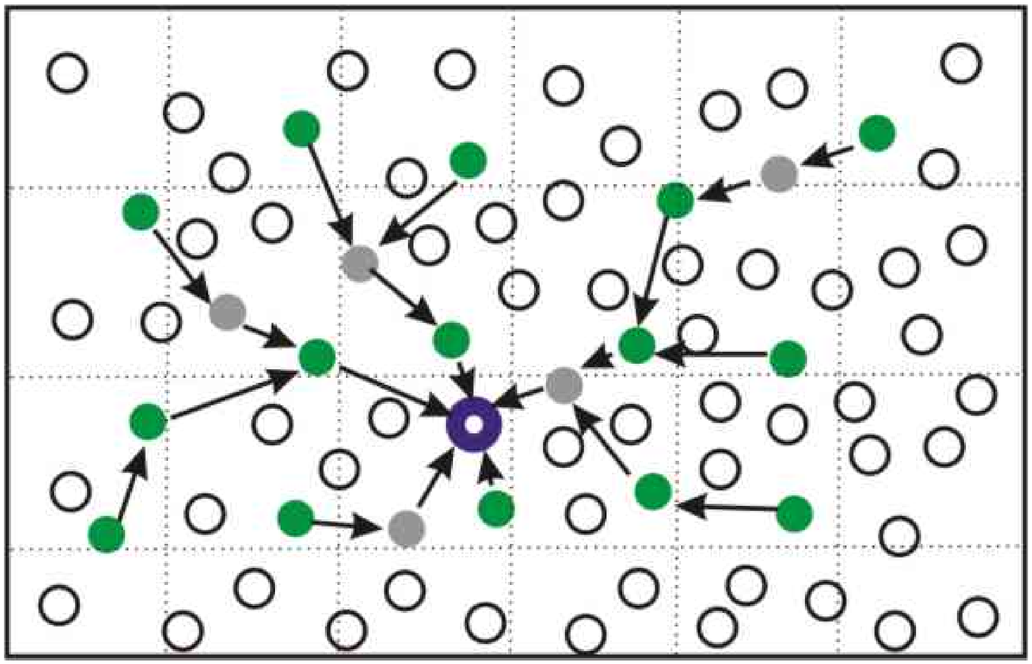
PROSE: Providing Robustness in Systems of Embedded Sensors

Yanyong Zhang, Shengchao Yu, Jaewon Kang, Badri Nath, Wade Trappe

WINLAB, Rutgers University

WINLAB WIRELESS INFORMATION NETWORK LABORATORY

Sensor Network Model

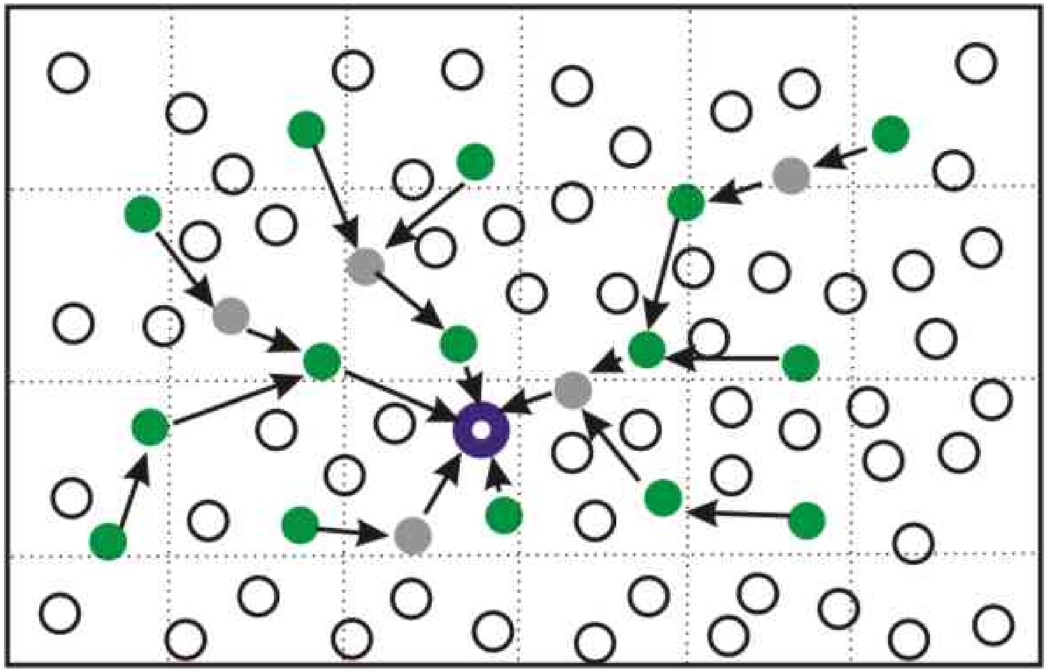


- Sensor net connectivity model
  - Multi-hop networking
  - More active nodes may be needed

