic = resource availability
- Unrealistic for sensor net

- Resource availability varies with time

$$R_i(t+1) \rightarrow R_i(t+2)$$

- More resources are allocated to higher fidelity-requirement path

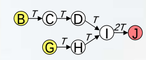
Capacity Analysis Model Description

- **Capacity = max throughput of sinks**
  - **Less than perfect 1-hop max because of interference**
  - **TARA estimation based on theoretical optimum**
    - **$(m/n)C^{max}$**
    - **(m/n) is the capacity fraction (m=n in 1-hop)**
    - **C^{max} is the 1-hop maximum throughput**
- **4 mapping steps to estimate capacity**
  1. **Topology map**
  2. **Spatial interference graph**
  3. **Spatial reuse graph**
  4. **Colored graph**
  5. **Time frame assignment**

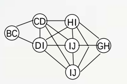
Capacity Analysis Model: Graph Example

- **Core of the TARA approach**
- **Estimates end-to-end throughput of different topologies**
- **Uses graph-coloring method to solve**

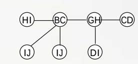
Goal: Capture the degree of interference of a given topology



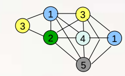
Topology Graph



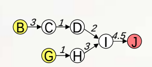
Spatial Interference Graph



Spatial Reuse Graph



Colored Graph



Time Frame Assignment

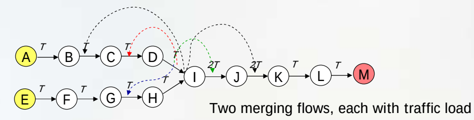
Estimating Capacity (for a Large-Scale Network)

- Number of nodes has big impact on time
  - Graph coloring takes time to solve
  - NP hard problem
- Re-image the topology in terms of bottleneck links
  - Reduces number of nodes addressed
- Calculate only the capacity fraction of bottleneck
  - This will be a smaller subset
  - Can be calculated within acceptable time limits

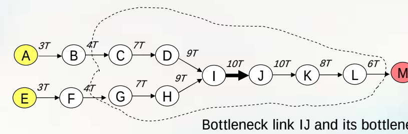
Finding Bottlenecks

Congestion Sum **of a link indicates if it is a bottleneck**

Bottleneck Zone **is much smaller than whole topology**



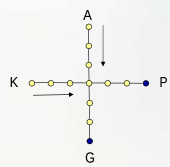
Two merging flows, each with traffic load T

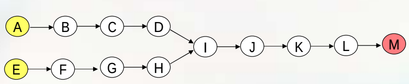


Bottleneck link IJ and its bottleneck zone

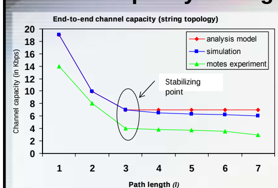
Topologies

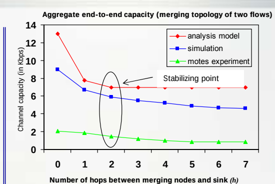
- Intersections occur in many topologies
- Three key types are considered
  - String
    - One path from I to J to K to M
    - Loss of data due to "full" path
  - Merging
    - Path from A to M and E to M intersect at I
    - Sink can become overloaded
  - Crossing
    - Path from A to D and B to E cross at C
    - Multiple cross types possible





Channel Capacity: String & Merging Topologies





$$\varepsilon = \begin{cases} 1 & \text{if} \quad l = 1 \\ ½ & \text{if} \quad l = 2 \\ \mathbf{1/3} & \text{if} \quad l \geq 3 \end{cases}$$

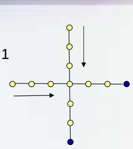
Leads to Lessons #1 & #2

$$\varepsilon = \begin{cases} n/(n+1) & \text{if} \quad h = 0 \\ n/(2n+1) & \text{if} \quad h = 1 \\ n/3n = \mathbf{1/3} & \text{if} \quad h \geq 2 \end{cases}$$

Leads to Lesson #3

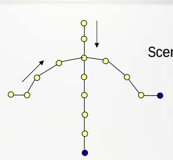
Crossing Flow Scenarios

Scenario 1

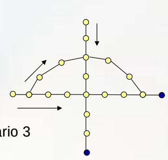


Forwarder congestion by crossing traffic

Scenario 2

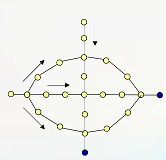


Alleviating congestion by alternative path



Scenario 3

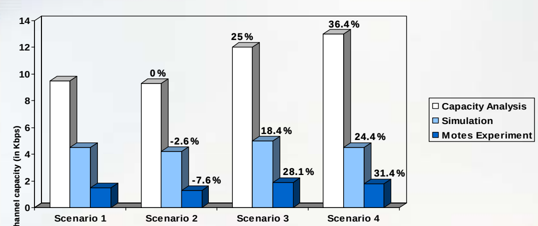
Alleviating congestion by additional path



