Sensor Network Protocol Design and Implementation

Philip Levis
UC Berkeley

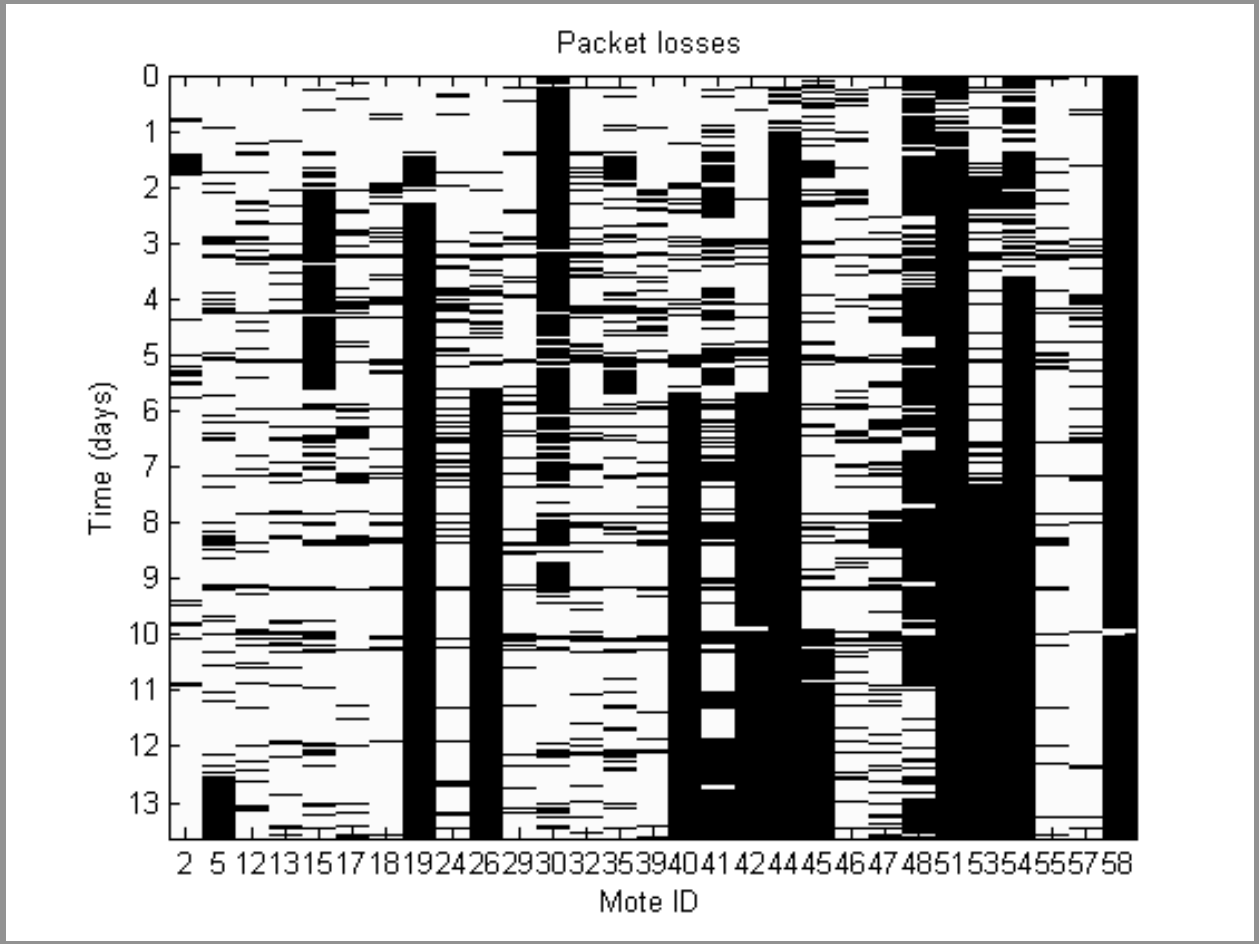
Sensor Network Constraints

- Distibuted, wireless networks with limited resources
  - Energy, energy, energy.
- Communication is expensive.
  - Idle listening is the principal energy cost.
  - Radio hardware transition times can be important.
  - Low transmission rates can lower cost of idle listening.
- Nodes cannot maintain a lot of state.
  - RAM is at a premium.

Constraints, continued

- Uncontrolled environments that drive execution
- Variation over time and space
  - The uncommon is common
  - Unforseen corner cases and aberrations

Sensor Network Behavior



Design Considerations

- Uncontrolled environment: simplicity is critical.
  - The world will find *y*our edge conditions for *y*ou.
  - Simplicity and fault tolerance can be more important than raw performance.
- Wireless channel: cheap broadcast primitive.
  - Protocols can take advantage of spatial redundancy.
- Redundancy requires idempotency
  - But we have limited state.

A Spectrum of Protocol Classes

- Dissemination: One to N
- Collection Routing: N to One
- Landmark Routing: N to changing one
- Aggregation Routing: N to One
- An*y*-to-An*y*

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Dissemination

- Fundamental networking protocol
  - Reconfiguration
  - Reprogramming
  - Management
- Dissemination: reliably deliver a datum to every node in a network.

To Every Node in a Network

- Network membership is not static
  - Loss
  - Transient disconnection
  - Repopulation
- Limited resources prevent storing complete network population information
- *To ensure dissemination to every node, we must periodically maintain that every node has the data.*

The Real Cost

- Propagation is costly
  - Virtual programs (Maté, TinyDB): 20-400 bytes
  - Parameters, predicates: 8-20 bytes
  - To every node in a large, multihop network…
- But maintenance is more so
  - For example, one maintenance transmission every minute
  - Maintenance for 15 minutes costs more than 400B of data
  - For 8-20B of data, two minutes are more costly!
- *Maintaining that everyone has the data costs more than propagating the data itself.*

Three Needed Properties

- Low maintenance overhead
  - Minimize communication when everyone is up to date
- Rapid propagation
  - When new data appears, it should propagate quickly
- Scalability
  - Protocol must operate in a wide range of densities
  - Cannot require *a priori* density information

Existing Algorithms Are Insufficient

- Epidemic algorithms
  - End to end, single destination communication, IP overlays
- Probabilistic broadcasts
  - Discrete effort (terminate): does not handle disconnection
- Scalable Reliable Multicast
  - Multicast over a wired network, latency-based suppression
- SPIN (Heinzelman et al.)
  - Propagation protocol, does not address maintenance cost

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- Behavior (simulation and deployment):
  - Maintenance: a few sends per hour
  - Propagation: less than a minute
  - Scalability: thousand-fold density changes

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- Behavior (simulation and deployment):
  - Maintenance: a few sends per hour
  - Propagation: less than a minute
  - Scalability: thousand-fold density changes
- Instead of flooding a network, establish a trickle of packets, just enough to stay up to date.

Trickle Assumptions

- Broadcast medium
- Concise, comparable metadata
  - Given A and B, know if one needs an update
- Metadata exchange (maintenance) is the significant cost

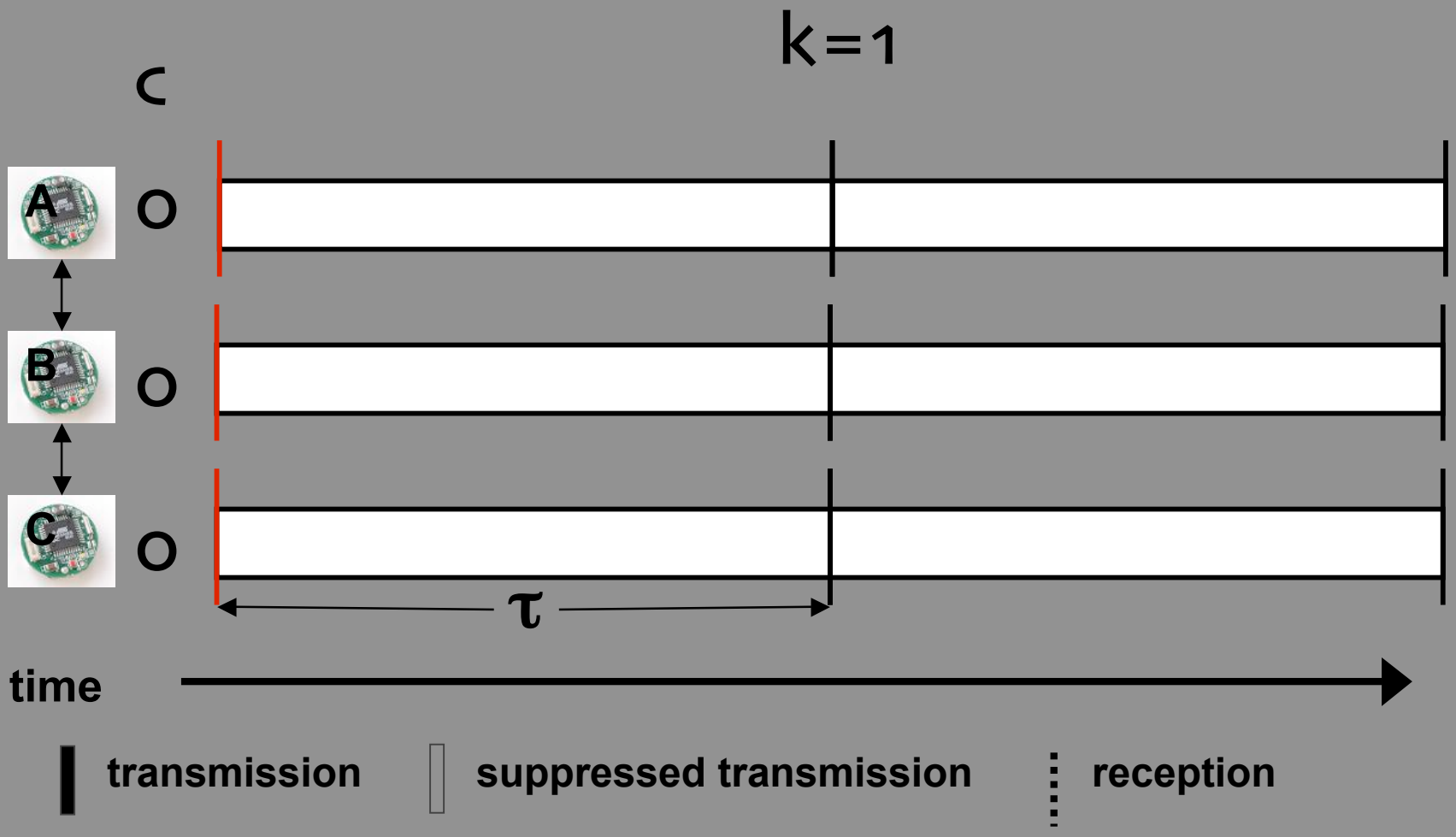
Detecting That a Node Needs an Update

- As long as each node *communicates* with others, inconsistencies will be found
- Either reception or transmission is sufficient
- Define a desired detection latency, τ
- Choose a redundancy constant k
  - k = (receptions + transmissions)
  - In an interval of length τ
- Trickle keeps the rate as close to k/ τ as possible

Trickle Algorithm

- Time interval of length τ
- Redundancy constant k (e.g., 1, 2)
- Maintain a counter c
- Pick a time t from $[0, \tau]$
- At time t, transmit metadata if $c < k$
- Increment c when you hear identical metadata to your own
- Transmit updates when you hear older metadata
- At end of τ, pick a new t

Example Trickle Execution



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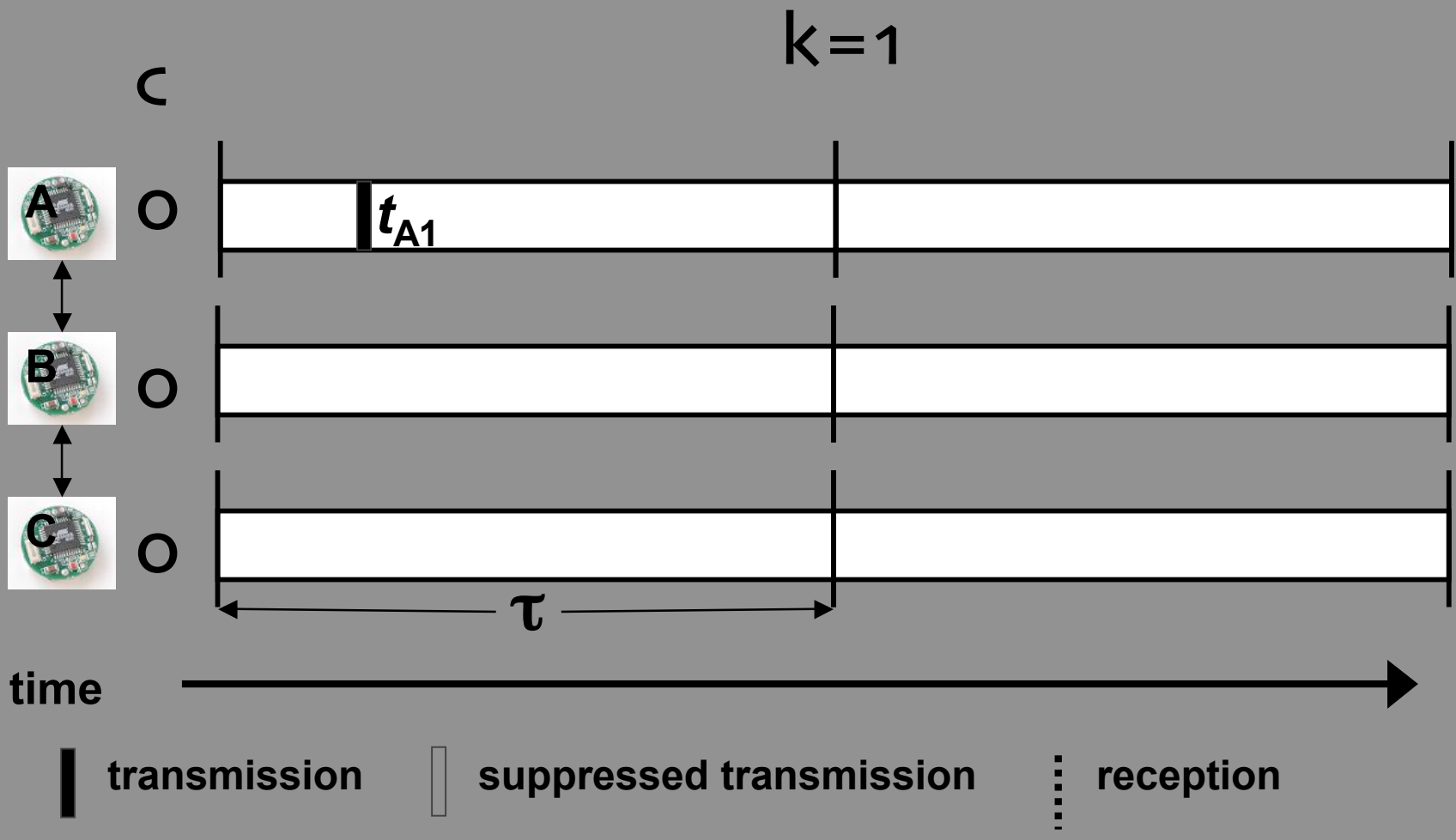

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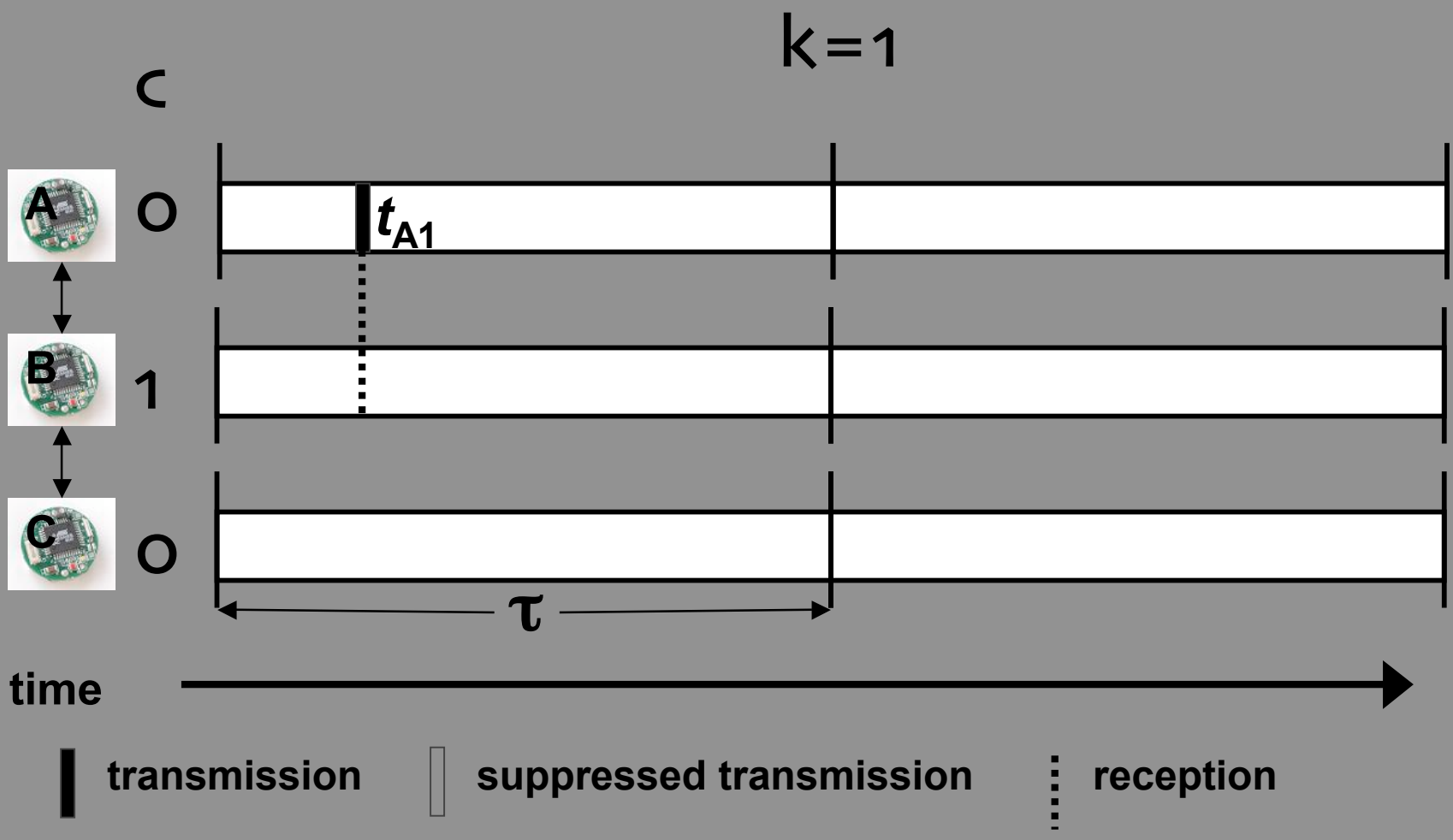