- A sensor net deployment has:
  - Many inexpensive sensor nodes
    - capable of sensing, computing, and communication
    - Resource constraints (energy)
    - Deployment redundancy
    - Stationary nodes
  - One or several data sinks
    - Connected with apps
- Sensor net coverage model:
  - Lifetime vs. coverage
    - a minimum set of active nodes
  - Grid-based coverage model
    - Network partitioned into grids
    - A node is able to monitor at least one grid point
    - Every grid point must be monitored

WINLAB
WIRELESS INFORMATION NETWORK LABORATORY

Challenges in Sensor Networks

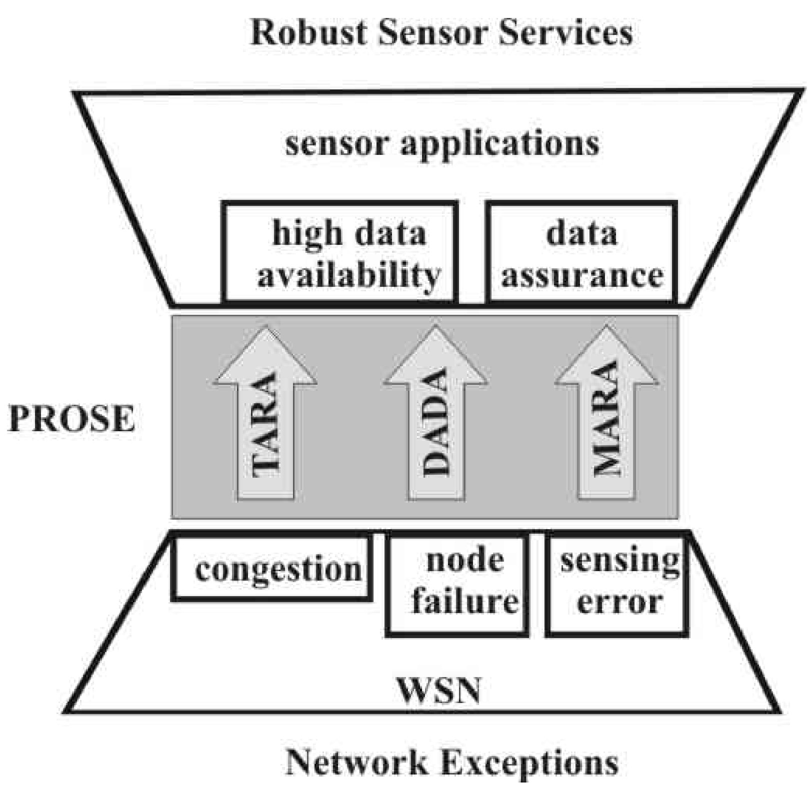


How to extract a steady stream of valid data from all the interesting spots in the presence of unexpected interrupts?

- Many challenges in building sensor systems/applications (at WINLAB)
  - Sensor deployment
  - Lifetime maximization
  - Programming model
  - Routing and MAC protocols
  - Localization algorithms
  - Security and privacy
- This project focuses on robust sensor services
  - Unattended operations
  - Hostile environment
    - Fire
    - landfill
  - Many unexpected events may happen
    - Node failure
    - Congestion
    - Erroneous data

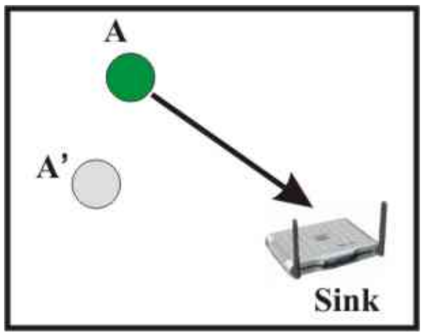
WINLAB
WIRELESS INFORMATION NETWORK LABORATORY