Scenario 4

Alleviating congestion by multiple additional paths

Channel Capacity of Crossing Flow Scenarios



Aggregate end-to-end channel capacity (crossing topology of two flows)

This leads to Lesson #4

"Actual experiments have more interference than simulations… [and] more complicated interference than the model"

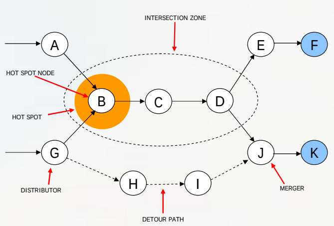
Lessons

1. Shortening a string topology does not increase the capacity if the resulting capacity fraction remains the same
2. If the node whose incoming traffic volume is less than C^{min} experiences congestion due to interference with other flows, the congestion can be eliminated by re-routing traffic onto the *non-interfered* path
3. Capacity of a merging topology can be increased by moving the merging point within a small number of hops from the sink
4. To increase capacity of a crossing topology, at least one flow should have multiple paths, and split its traffic onto these paths

Topology-Aware Resource Adaptation Scheme

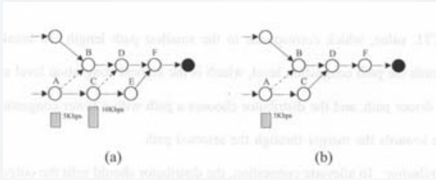
- Increasing Resources During Crisis States
  - Congestion detection & hot spot node
    - Actual congestion detection much harder than in wired networks
    - TARA looks at both buffer occupancy and channel loading
    - Hot spot declared when upper watermark level is reached
  - Traffic distributor
    - Maintain extra data field (neighbor packet injection count)
    - Control packet throttles upstream until a distributor is found
  - Traffic merger
    - Downstream control packet seeks merger point
    - On path between distributor and sink
    - Location and congestion are both important (affects capacity)
    - (slide 22, node J qualifies as merger)
  - Detour path
    - Uses REQ packet flooding to locate candidate distributor
    - Ties broken by path congestion comparison
  - Traffic distribution
    - Split outgoing traffic between original and detour paths
    - Streams aggregate data to same sink
    - Weighted fair share scheduling

Illustration of TARA



Topology-Aware Resource Adaptation Scheme (continued)

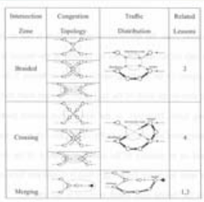
- Shrinking Resources During Dormant States
  - Increase resources during congestion
  - Return/reduce during low traffic



Shrinking resource provisioning using low watermark

Intersections & Congestion

- Interference zones for 2 flows (column 2)
- Possible detour paths & traffic distribution (column 3)
- Column 4 applies to lessons (slide 20)



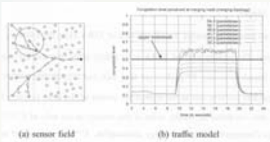
Three types of intersection zones

Performance Evaluation

- Performance metrics
  - Fidelity index: F/F^0
  - Total energy consumption:

$$E^{total} = \sum_{i=1}^{n}(p^{send} \times t_i^{send} + p^{recv} \times t_i^{recv} + p^{idle} \times t_i^{idle}),$$

- Simulation environment



Topologies for congestion control strategies

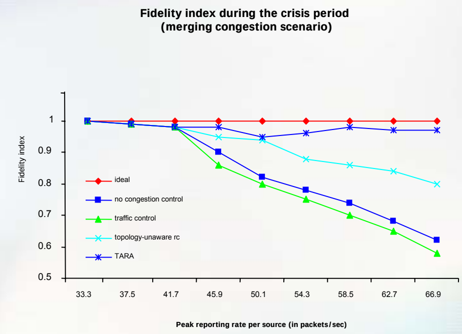
Topology examples with crossing intersections