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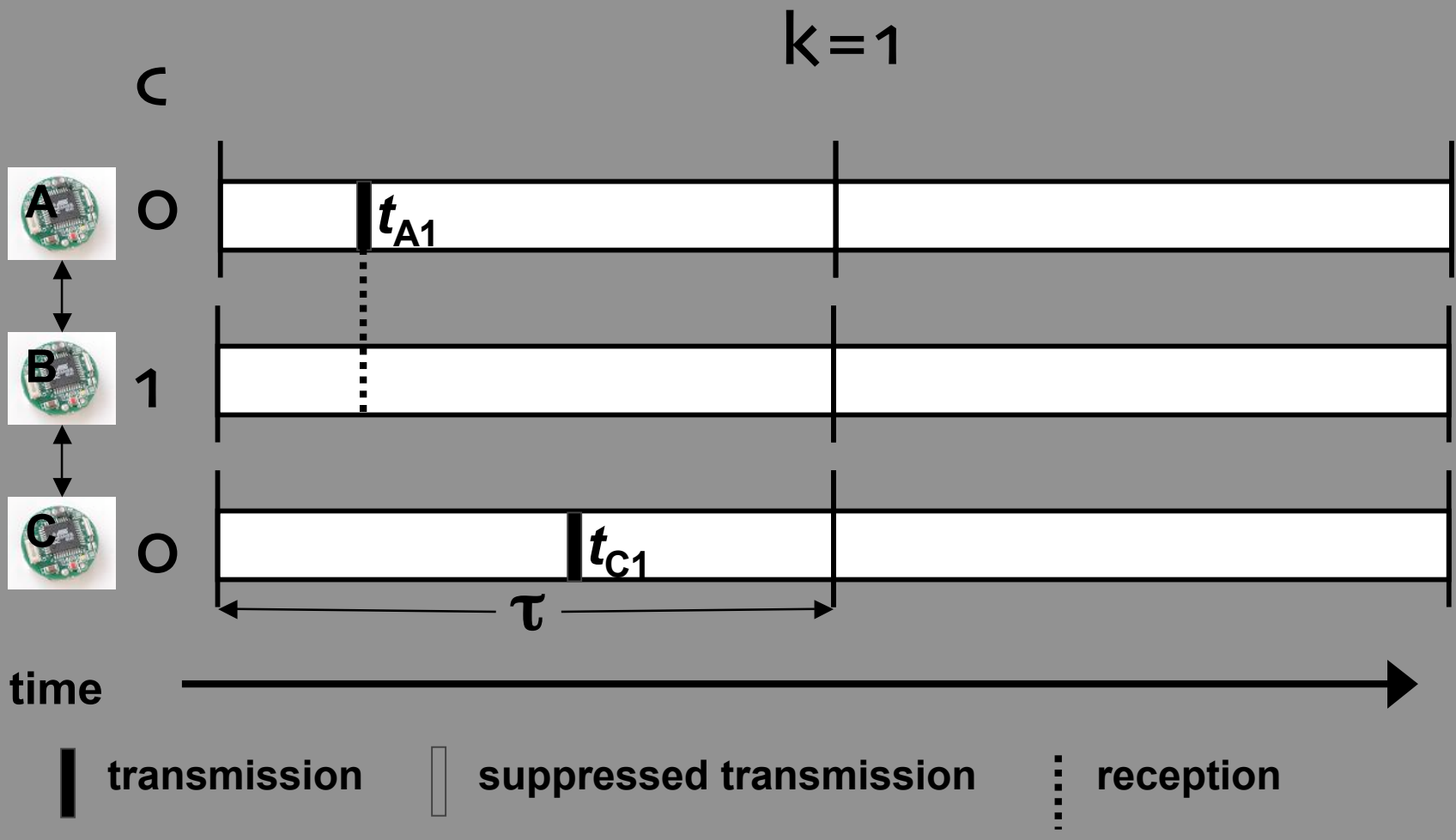

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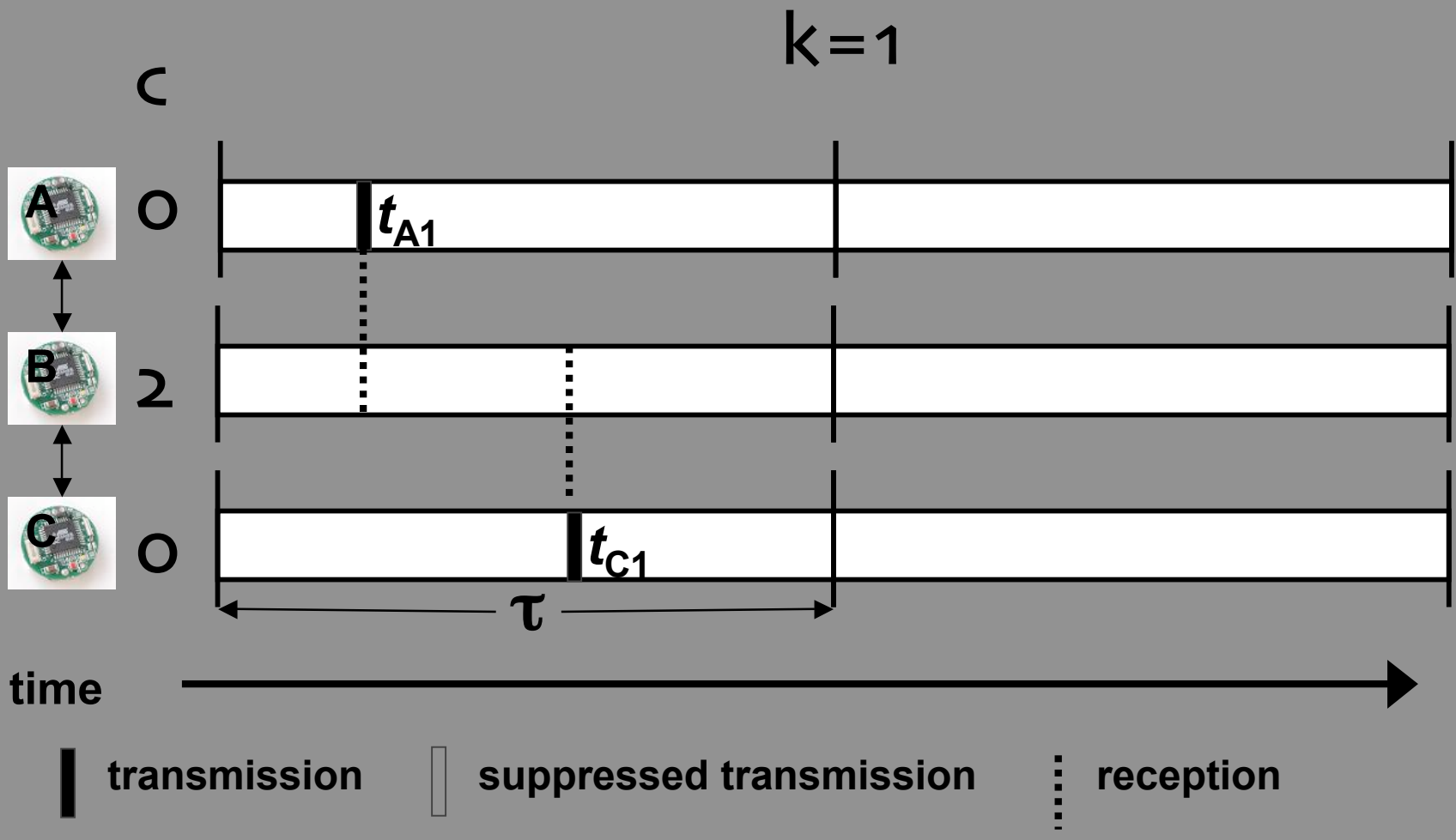

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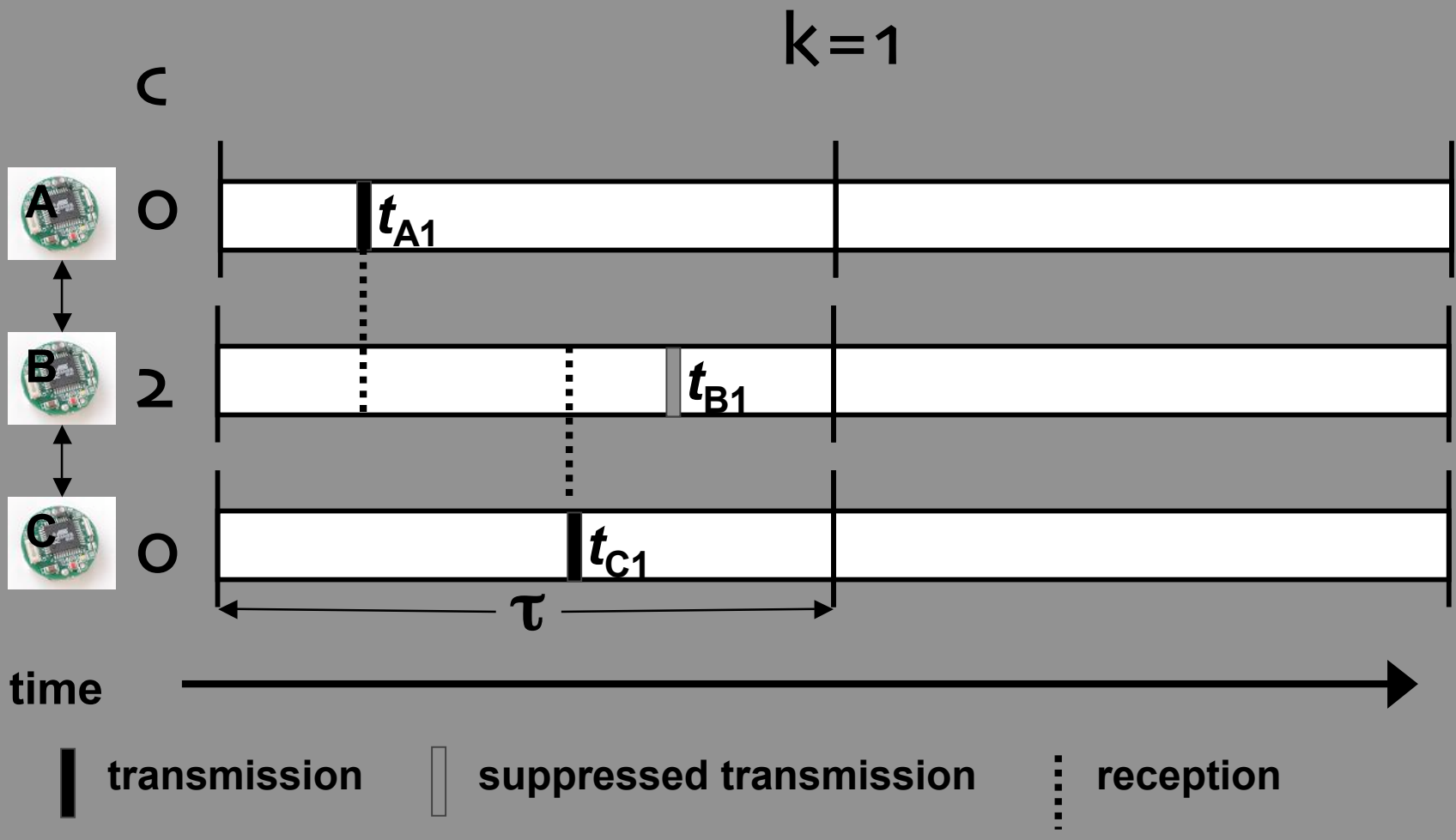

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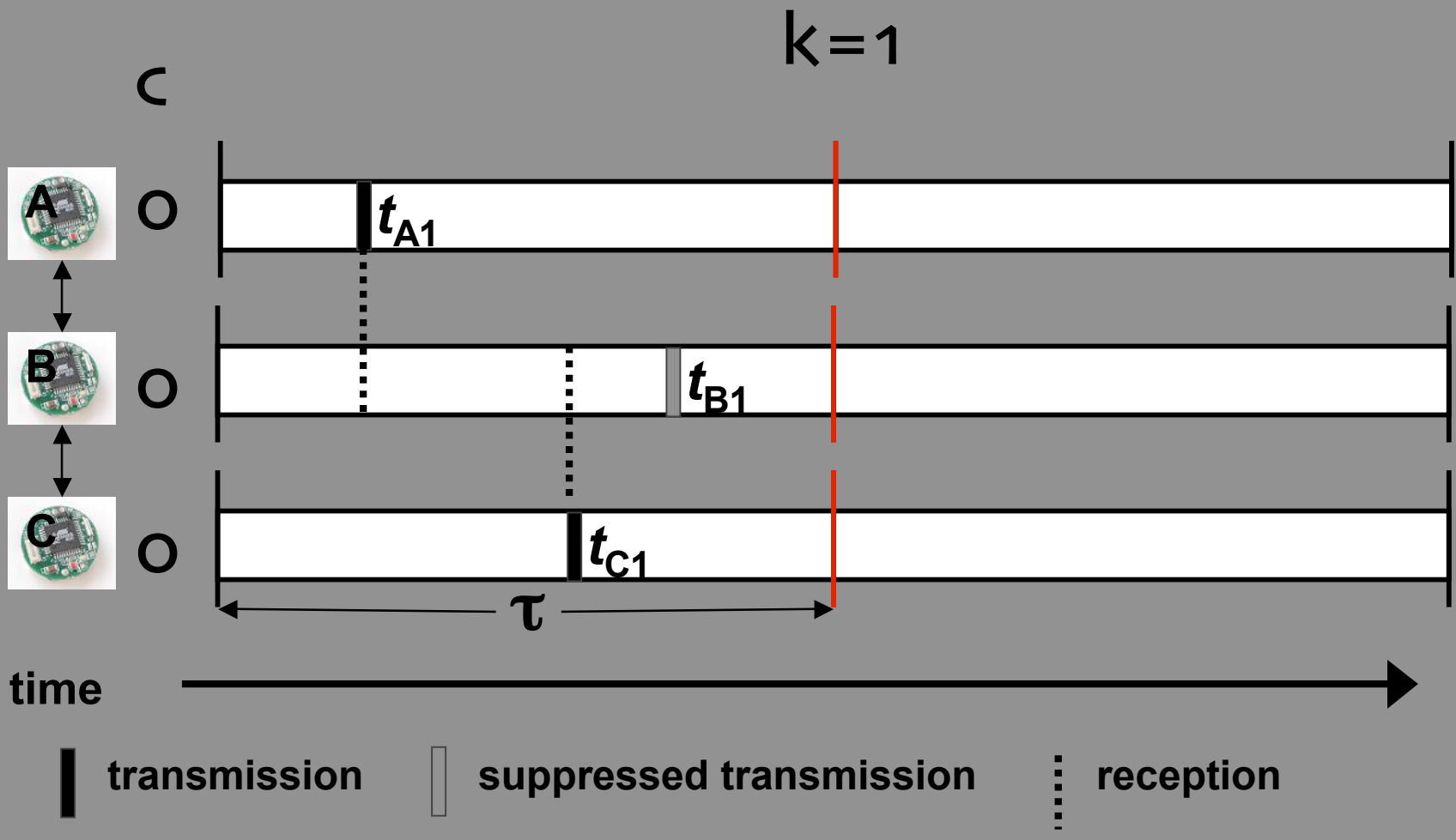

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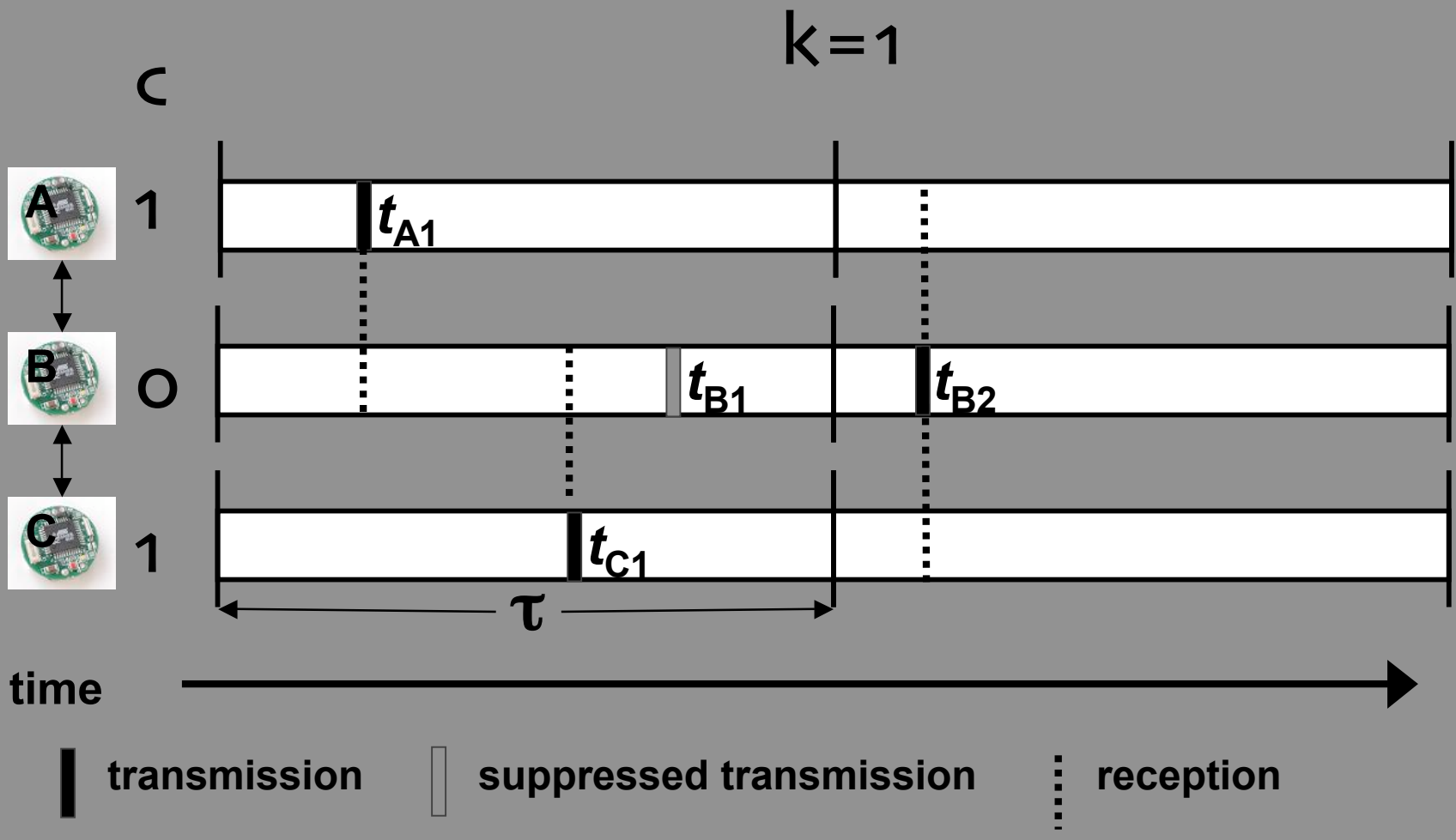