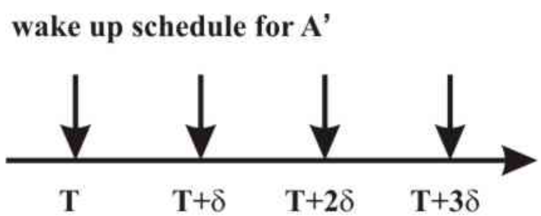
Prose Overview

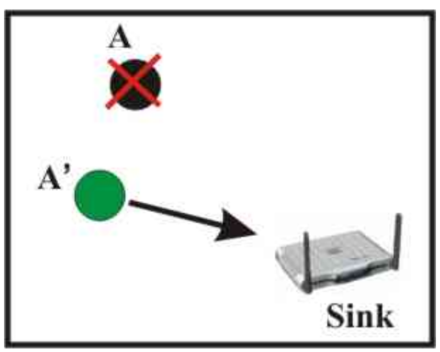


- PROSE has three components:
  - DADA: a 2-Dimensional Adaptive Node Scheduling Framework
    - Provides data availability against random node failures
    - Repairs network coverage and connectivity by cleverly waking up redundant nodes upon node failures
  - TARA: a Topology-Aware Resource Adaptation Framework
    - Provides data availability against congestion
    - Brings more sensor nodes "online" to accommodate higher traffic rate to eliminate congestion
  - MARA: a Measurement Assurance and Robust Aggregation Framework
    - Provides data assurance
    - Classifies and cleanses sensed data
- Each component has two units:
  - Exception detection
  - Exception handling

DADA: Overview



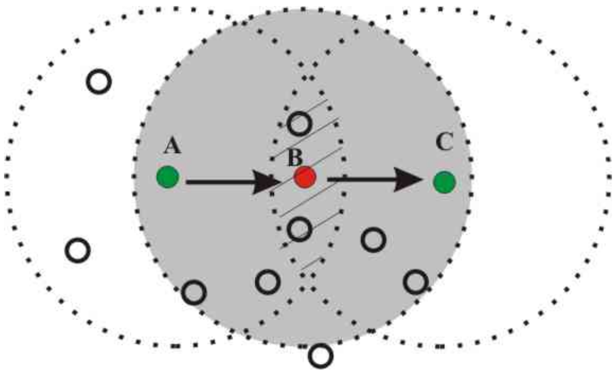


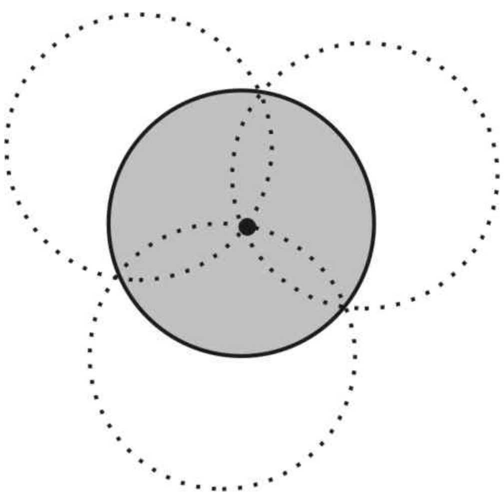


- DADA balances the tradeoff between network lifetime and network quality
- DADA achieves two goals:
  - Bounded recovery time upon node failures (recovery time <= δ)
  - Minimize energy consumption
- Basic idea for DADA
  - A minimum set of active nodes
  - The redundant node wakes up every δ time
  - When it wakes up, it finds out whether it needs to become active
  - If the active node dies at time t, its redundant node will wake up at latest t+δ to, and will become active
- Complications
  - How to decide an active node's redundant nodes?
  - How to schedule multiple redundant nodes?

WINLAB
WIRELESS INFORMATION NETWORK LABORATORY

DADA: Gangs





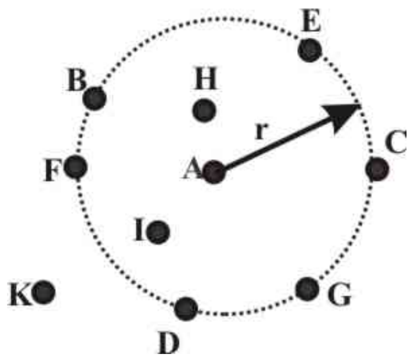
- A node can not always replaced by one redundant node
  - On average, 3-5 nodes are needed to replace a node's sensing area
  - One node may not be enough to repair the communication hole even if it is in the radio range
- The concept of "gangs"
  - A *gang* consists of a group of nodes that can completely replace an active node
  - A *minimum gang* is a gang itself, but none of its subsets is a gang
  - All the nodes belong to a minimum gang should wake up together
  - The minimum gangs are analogous to "sentries" in real life.