No congestion control and traffic control

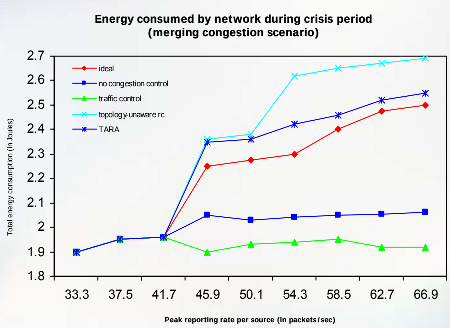
Topology-unaware rc

Ideal rc and TARA

Fidelity index during crisis period

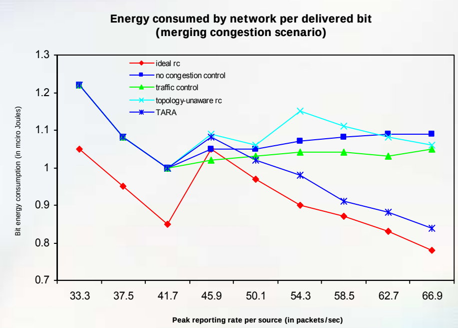


Total energy consumption by network during crisis period



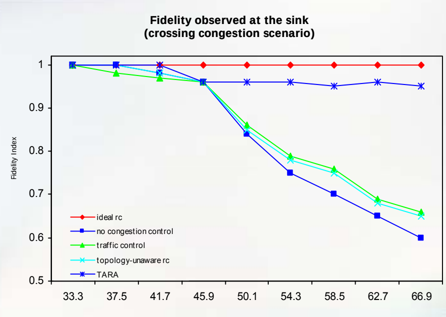
TARA delivers 70% more packets @ 33% increased energy consumption (but only 4% higher than ideal energy consumption at this delivery rate)

Bit energy consumption during crisis period



Detour path is more utilized as traffic rate increases – not a linear event

Fidelity index during crisis period



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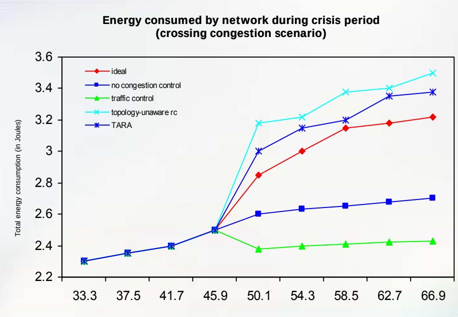
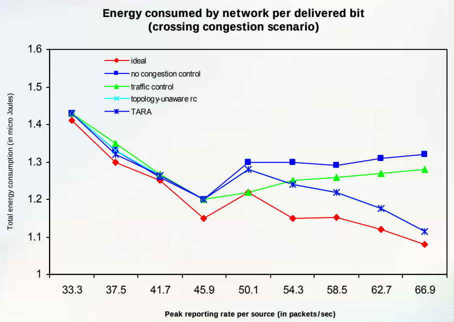
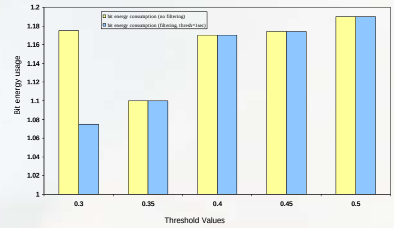


Bit energy consumption during crisis period



Comparison with upper watermark values



Setting the appropriate watermark level is tricky

Stated goals

- **Primary goal: satisfy fidelity requirements**
  - **Is this achieved?**
  - **Could something else do a better job in this application scenario?**
- **Total energy consumption**
  - **Specific goal not stated**
  - **Assumed goal is to not cause excess energy consumption**
- **Bit energy consumption**
  - **Again, specific goal not stated**
  - **Assume target is effective energy usage wrt end user application**

Discussion: Positive Points

- **Predict reader's questions and address them.**
  - **Examples**
- **Used 3 approaches to test their idea**
  - **Mica2 motes running TinyOS**
  - **NS2 simulation**
  - **Model's theoretical results**
- **Interesting theory, with apparently useful application**
  - **Mica motes experiments worked**
  - **Field testing would be nice**

Discussion: Issues

- **Minor point: grammatical errors scattered throughout**
- **List only 3 hot spot scenarios. Are there others that should be addressed?**
- **Is graph coloring approach practical in a deployed sensor net with large numbers of nodes?**
- **How does this solution impact lifetime of sensor net (energy)?**
- **What happened to transient congestion?**
- **Does increasing paths (to relieve congestion) really result in increased fidelity (i.e., increased fidelity)**
- **Transitions from string & merging topologies to crossing topologies is awkward.**

References

- **Link to the author's web page on TARA: http://paul.rutgers.edu/~jwkang/research/tara.html**
  (note: the paper has not been published yet)
- **C. T. Ee and R. Bajcsy. *Congestion control and fairness for many-to-one routing in sensor networks*. In ACM SenSys, pages 134--147, 2004 http://citeseer.ist.psu.edu/context/2676965/0**
- **Bret Hull, Kyle Jamieson , and Hari Balakrishnan. *Mitigating Congestion in Wireless Sensor Networks* ACM SenSys 2004, Baltimore, MD, November, 2004. http://nms.lcs.mit.edu/papers/hbhfc-sensys04.pdf**