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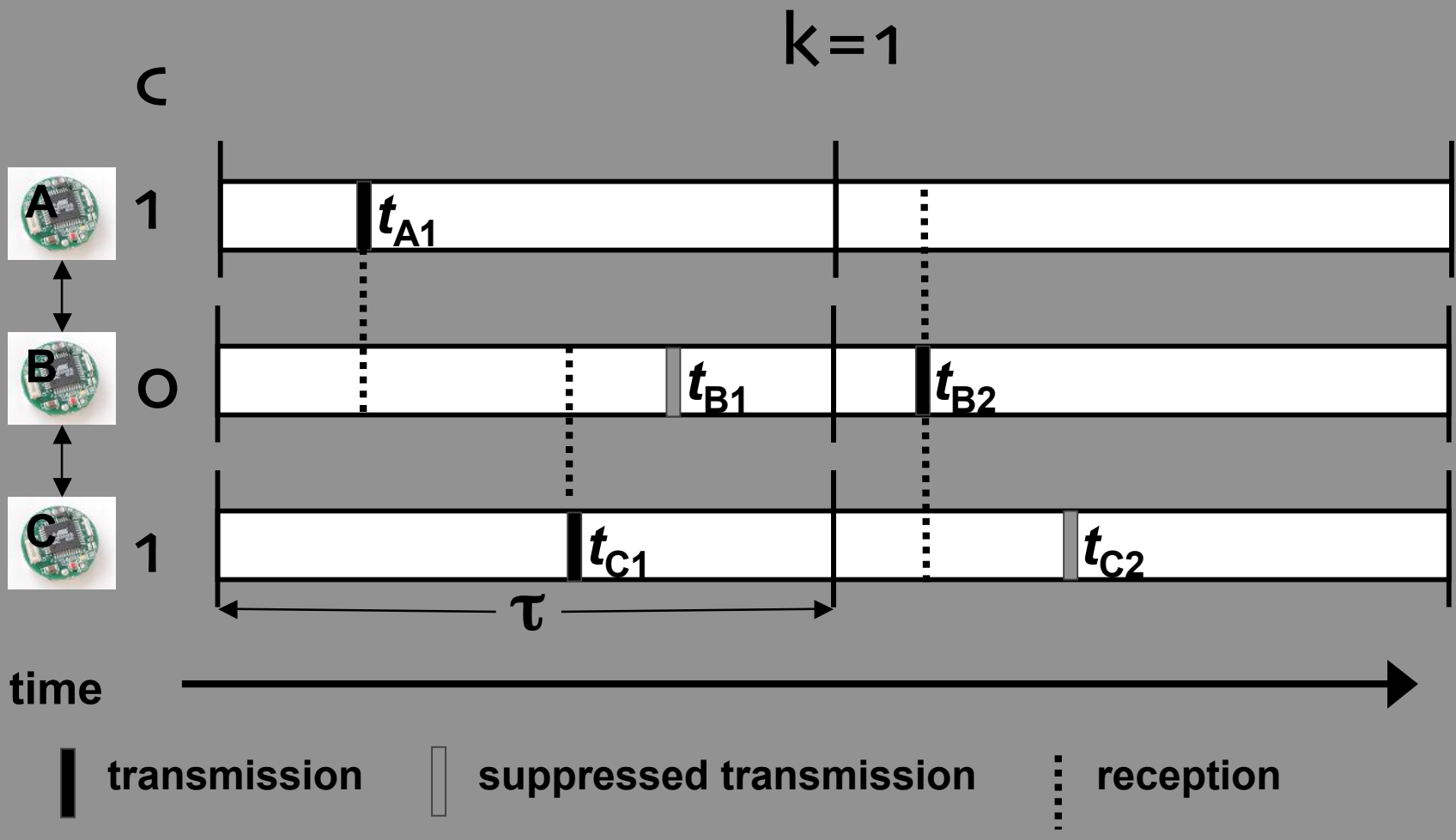

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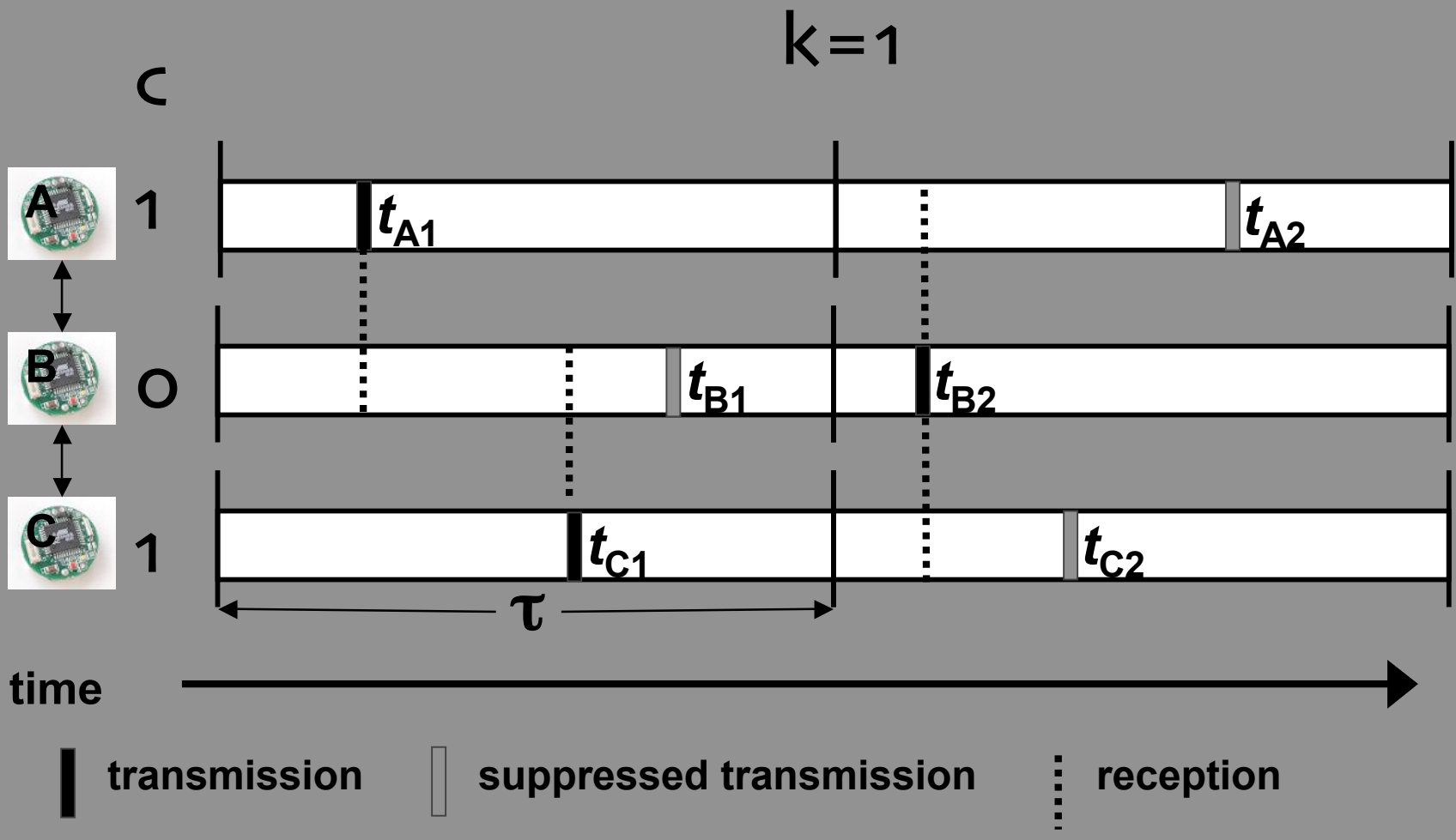


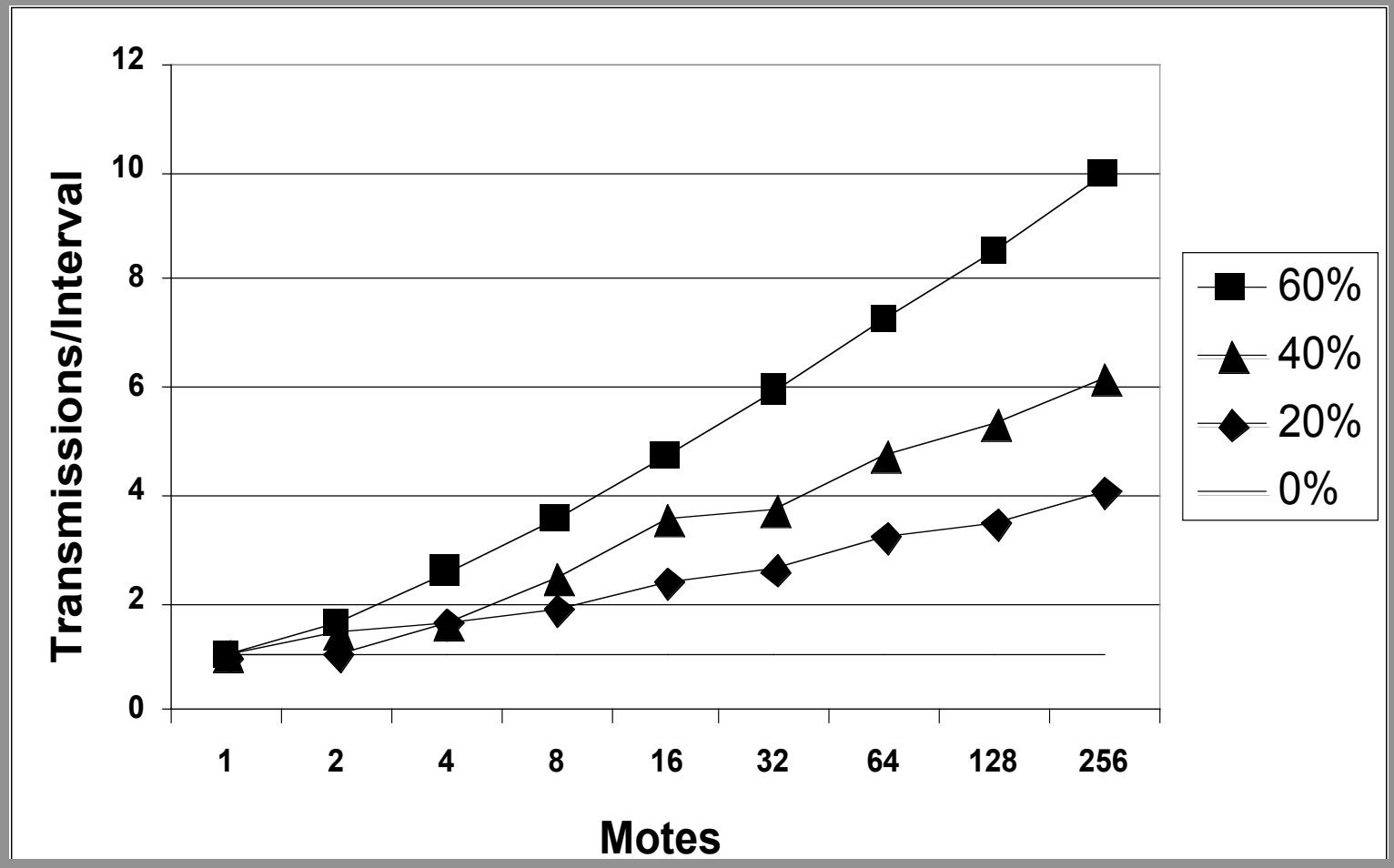
Experimental Methodology

- High-level, algorithmic simulator
  - Single-hop network with a uniform loss rate
- TOSSIM, simulates TinyOS implementations
  - Multi-hop networks with empirically derived loss rates
- Real world deployment in an indoor setting
- In experiments (unless said otherwise), k =1

Maintenance Evaluation

- Start with idealized assumptions, relax each
  - Lossless cell
  - Perfect interval synchronization
  - Single hop network
- Ideal: Lossless, synchronized single hop network
  - *k* transmissions per interval
  - First k nodes to transmit suppress all others
  - Communication rate is independent of density
- First step: introducing loss

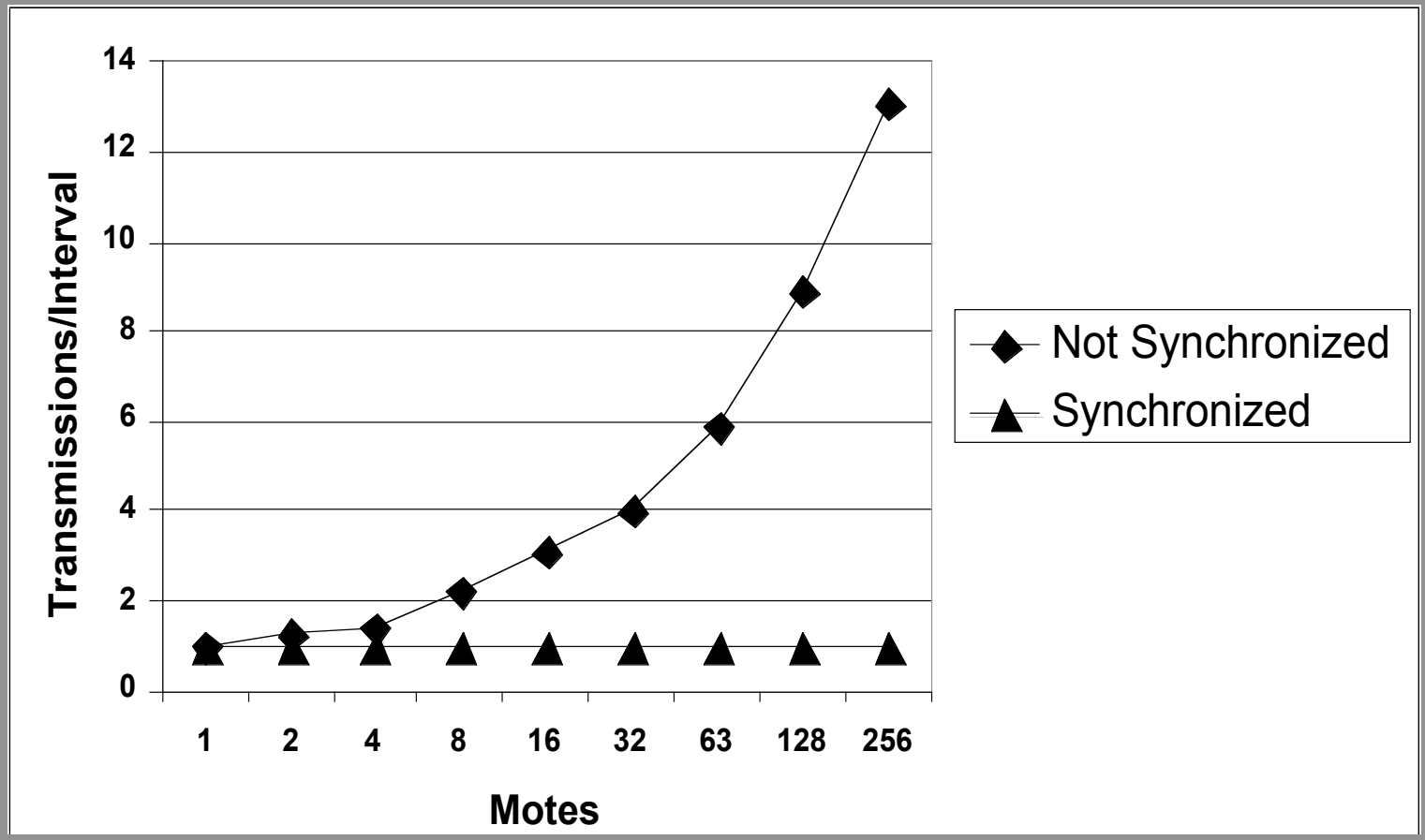
Loss
(algorithmic simulator)



Logarithmic Behavior of Loss

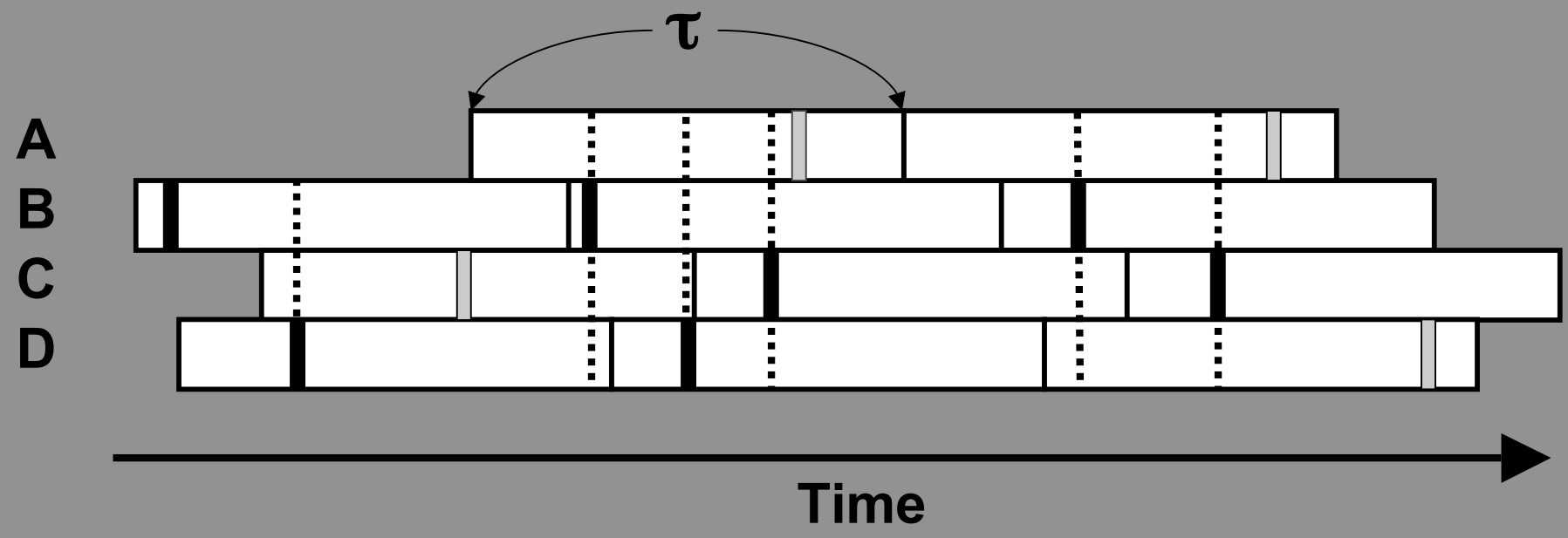
- Transmission increase is due to the probability that one node has not heard *n* transmissions
- Example: 10% loss
  - 1 in 10 nodes will not hear one transmission
  - 1 in 100 nodes will not hear two transmissions
  - 1 in 1000 nodes will not hear three, etc.
- Fundamental bound to maintaining a per-node communication rate