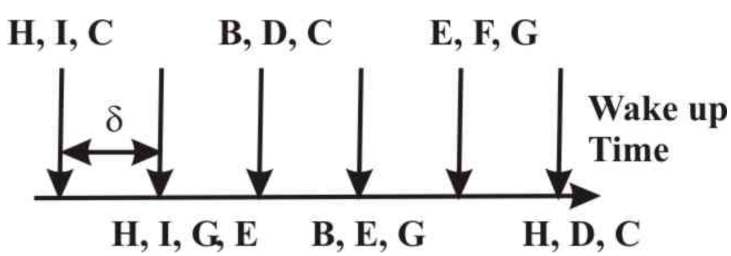
DADA: P-Sentry Algorithm

- Persistent Sentry (P-Sentry) provides interrupt-less network operations
  - One minimum gang stays awake all the time (the sentry)
  - The sentries can take over when the active node fails
  - The other redundant nodes can sleep for a much longer time
- Issues with P-Sentry algorithm
  - How do the sentries detect the failure of the active node?
    - Passive listening
    - Active probing
  - Which nodes should be chosen as sentries?
    - Energy
    - Functionality
    - Redundancy
  - How long should the non-sentry redundant nodes sleep?
    - Estimate the remaining lifetime
    - Considering the random failure rate
  - How to synchronize multiple schedules a redundant node may have?
    - Active node maintains states

WINLAB WIRELESS INFORMATION NETWORK LABORATORY

DADA: R-Sentry Algorithm

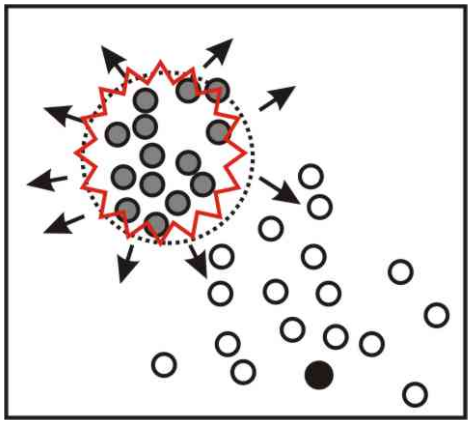




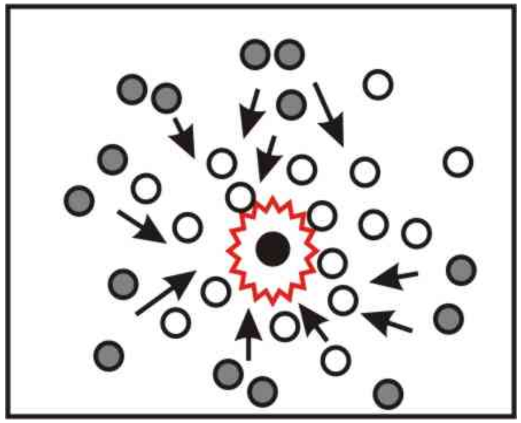
- Rotary sentries (R-Sentry) limits service loss
  - All the minimum gangs take turns to wake up, with δ between two subsequent wakeups.
- An example scenario
  - A's minimum gangs {H,I,C}, {H,I,G,E}, {B,D,C}, {B,E,G}, {E,F,G}, and {H,D,C}
- Issues to be considered
  - How to detect failures?
    - Probing for sensing ranges
    - Listening for HELP messages
  - How to synchronize multiple schedules a redundant node may have?
  - How to dynamically adapt the schedule when the redundant node fails?