Synchronization
(algorithmic simulator)



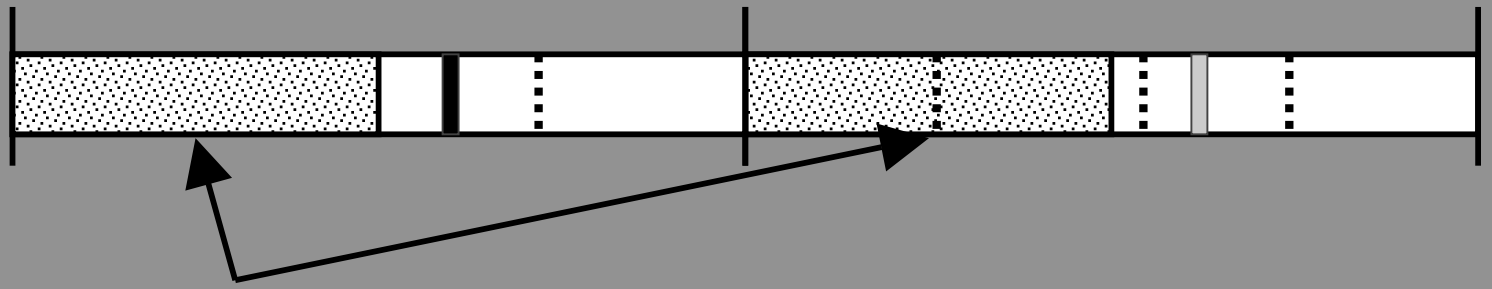
Short Listen Effect

- Lack of synchronization leads to the "short listen effect"
- For example, B transmits three times:



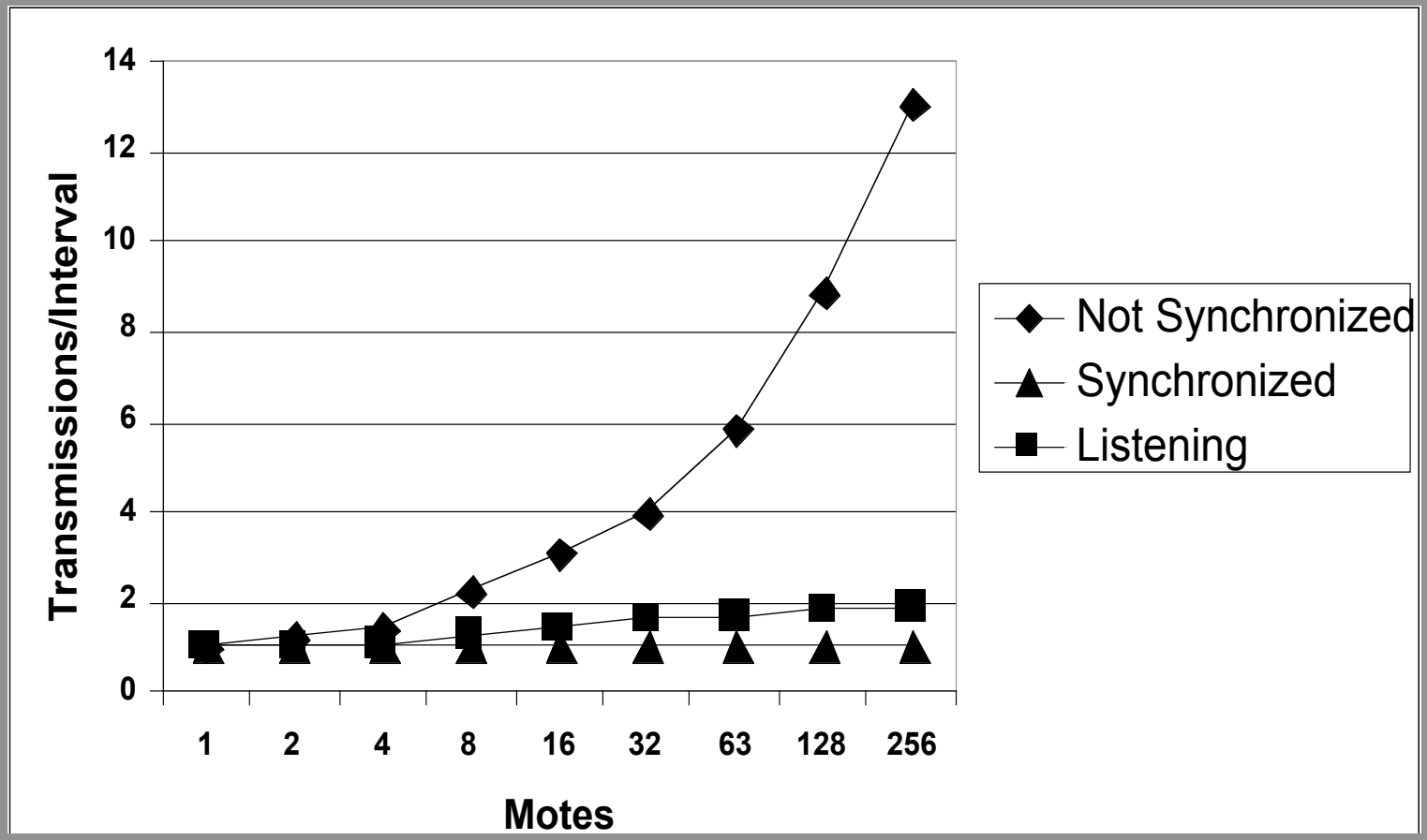
Short Listen Effect Prevention

- Add a listening period: *t* from [0.5τ, τ]



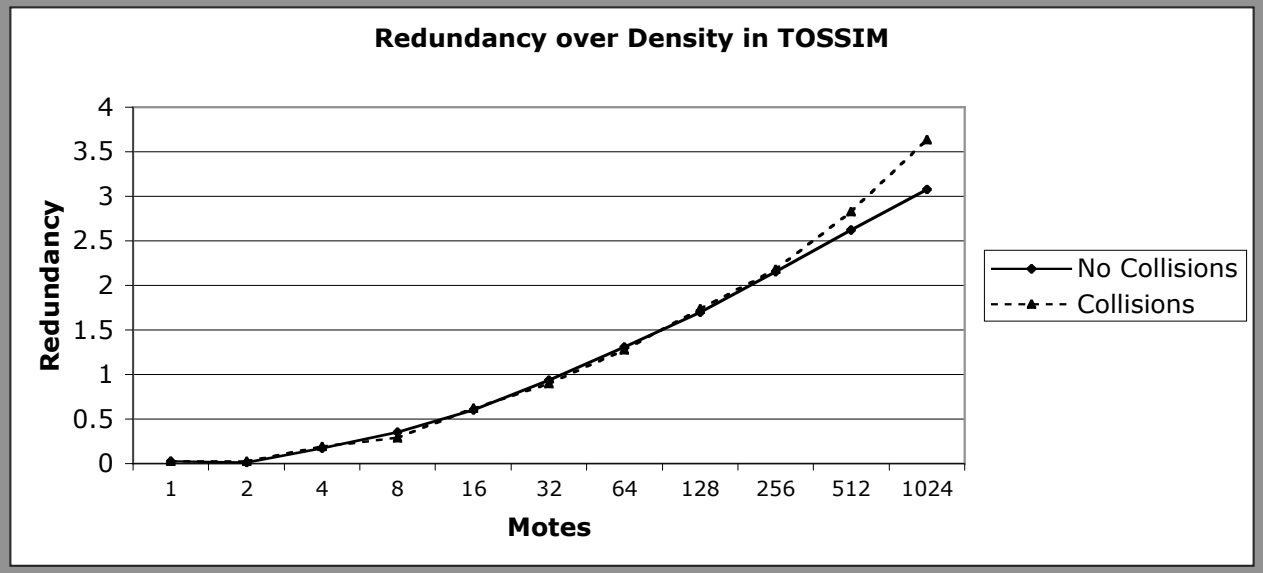
Listen-only period

Effect of Listen Period
(algorithmic simulator)



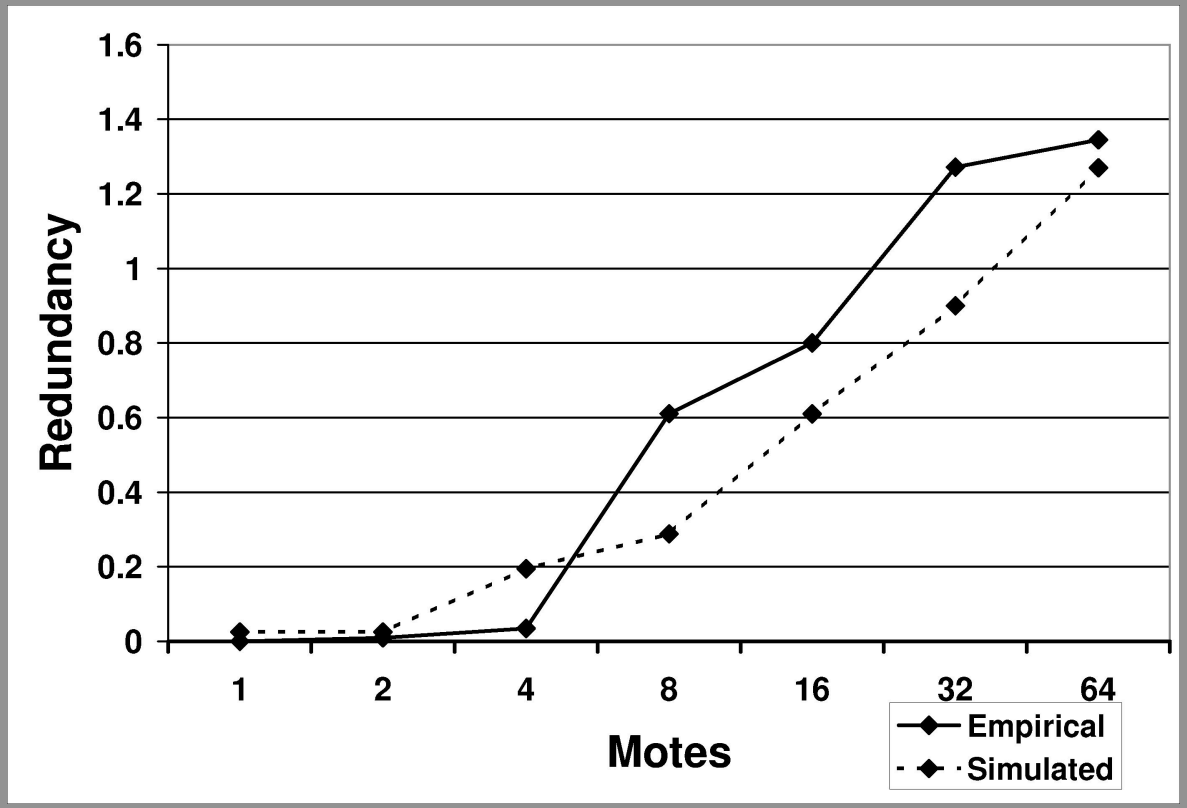
Multihop Network
(TOSSIM)

- Redundancy: $\frac{(transmissions + receptions)}{intervals} - k$
- Nodes uniformly distributed in 50'x50' area
- Logarithmic scaling holds



Empirical Validation (TOSSIM and deployment)

- 1-64 motes on a table, low transmit power



Maintenance Overview

- Trickle maintains a per-node communication rate
- Scales logarithmically with density, to meet the per-node rate for the worst case node
- Communication rate is really a number of transmissions *over space*

Interval Size Tradeoff

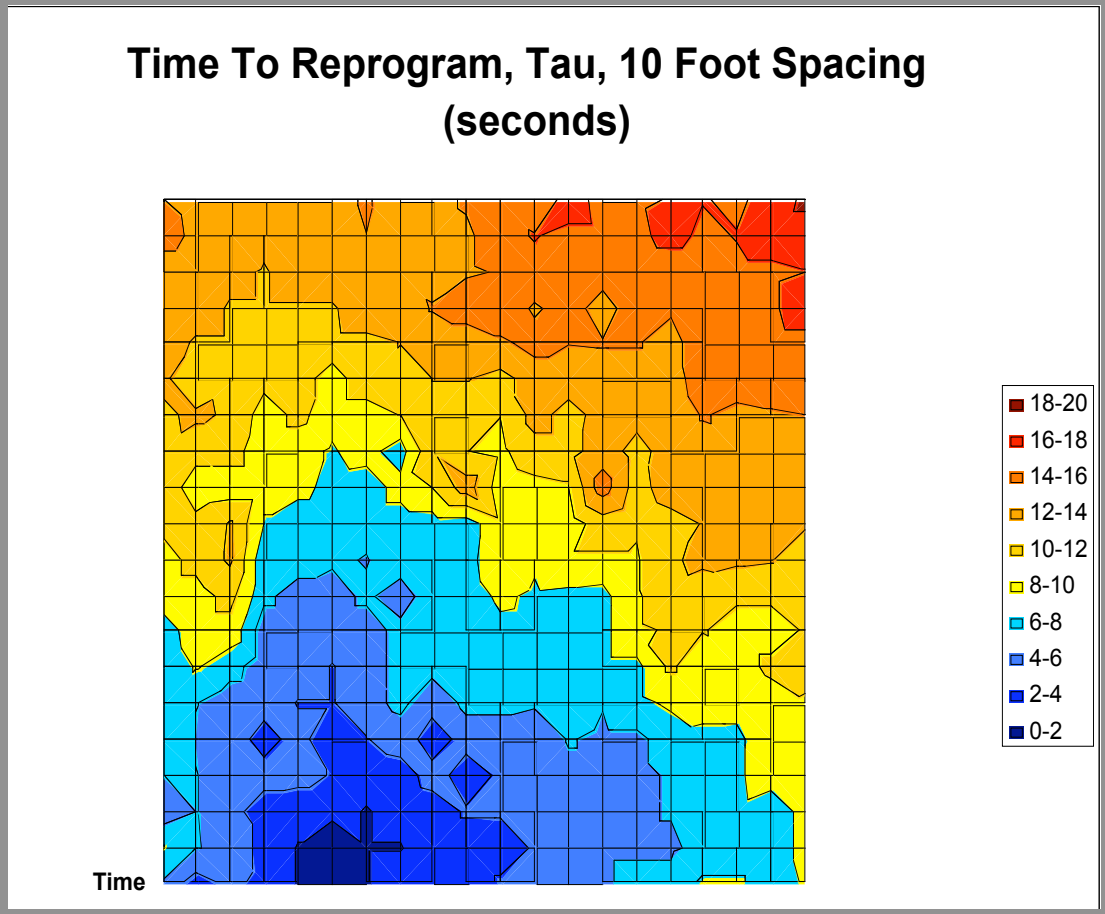
- Large interval τ
  - Lower transmission rate (lower maintenance cost)
  - Higher latency to discovery (slower propagation)
- Small interval τ
  - Higher transmission rate (higher maintenace cost)
  - Lower latency to discovery (faster propagation)
- Examples (k=1)
  - At τ = 10 seconds: 6 transmits/min, discovery of 5 sec/hop
  - At τ = 1 hour: 1 transmit/hour, discovery of 30 min/hop

Speeding Propagation

- Adjust τ: τ_l, τ_h
- When τ expires, double τ up to τ_h
- When *you* hear newer metadata, set τ to τ_l
- When *you* hear newer data, set τ to τ_l
- When *you* hear older metadata, send data

Simulated Propagation

- New data (20 bytes) at lower left corner
- 16 hop network
- Time to reception in seconds
- Set τ_l = 1 sec
- Set τ_h = 1 min
- 20s for 16 hops
- Wave of activity



Empirical Propagation

- Deployed 19 nodes in office setting
- Instrumented nodes for accurate installation times
- 40 test runs

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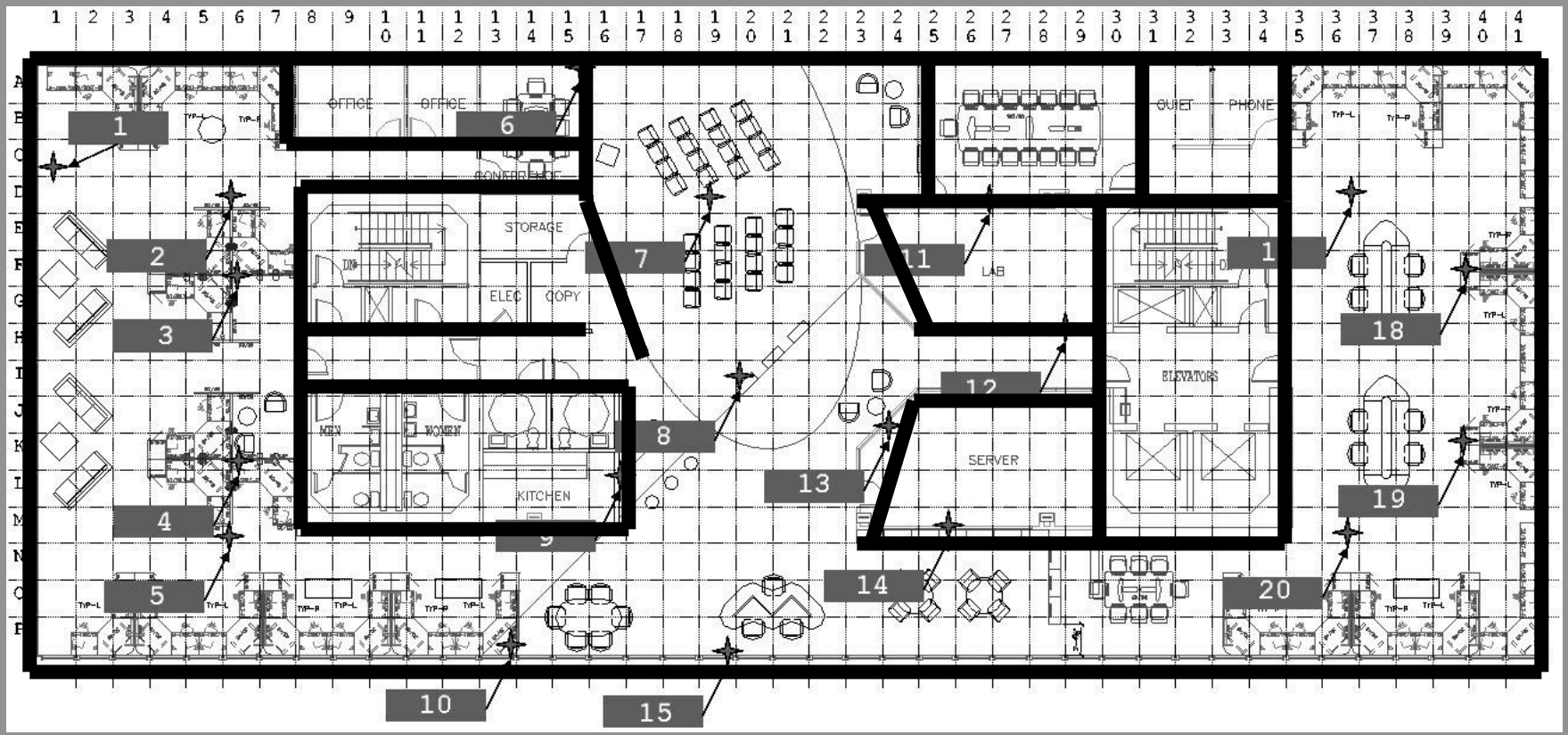
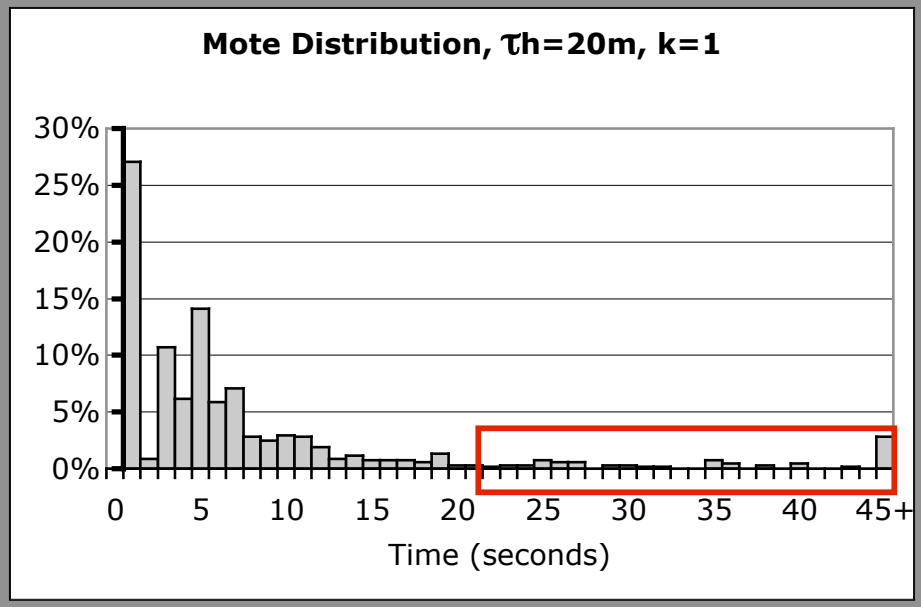
Network Layout
(about 4 hops)



Empirical Results

k=1, τ_l=1 second, τ_h=20 minutes



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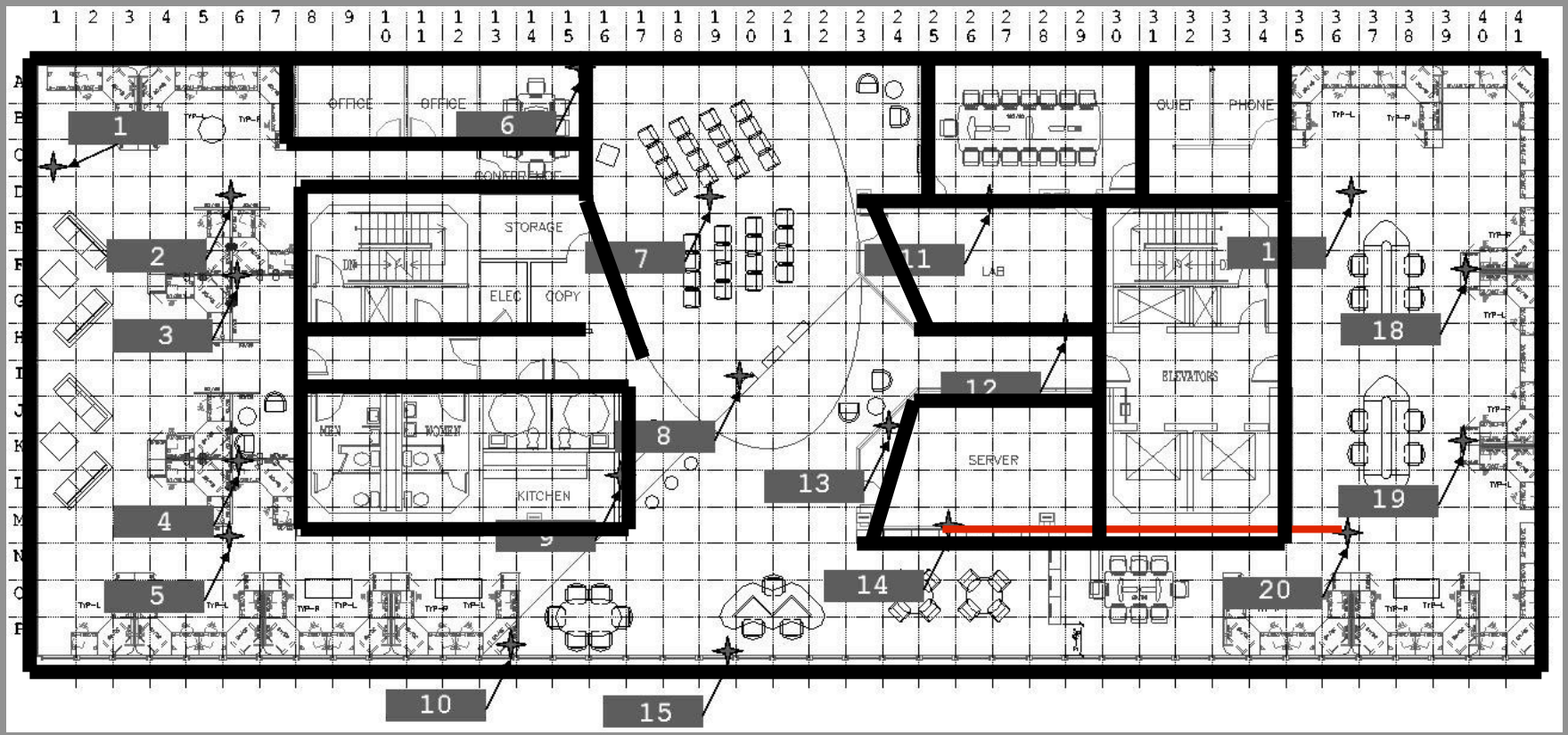

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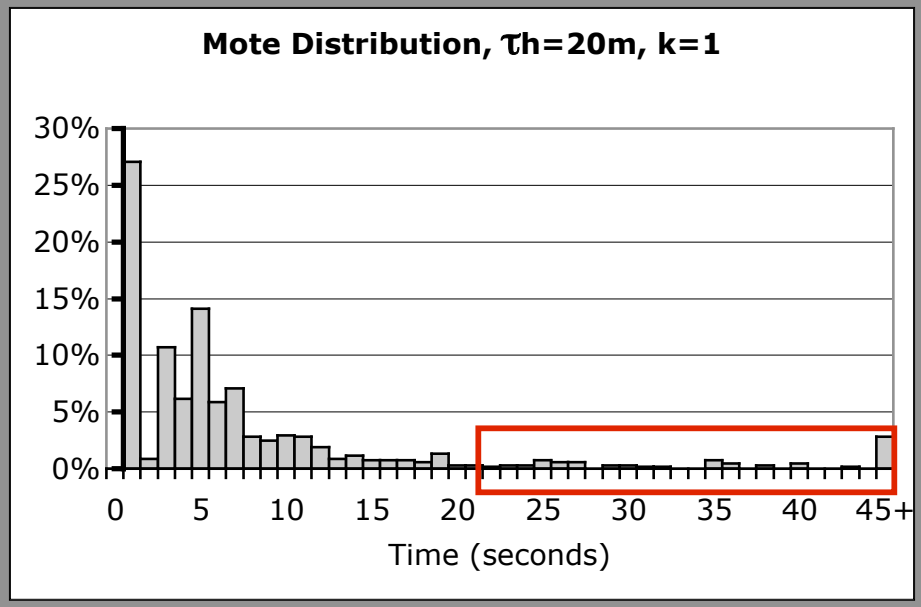


- Sparse networks can have a few stragglers.

Dissemination

- Trickle scales logarithmically with density
- Can obtain rapid propagation with low maintenance
  - In example deployment, maintenance of a few sends/hour, propagation of 30 seconds
- Controls a transmission rate over space
  - Coupling between network and the physical world
- Trickle is a nameless protocol
  - Uses wireless connectivity as an implicit naming scheme
  - No name management, neighbor lists…
  - Stateless operation (well, eleven bytes)

A Spectrum of Protocol Classes

- Dissemination: One to N

- Aggregation Routing: N to One

Aggregation Routing

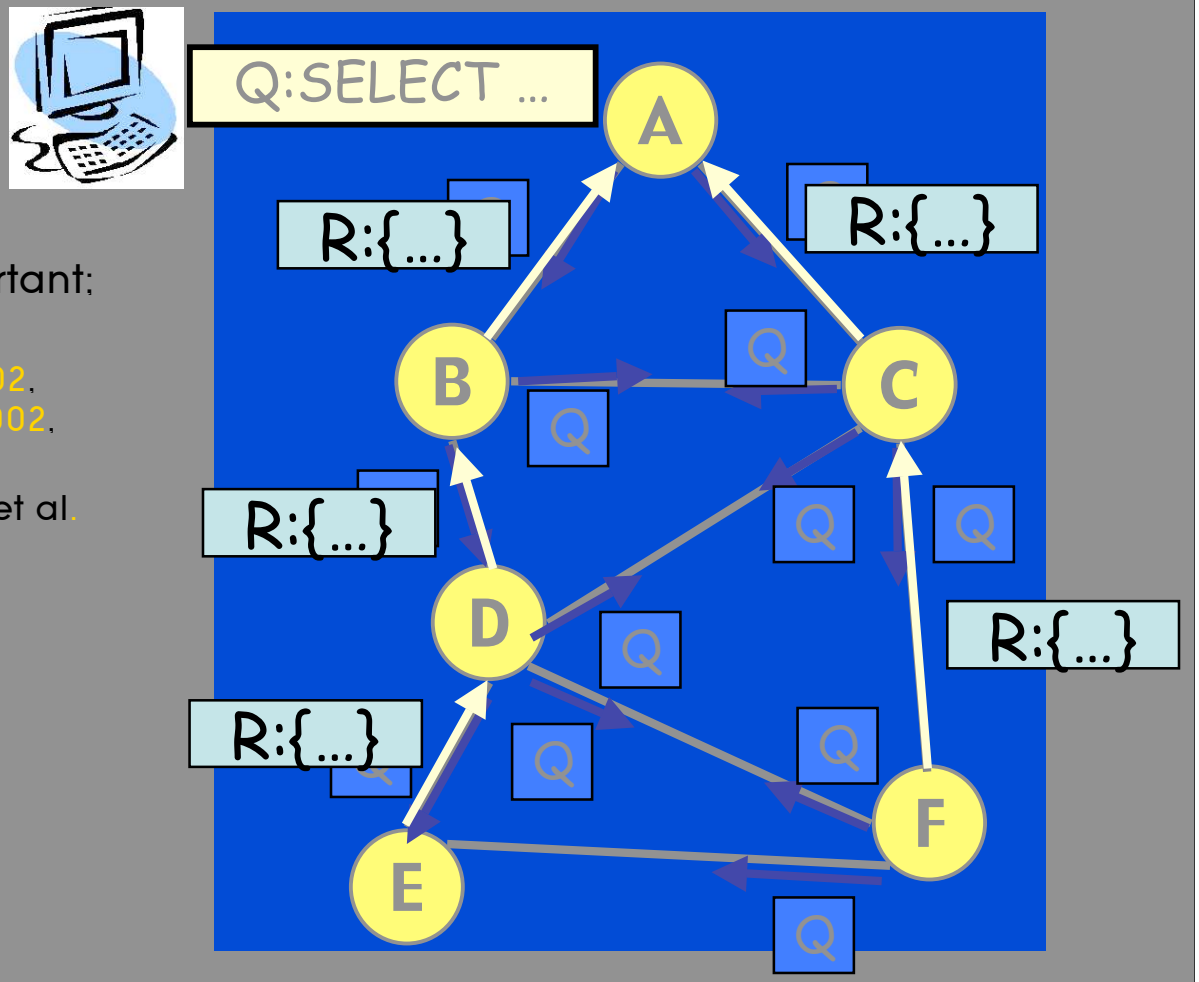
- Collect data *aggregates* from a network
  - "How many nodes are there?"
  - "What is the mean temperature?"
  - "What is the median temperature?"
- Deliver aggregate to a central point (root)
- Two examples: Tiny*D*B and S*y*nopsis Diffusion

TinyDB: Tiny Aggregation (TAG)

- Proposed by Sam Madden et al.
- Compute aggregates over a collection tree

Query Propagation Via Tree-Based Routing

- Tree-based routing
  - Used in:
    - Query delivery
    - Data collection
  - Topology selection is important; e.g.
    - Krishnamachari, DEBS 2002, Intanagonwiwat, ICDCS 2002, Heidemann, SOSP 2001
    - LEACH/SPIN, Heinzelman et al. MOBICOM 99
    - SIGMOD 2003
  - Continuous process
    - Mitigates failures



Basic Aggregation

- In each epoch:
  - Each node samples local sensors once
  - Generates partial state record (PSR)
    - local readings
    - readings from children
  - Outputs PSR during assigned comm. interval
- At end of epoch, PSR for whole network output at root
- New result on each successive epoch
- Extras:
  - Predicate-based partitioning via GROUP BY

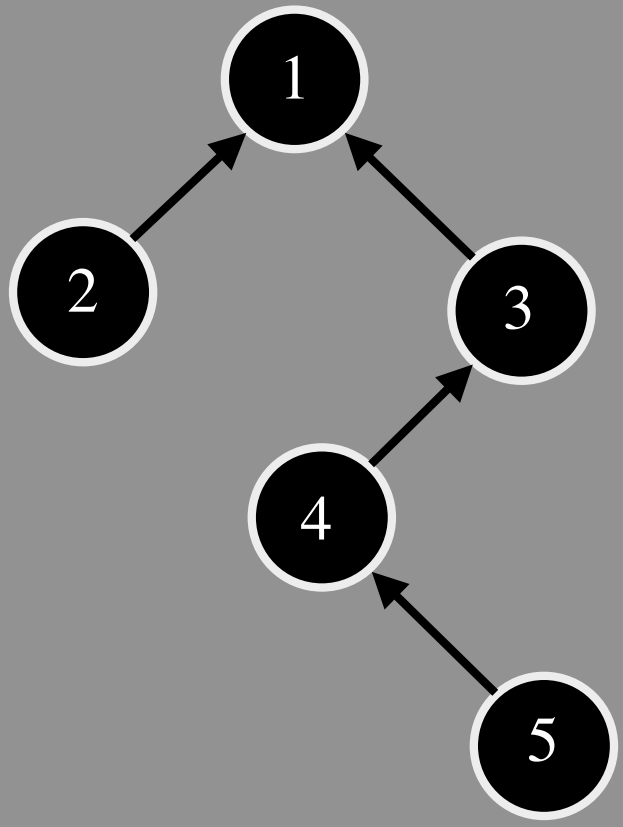


Illustration: Aggregation

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SELECT COUNT(*)
FROM sensors
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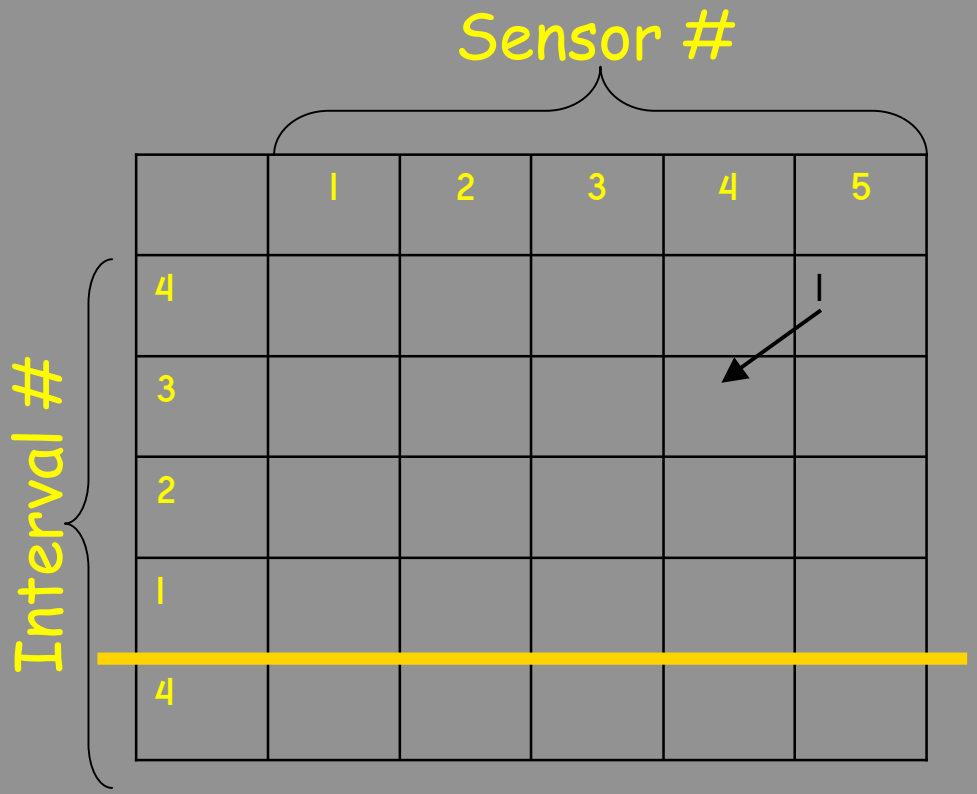