WINLAB
WIRELESS INFORMATION NETWORK LABORATORY

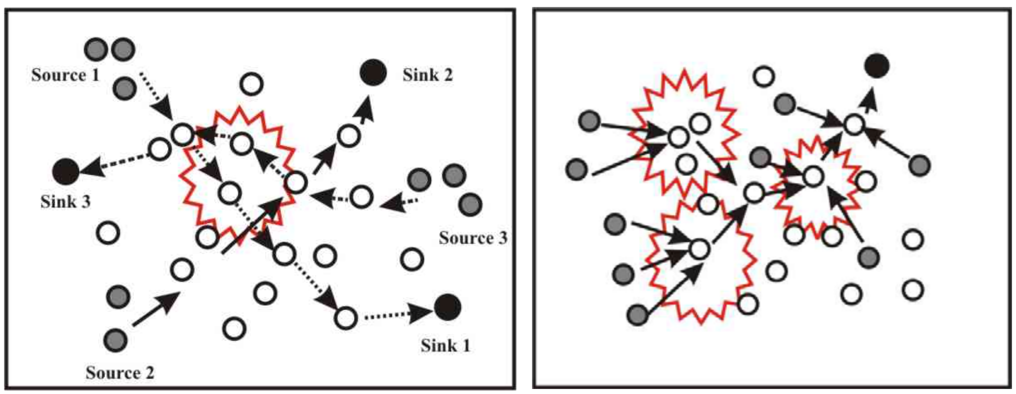
TARA: Overview I



Source hot spot



Sink hot spot



intersection hot spot

- A monitoring sensor network alternates between dormant periods and crisis periods
  - During dormant periods, minimum resources are kept online (DADA)
  - A hot spot will form during crisis periods
- Three types of hot spots:
  - Source hot spot
  - Sink hot spot
  - intersection hot spot

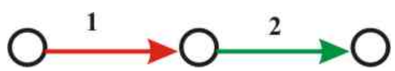
WINLAB WIRELESS INFORMATION NETWORK LABORATORY

TARA: Overview II

- Traffic control vs. resource control
  - Traffic control schemes throttle source traffic rates to eliminate hot spots
  - Resource control is preferred in sensor networks
    - Data packets during crisis states can NOT be dropped
      - Fidelity requirement
    - Sensor nets are deployed for peak load
    - Bringing resources online is realistic
      - e.g. sensor nodes
- Resource control schemes
  - Forming alternative routing topology
  - Multiple-path routing
- Topology-aware resource control
  - e.g. dose the new topology provide sufficient capacity?
- TARA has two main components:
  - Capacity estimation tool
  - Resource adaptation algorithm

WINLAB
WIRELESS INFORMATION NETWORK LABORATORY

TARA: Capacity Analysis



Capacity fraction = 1/2

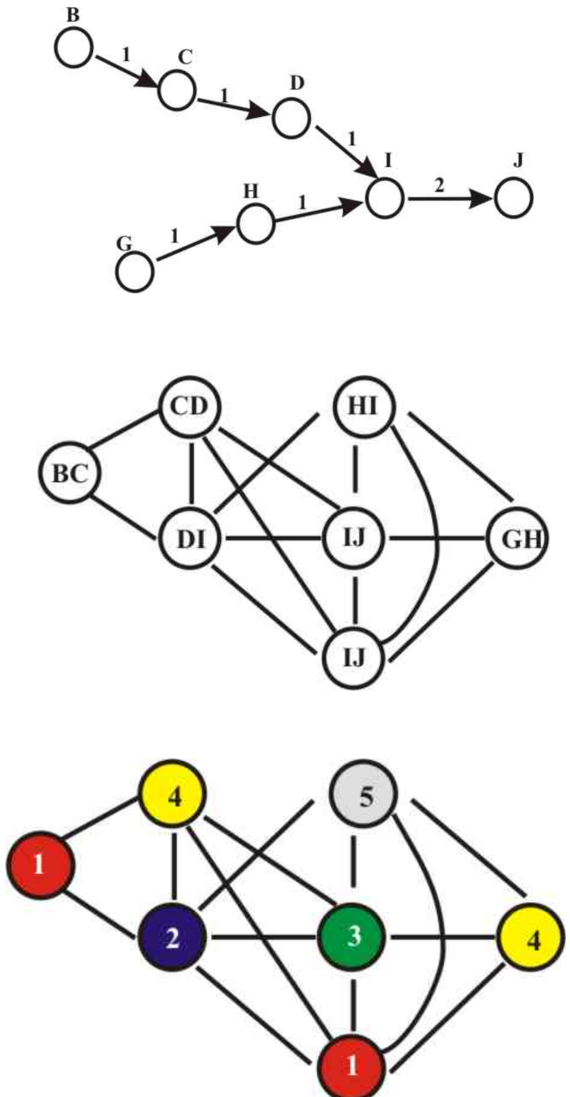
Capacity fraction = 1/3

Assumption: only adjacent nodes can hear/interfere each other

- Goal: to estimate the maximum end-to-end throughput of a given topology
  - The maximum rate at which the source can send packets towards the sink
- Idea: mapping this problem to a graph coloring problem
  - Due to link interference, the end-to-end throughput is a fraction of the 1-hop throughput (capacity fraction)
  - Suppose under an optimal schedule, the sink receives a packet every n time frames, then the capacity fraction is 1/n
  - The throughput is (1-hop throughput * capacity fraction)