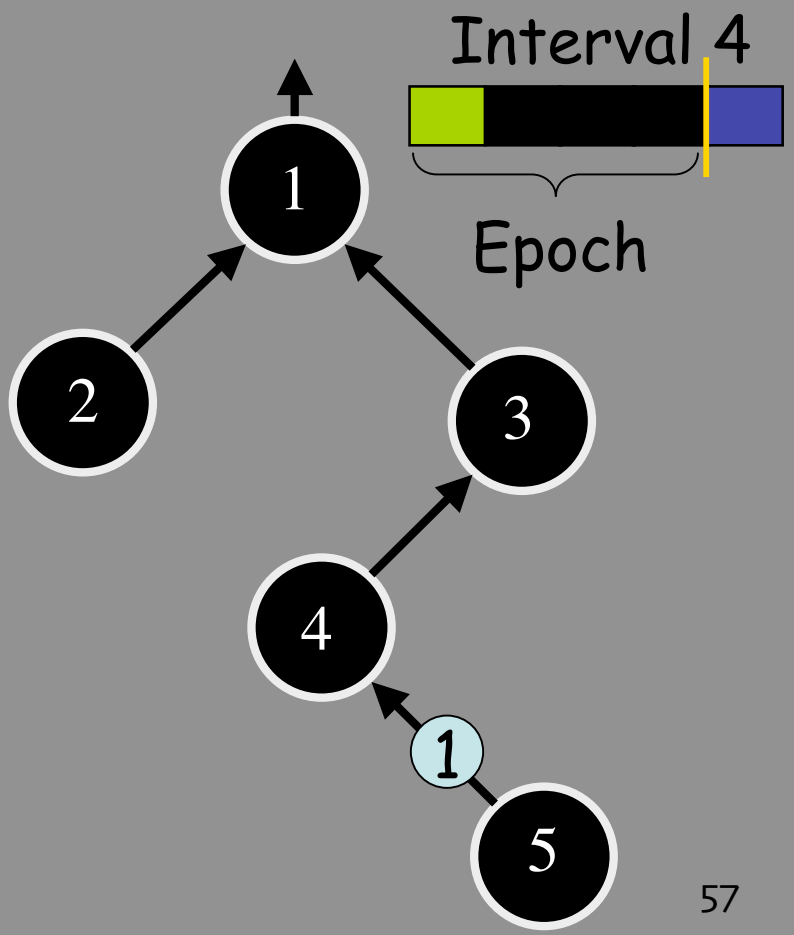

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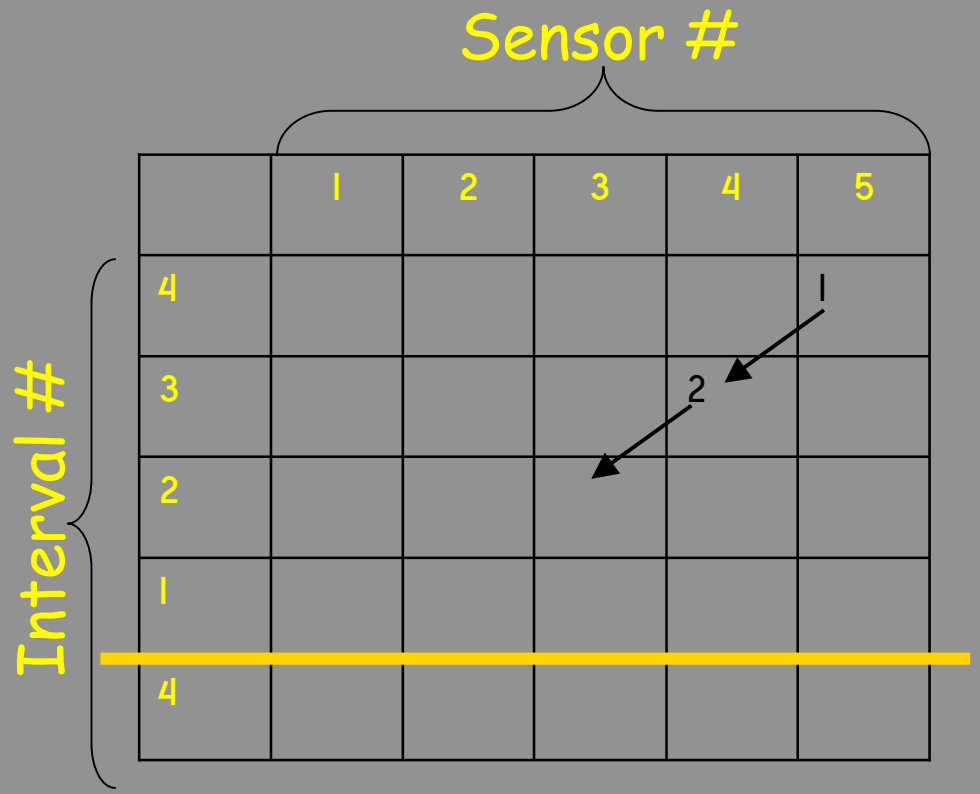

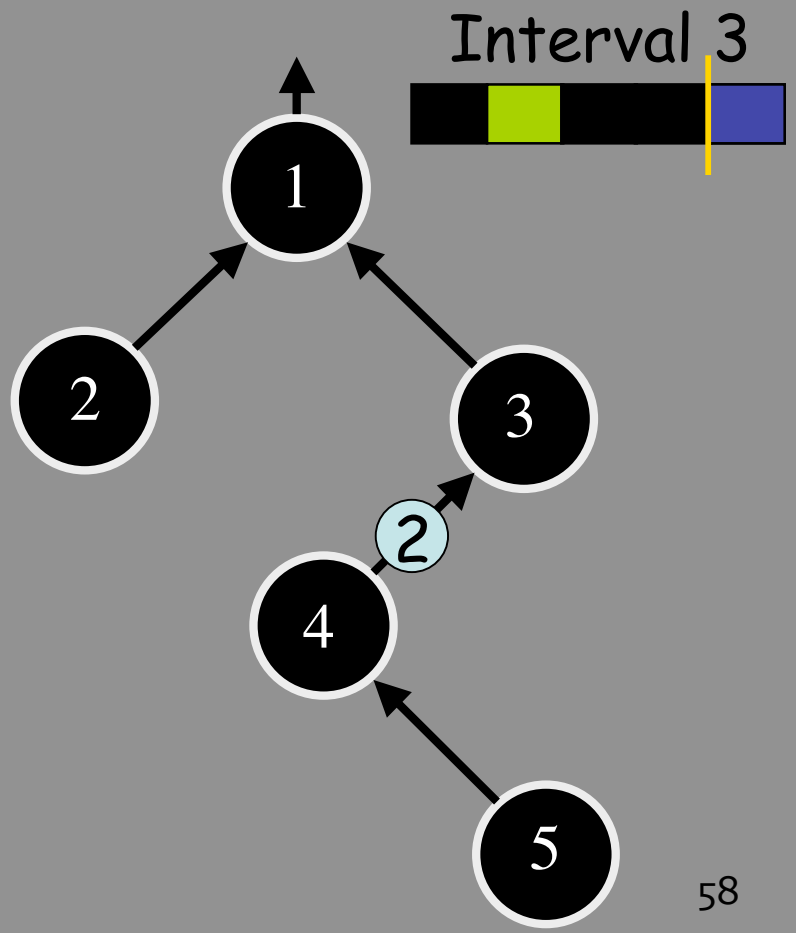

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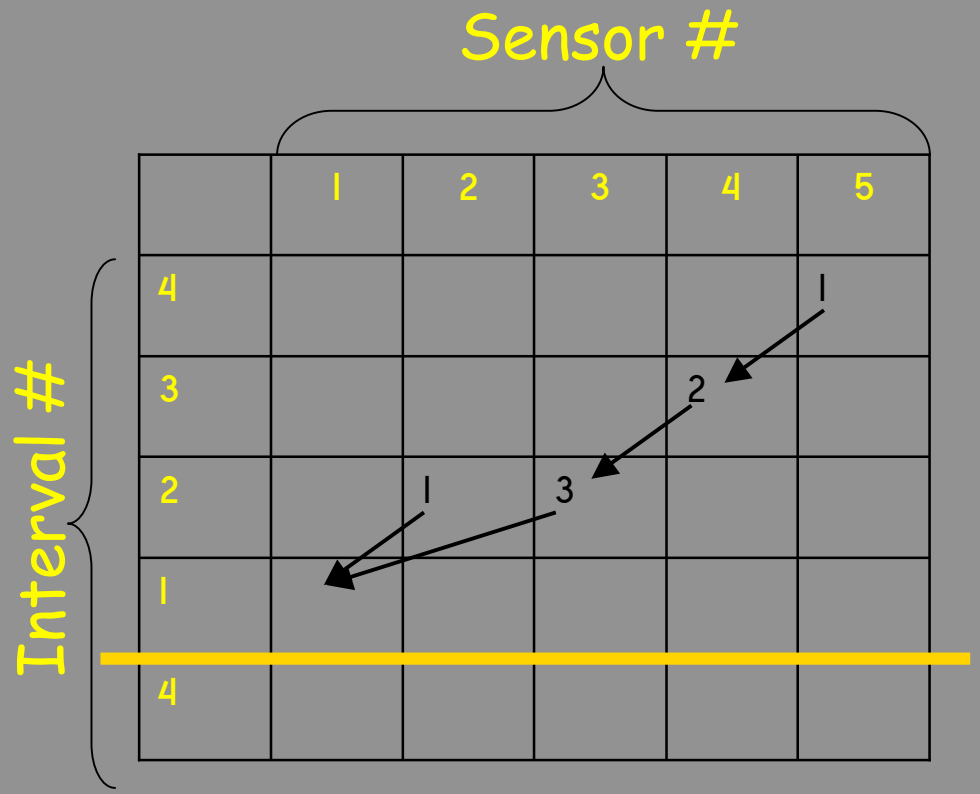

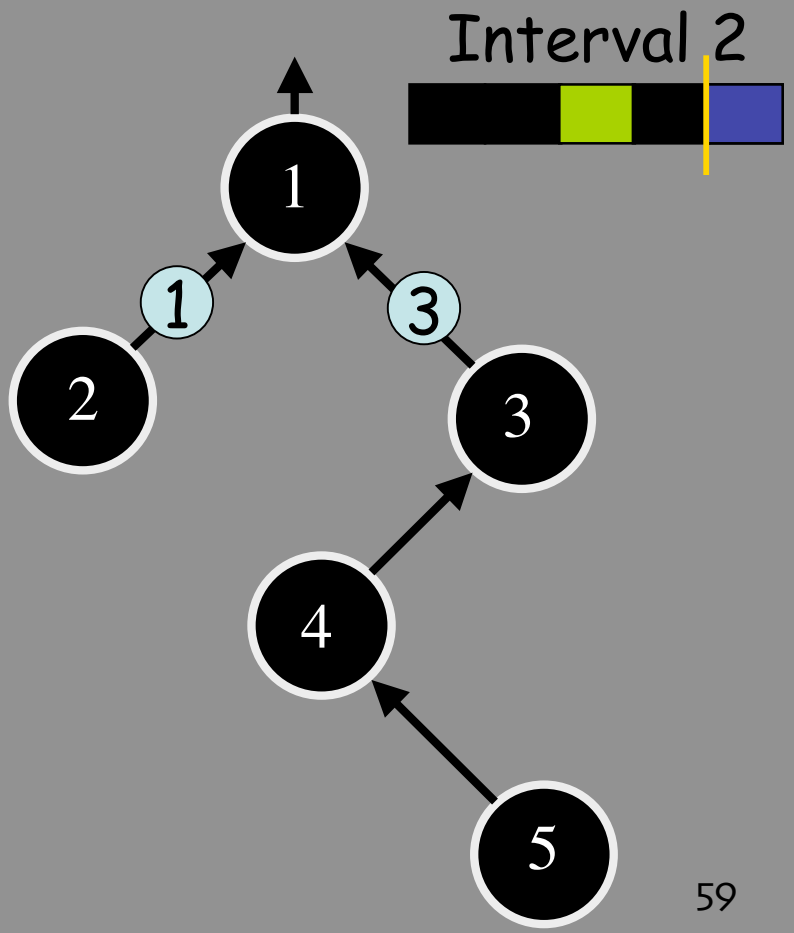

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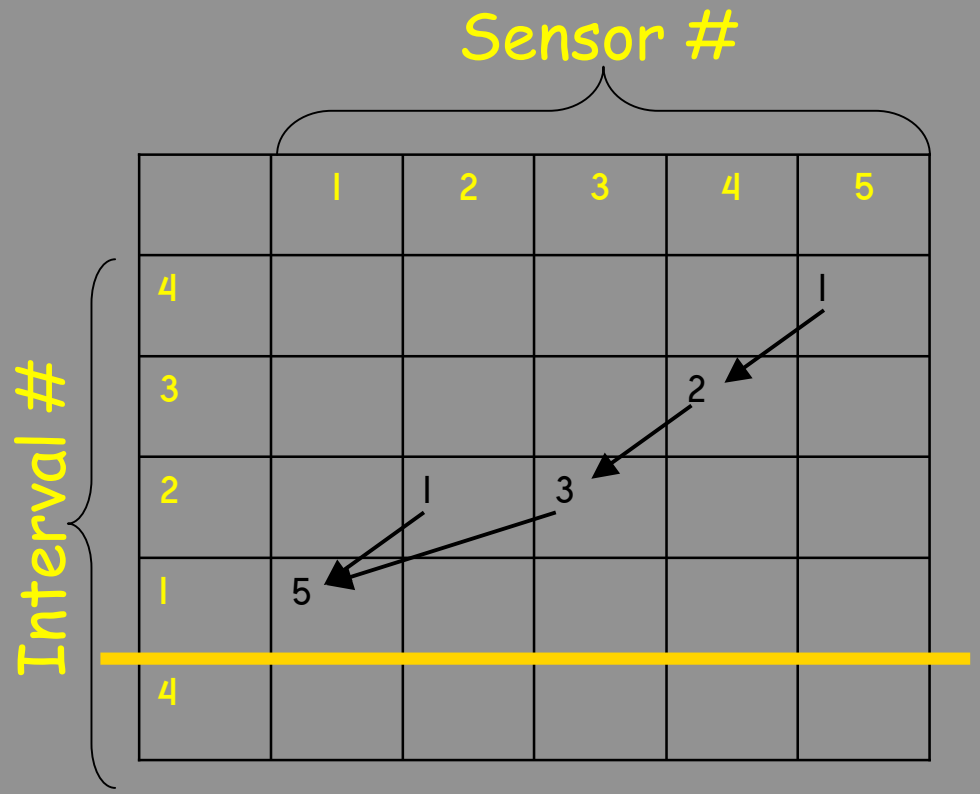