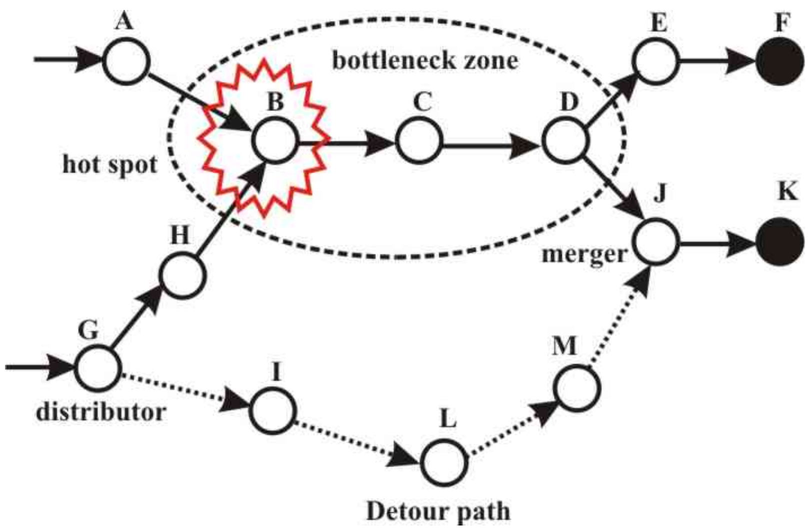
WINLAB WIRELESS INFORMATION NETWORK LABORATORY

TARA: Capacity Analysis



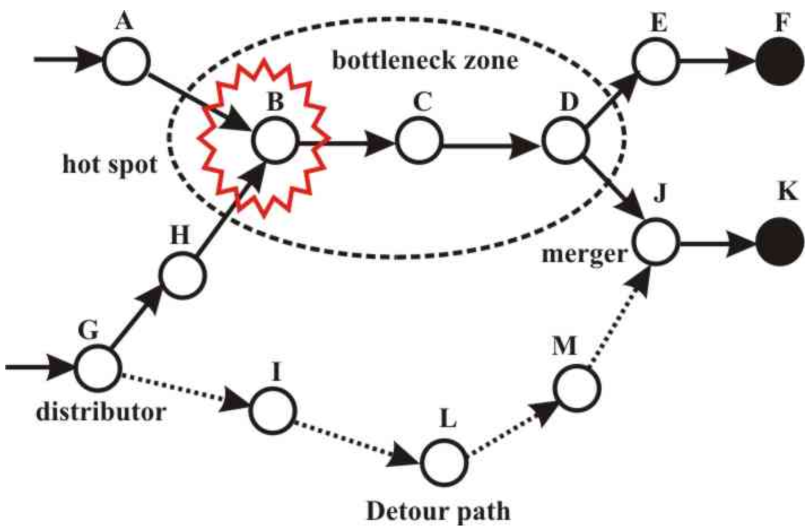
- Idea: mapping this problem to a graph coloring problem
  - Suppose under an optimal schedule, the sink receives a packet every n time frames, then the capacity fraction is 1/n
  - To estimate n
    - Spatial interference graph
      - Vertexes are wireless links
      - Edges mean that two links are within each other's interference ranges
    - N is equal to the number of colors assigned to the spatial interference graph
- Graph coloring problem
  - Theorems can provide an upper bound
  - Heuristic approaches provide tighter estimates