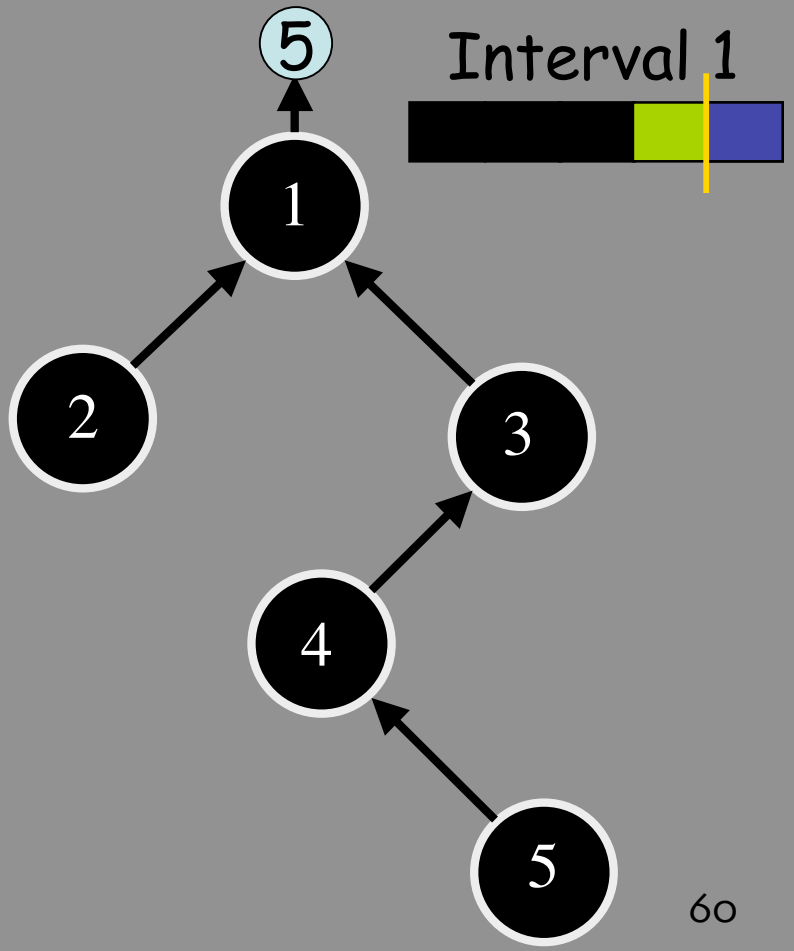

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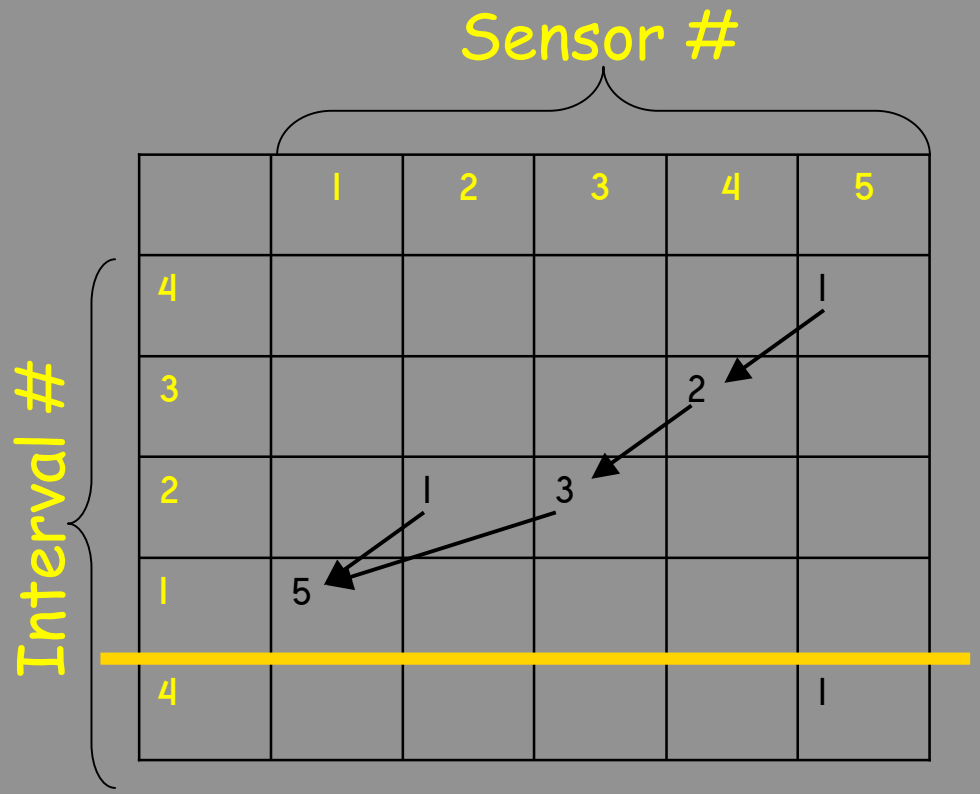
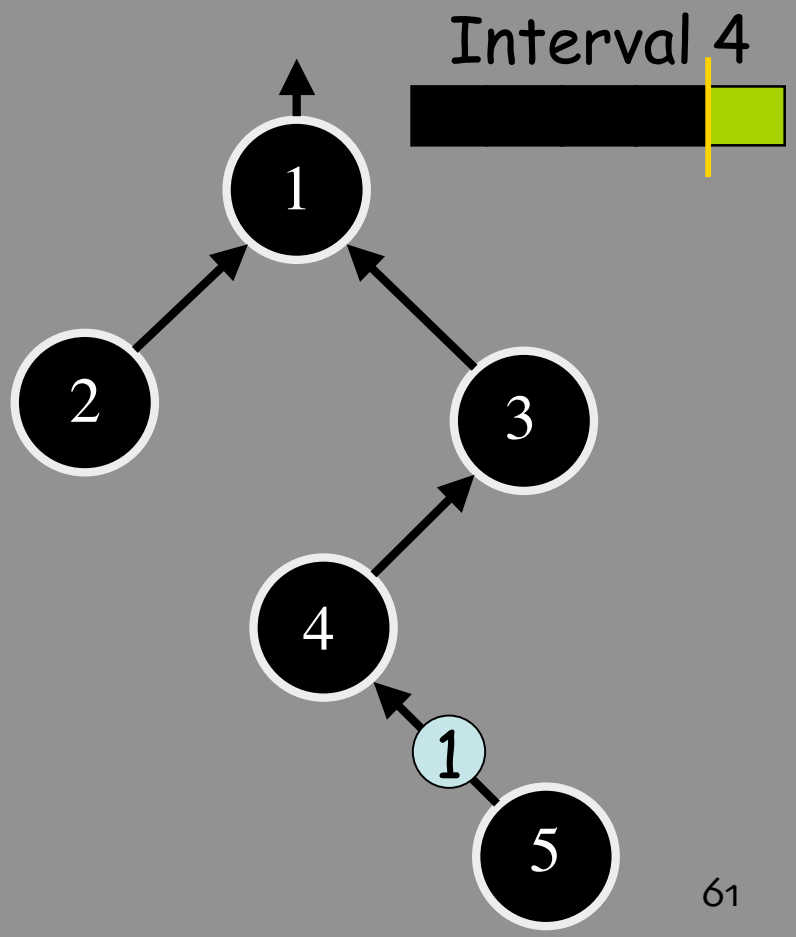




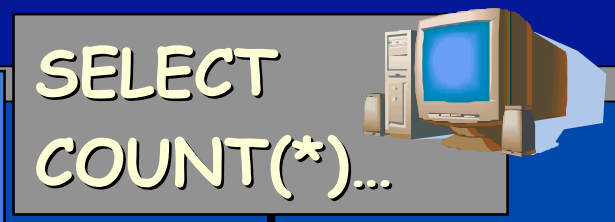
Interval Assignment: An Approach

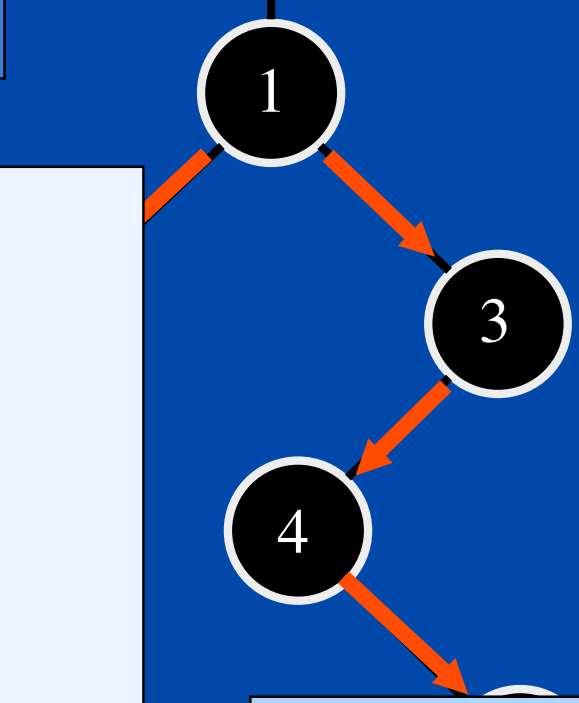
4 intervals / epoch

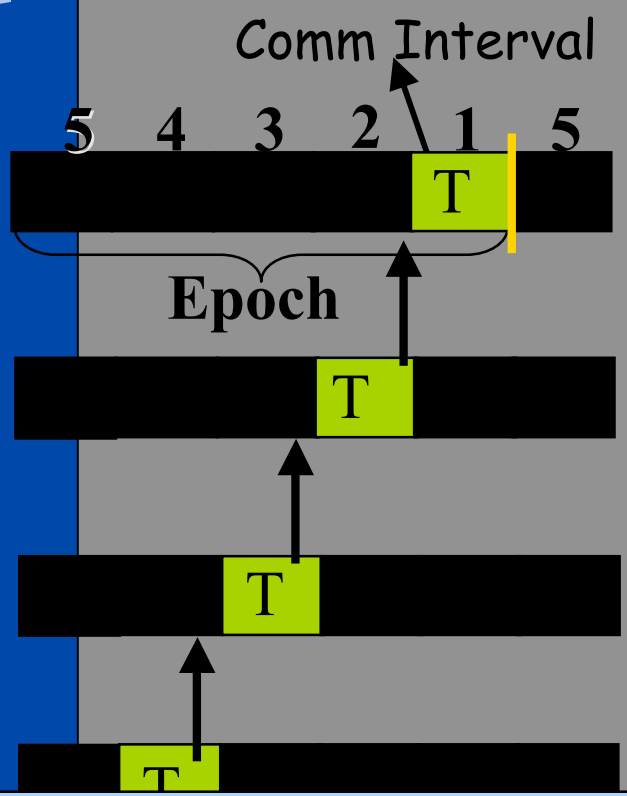
Interval # = Level

Level = 1

- **CSMA for collision avoidance**
- **Time intervals for power conservation**
- **Many variations**
- **Time Sync**







Pipelining: Increase throughput by delaying result arrival until a later epoch

Aggregation Framework

- Support any aggregation function conforming to:

$Agg_n = \{f_{init}, f_{merge}, f_{evaluate}\}$

$F_{init}\ \{a_0\} \rightarrow \langle a_0 \rangle$

$F_{merge}\ \{\langle a_1 \rangle, \langle a_2 \rangle\} \rightarrow \langle a_{12} \rangle$

$F_{evaluate}\ \{\langle a_1 \rangle\} \rightarrow$ aggregate value

Partial State Record (PSR)

Example: Average

$AVG_{init}\ \{v\} \rightarrow \langle v, 1 \rangle$

$AVG_{merge}\ \{\langle S_1, C_1 \rangle, \langle S_2, C_2 \rangle\} \rightarrow \langle S_1 + S_2\ ,\ C_1 + C_2 \rangle$

$AVG_{evaluate}\{\langle S, C \rangle\} \rightarrow S/C$

Types of Aggregates

- SQL supports MIN, MAX, SUM, COUNT, AVERAGE
- An*y* function over a set *can* be computed via TAG
- In network benefit for man*y* operations
  - E.g. Standard deviation, top/bottom N, spatial union/intersection, histograms, etc.
  - Compactness of PSR

TAG/TinyDB Observations

- Complex: requires a collection tree as well as pretty good time synchronization
- Fragile: single lost result can greatly perturb result
- In practice, really hard to get working.
  - Sonoma data yield < 50%
  - Intel TASK project (based on TinyDB) has had many deployment troubles/setbacks (GDI 2004)

Another Take on Aggregation

- "Sketches" proposed by two groups
  - BU: Jeffrey Considine, Feifei Li, George Kollios and John Byers (ICDE 2004)
  - CMU: Suman Nath, Phillip B. Gibbons, Srinivasan Seshan, and Zachary Anderson (SenSys 2004)
- Based on work probabilistic counting algorithm work by Flajolet and Martin (1985)

Basic Observation

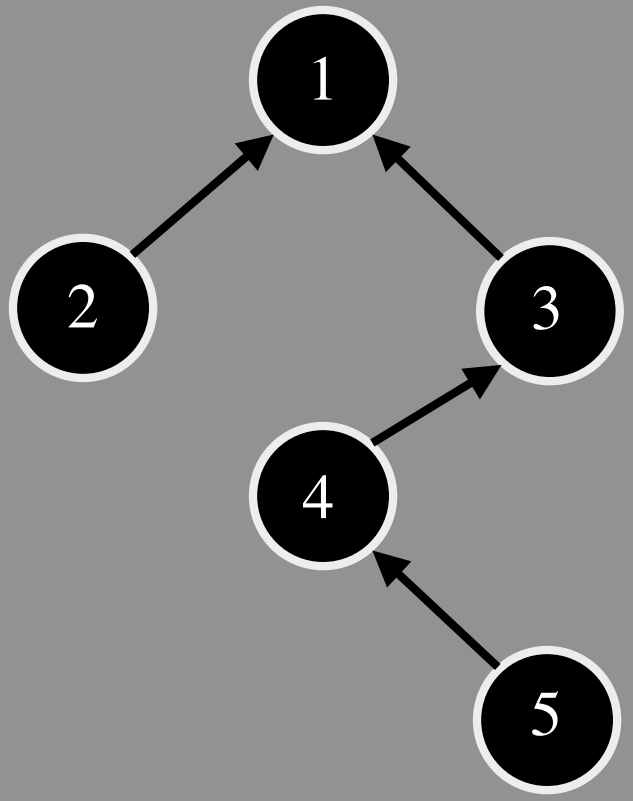
- Fragility comes from duplicate and order sensitivity
  - A PSR included twice will perturb the result
  - Computational model bound to communication model
- Decoupling routing from computation is desirable
  - Compute aggregates over *arbitrary* network layers, can take advantage of multipath propagation, etc.
  - Decoupling requires aggregates to be resistant to a single result being included multiple times, ordering

Synopsis Diffusion

- Order and duplicate insensitive (ODI) aggregates
- Every node generates a "sketch" of its value
- Aggregation combines sketches in an ODI way
  - E.g., take a boolean OR
- Compute aggregate result from combined sketch

More Specifically

- Three functions:
  - Generate initial sketch (produce a bit field)
  - Merge sketches (ODI)
  - Compute aggregate from complete sketch



Example

- Three functions:
  - Generate initial sketch (produce a bit field)
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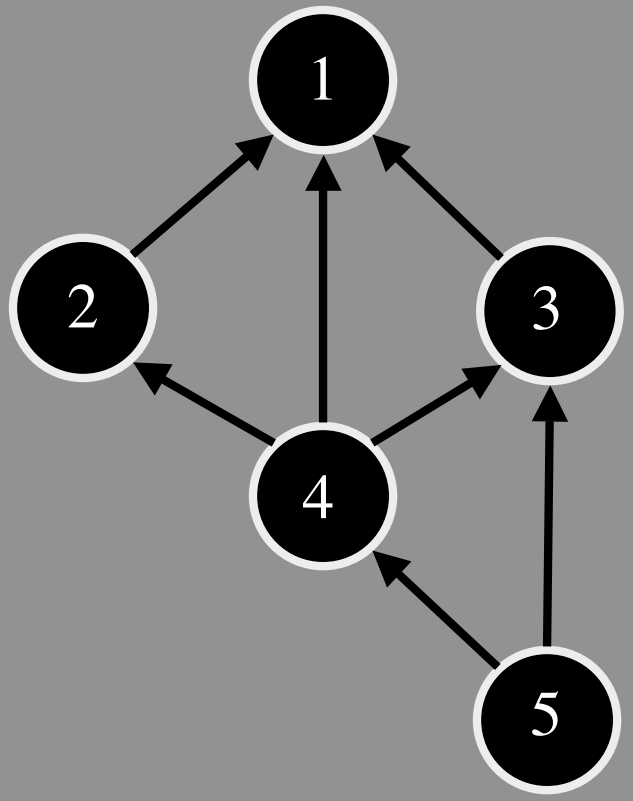
  - Compute aggregate from complete sketch



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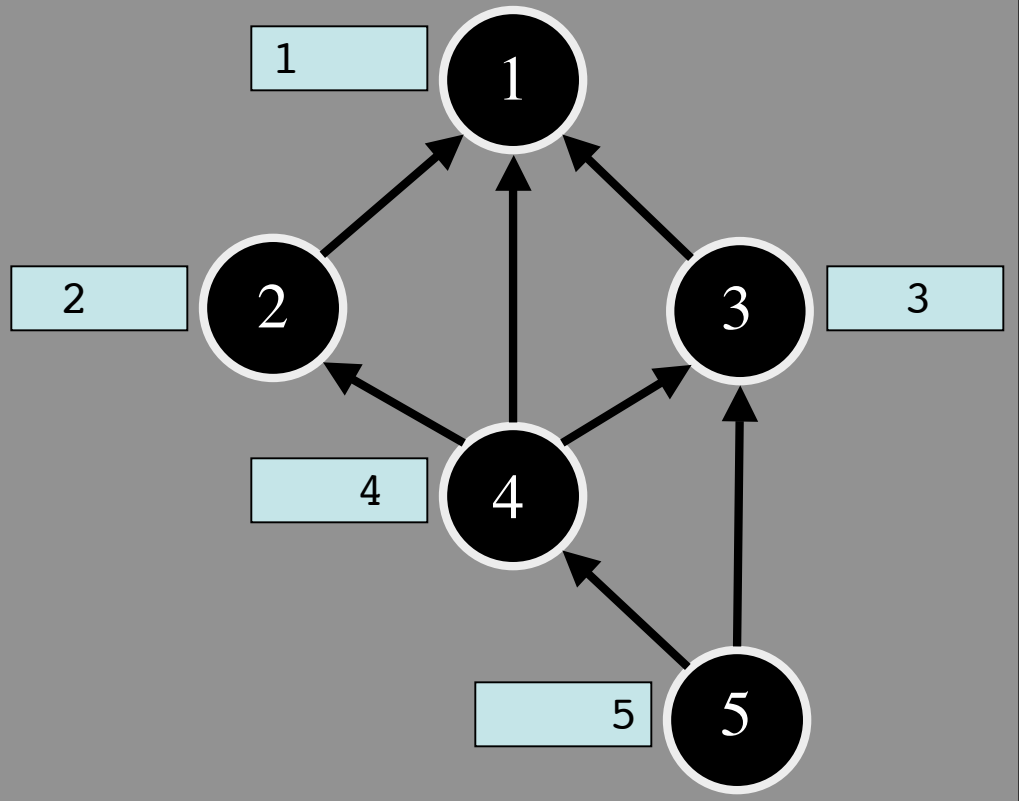

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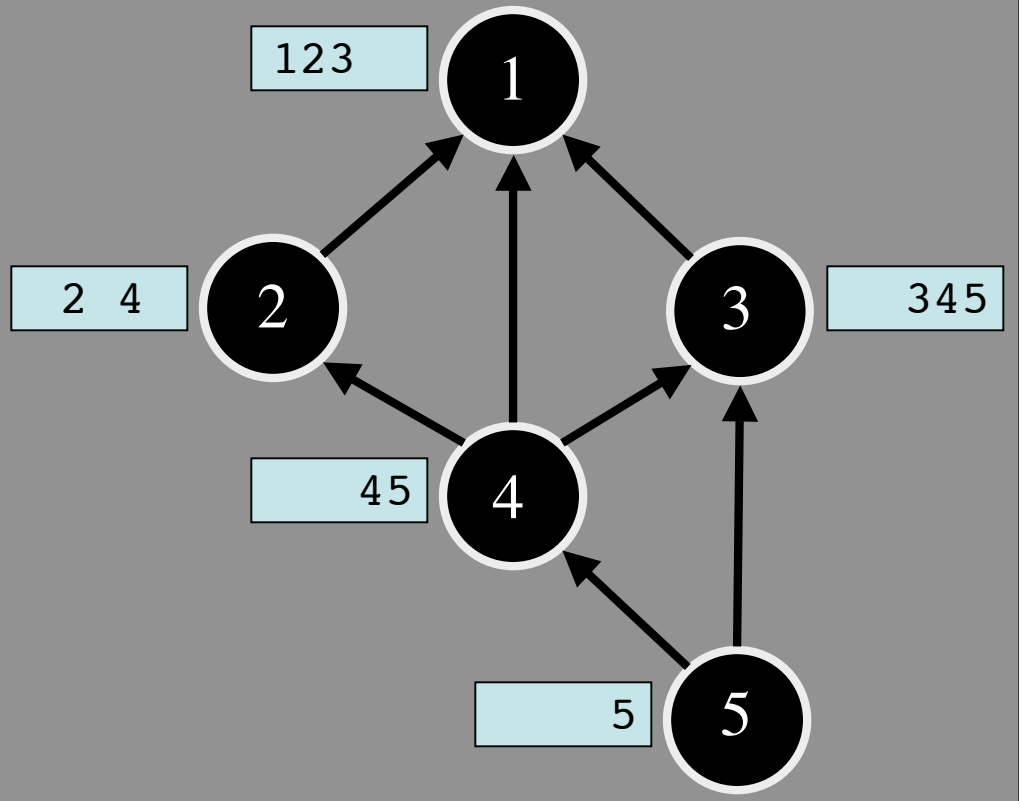