TARA: Resource Adaptation Scheme

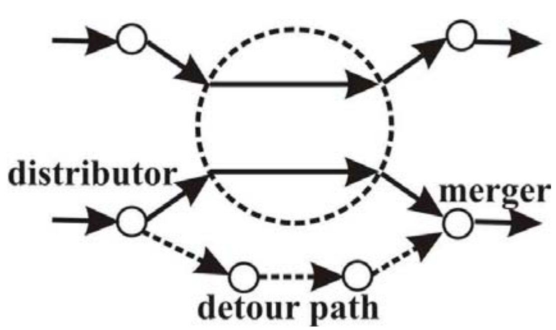


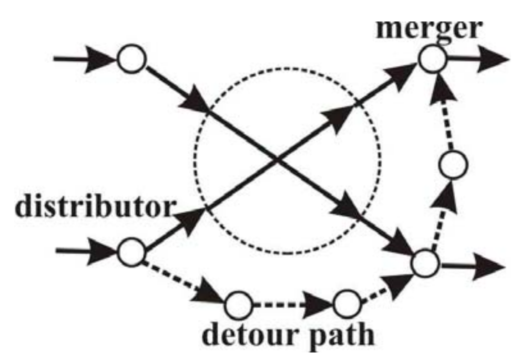
- TARA has the following steps:
  - Congestion detection
    - e.g. channel loading, packet drop ratio, queue occupancy, etc.
  - Traffic distributor
    - Each node maintains the incoming traffic rate from each neighbor

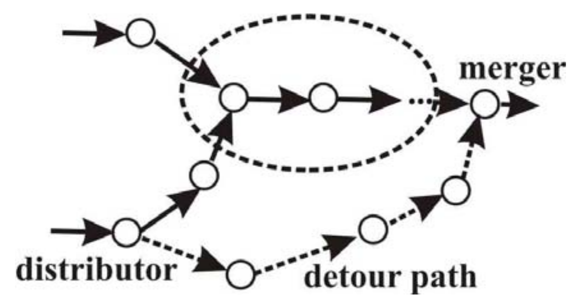
TARA: Resource Adaptation Scheme



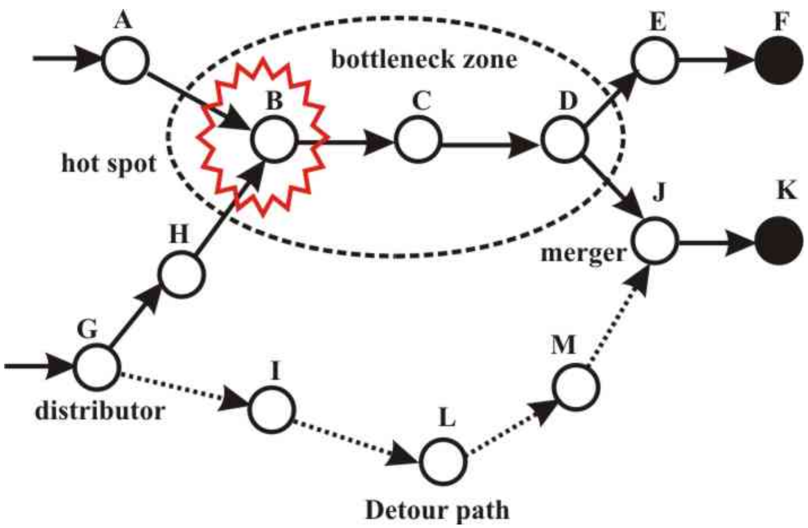
- TARA has the following steps:
  - Congestion detection
  - Traffic distributor
  - Traffic merger should
    - Have a low congestion level
    - Reside on the routing path to the intended sink
    - Result in sufficient capacity
      - Based on the observations gained using the capacity analytical tool







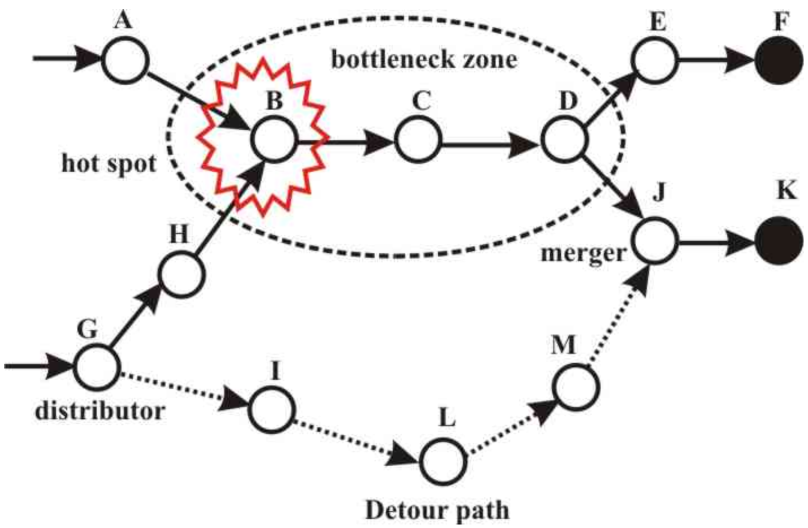
TARA: Resource Adaptation Scheme



- TARA has the following steps:
  - Congestion detection
  - Traffic distributor
  - Traffic merger
  - Build a detour path
    - The merger initiates the process with flooding a REQ message including the TTL
    - A node that receives the REQ message decrements the TTL, and forwards the message with the following optimizations:
      - A node drops REQ if its congestion level is high
      - A node drops REQ if it is on the original routing path
      - A node only forwards the REQ with a higher TTL
    - Multiple REQ messages will reach the distributor, and it chooses the path with highest TTL

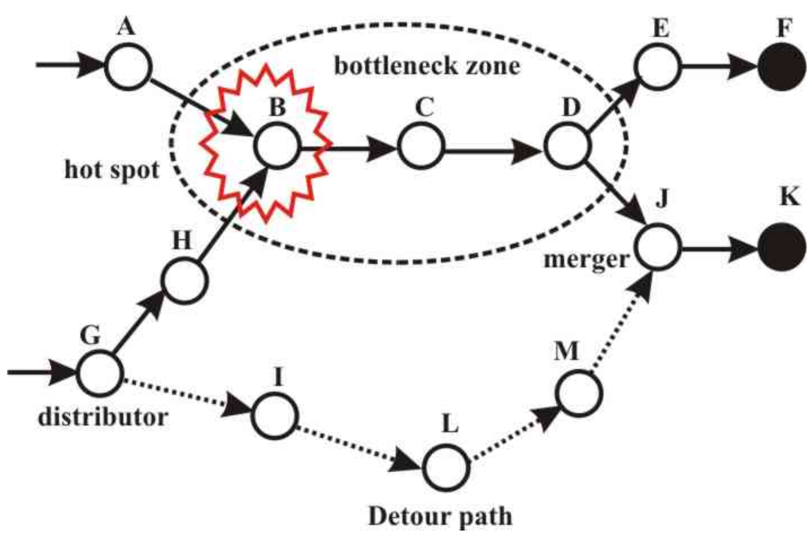
WINLAB
WIRELESS INFORMATION NETWORK LABORATORY

TARA: Resource Adaptation Scheme



- TARA has the following steps:
  - Congestion detection
  - Traffic distributor
  - Traffic merger
  - Build a detour path
    - The merger initiates the process by flooding a REQ message including a TTL field
    - A node that receives the REQ message decrements the TTL, and forwards the message with the following optimizations:
      - A node drops REQ if its congestion level is high
      - A node drops REQ if it is on the original routing path
      - A node only forwards the REQ with a higher TTL
    - Multiple REQ messages will reach the distributor, and it chooses the path with highest TTL

TARA: Resource Adaptation Scheme



- TARA has the following steps:
  - Congestion detection
  - Traffic distributor
  - Traffic merger
  - Build a detour path
  - The distributor distributes the traffic between two paths
    - Traffic allocation is topology-dependent

WINLAB WIRELESS INFORMATION NETWORK LABORATORY

TARA: A few issues …

- TARA also reduces the online resource when traffic decreases
- A three-tiered resource controlling scheme
  - For very short-term congestion
    - Larger buffer size
    - Prioritizing packets
    - Storing data locally
  - For short-term congestion
    - TARA
  - For longer-term congestion
    - Traffic control

MARA

- MARA provides data assurance against sensing errors
- Data classification mechanisms
  - Constraint-based Consistency Checks
    - Predefined constraints such as "temperature between 0 and 100"
  - Redundancy Consistency Checks
    - Multiple sensors monitoring the same variable
  - Multi-modal Consistency Checks
    - Multiple physical properties may exhibit correlation
- Data cleansing mechanisms
  - Robust statistical tool or robust aggregation tool
  - Challenge is to make them suitable for sensor platform

Conclusion

- Making the sensor system robust should not be an after-thought
- If you need more details on
  - DADA → Shengchao Yu's poster
  - TARA → Jaewon Kang's talk in the afternoon
  - MARA → Badri Nath's talk in the afternoon

Questions ???

WINLAB
WIRELESS INFORMATION NETWORK LABORATORY