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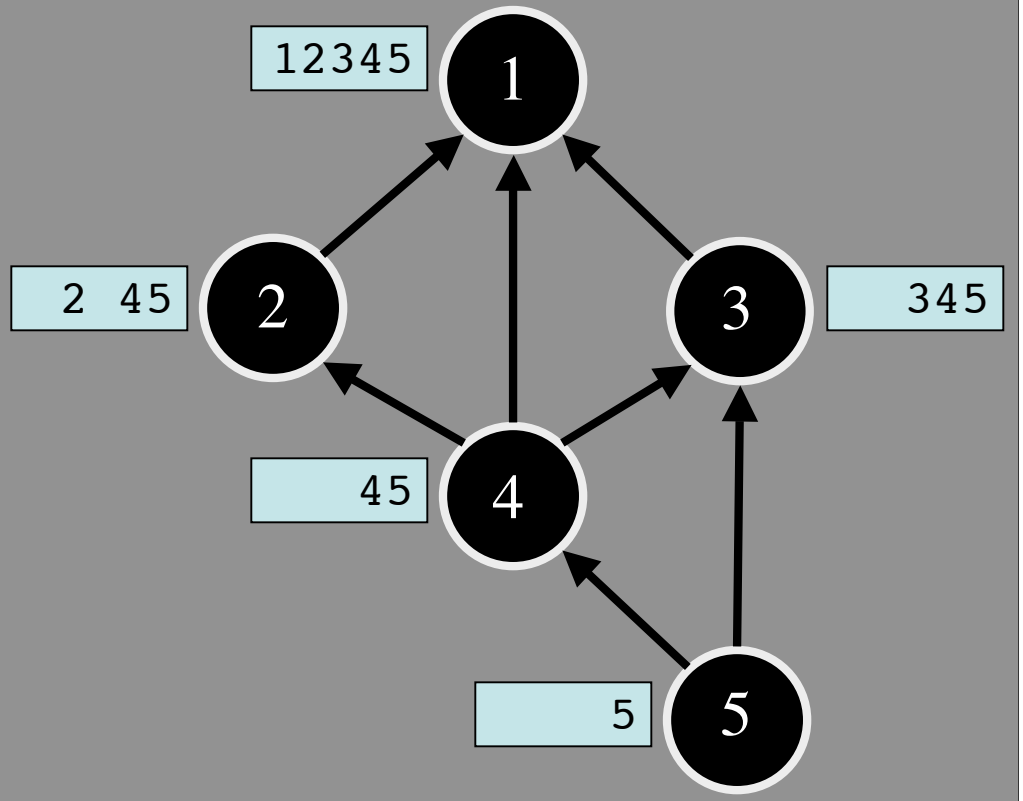

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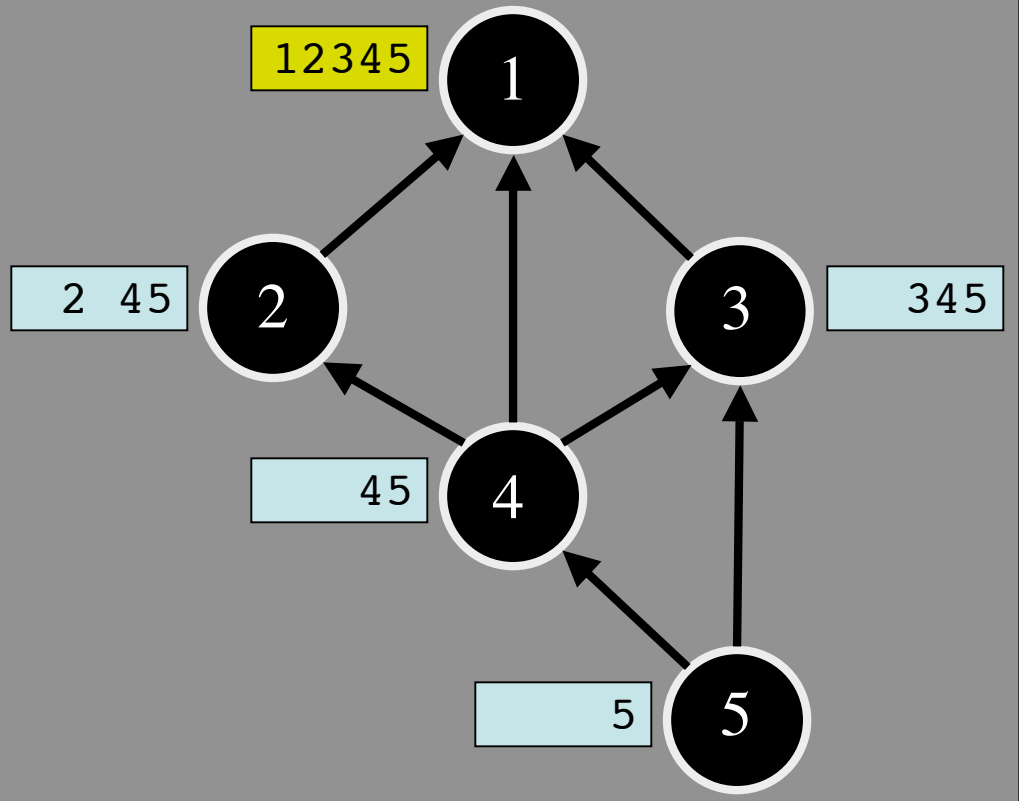
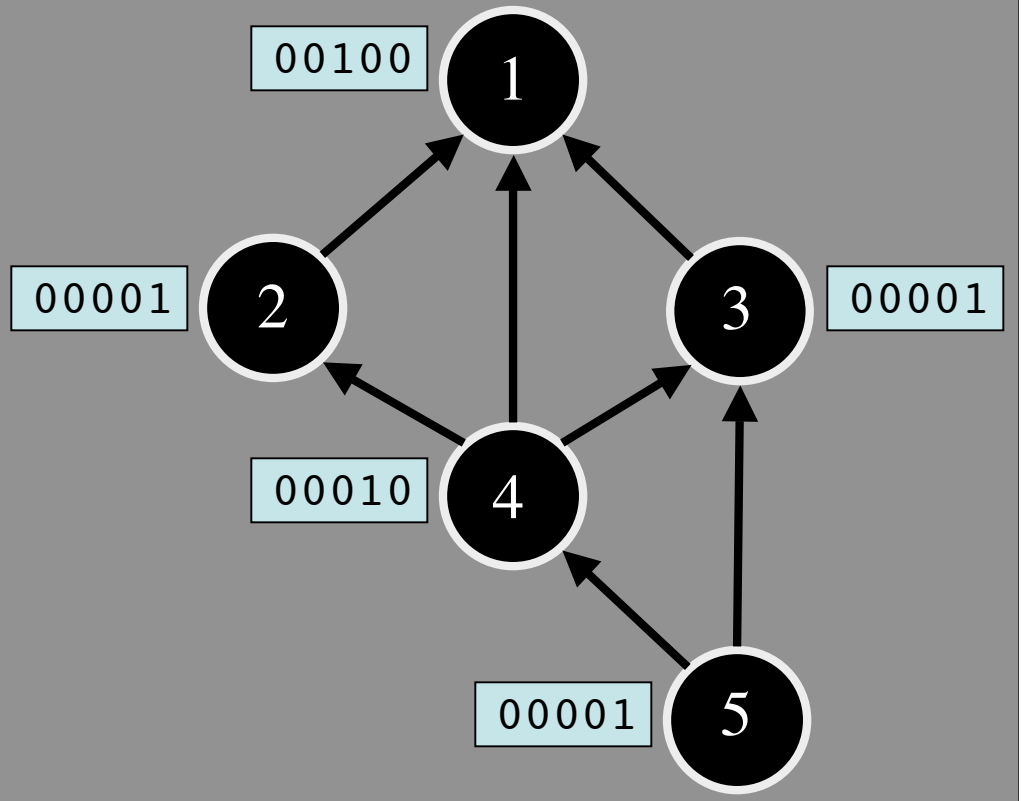


Example ODI: Count

- How many nodes are there in the network?
- Generating initial sketch
  - Generate a random number
  - Sketch is the least significant 0 bit in the number
  - E.g.: `0110101011101011 -> 0000000000000100`
- Merging sketches: binary OR of two sketches
- Resolving aggregate:
  - Final value is the least significant 0 in the sketch/1.546
  - `0000000101111111 -> 0000000010000000/1.546`

Count Example

- Three functions:
  - Generate initial sketch
  - Merge sketches (ODI)
  - Compute aggregate from complete sketch



Count Example

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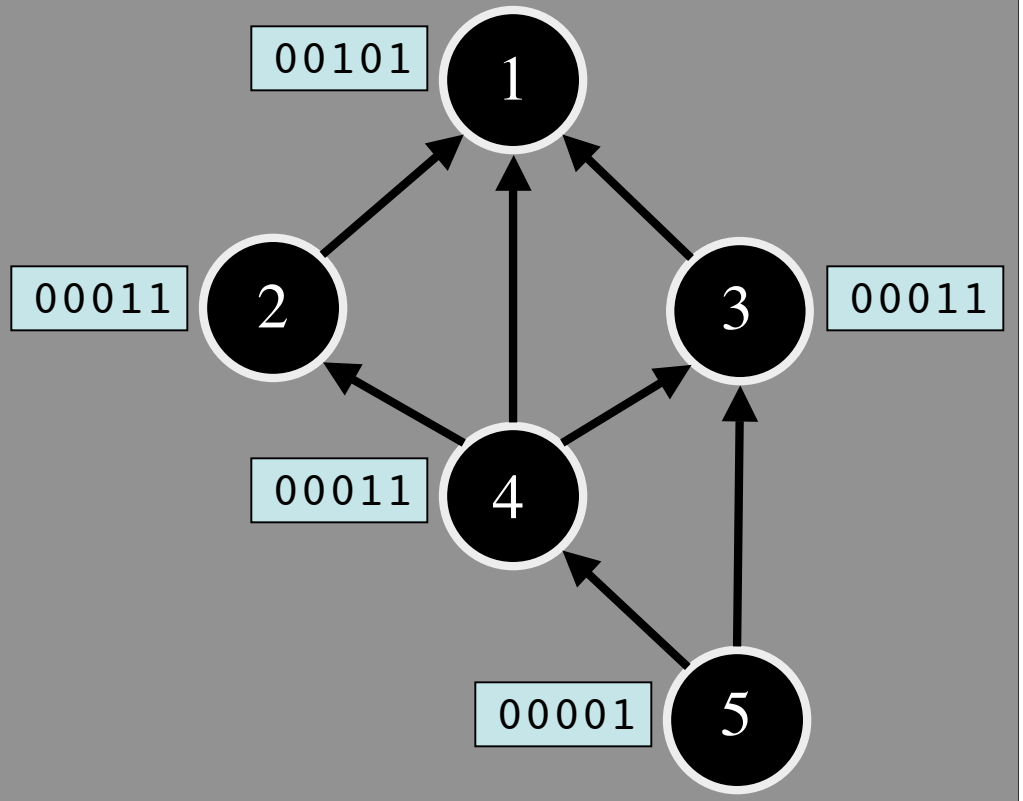
  - Merge sketches (ODI)
  - Compute aggregate from complete sketch



Count Example

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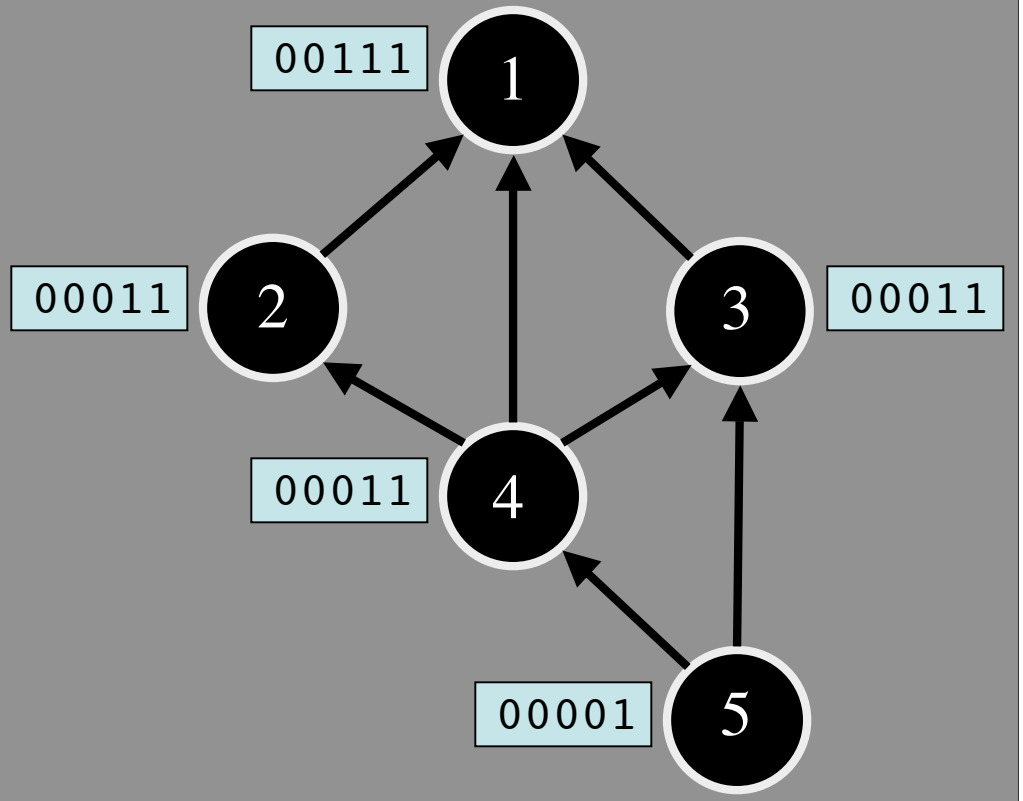
  - Generate initial sketch
  - Merge sketches (ODI)
  - Compute aggregate from complete sketch



Count Example

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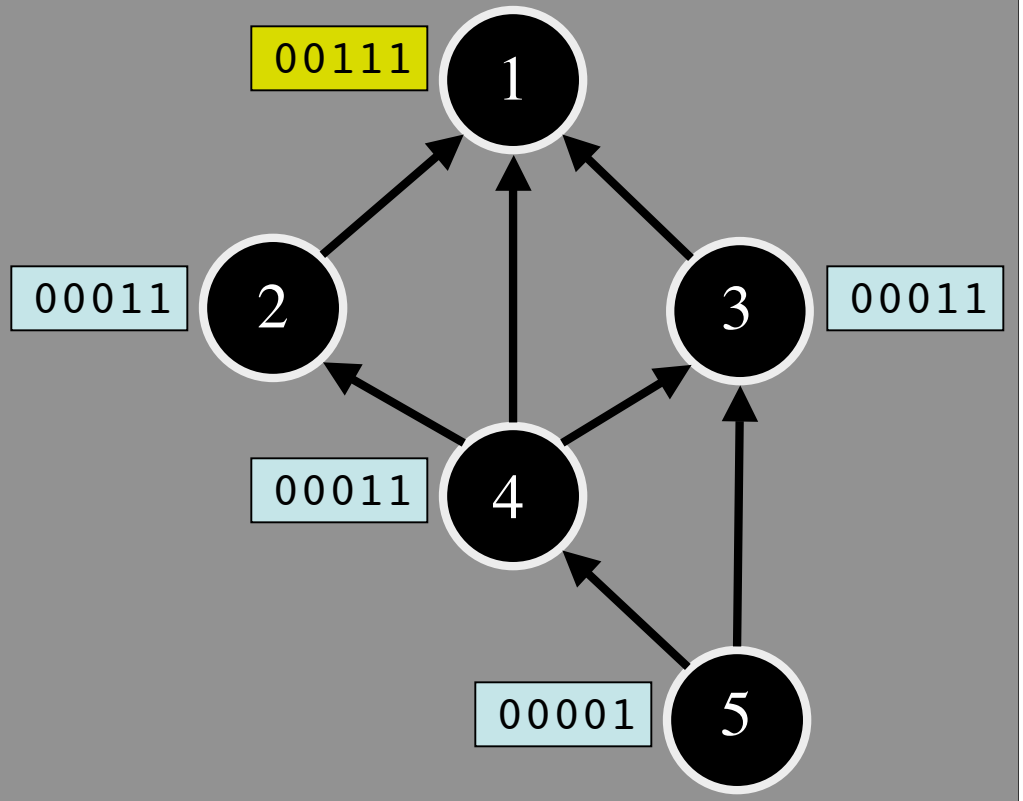
  - Compute aggregate from complete sketch



Count Example

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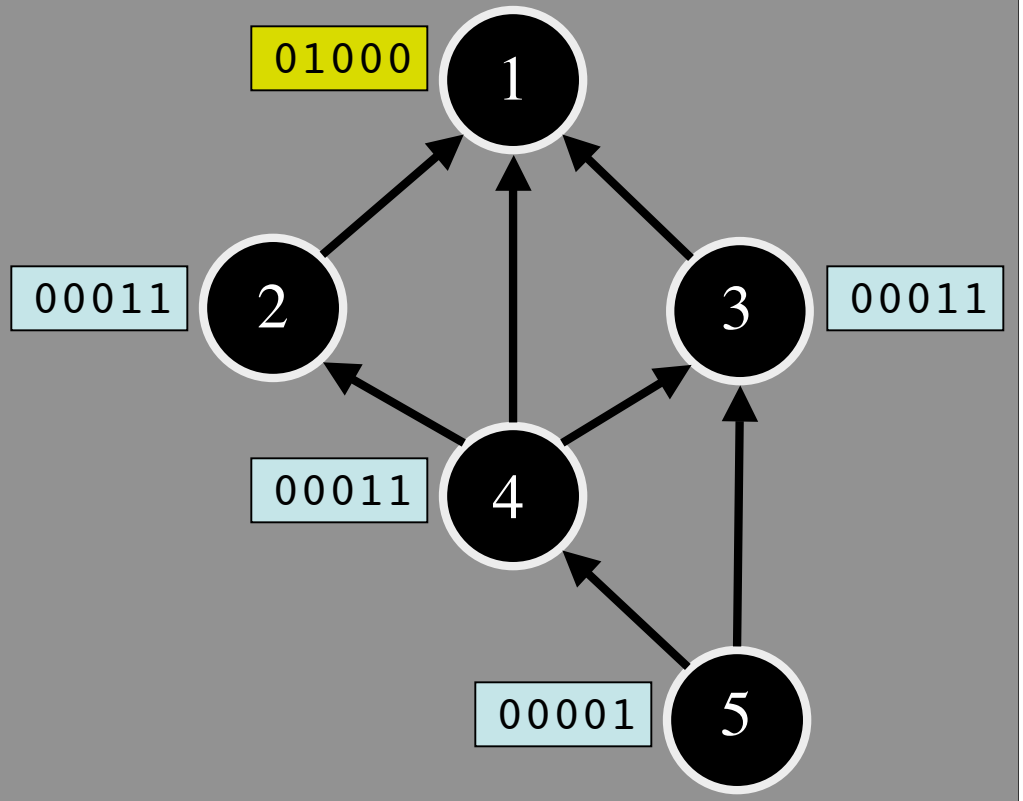
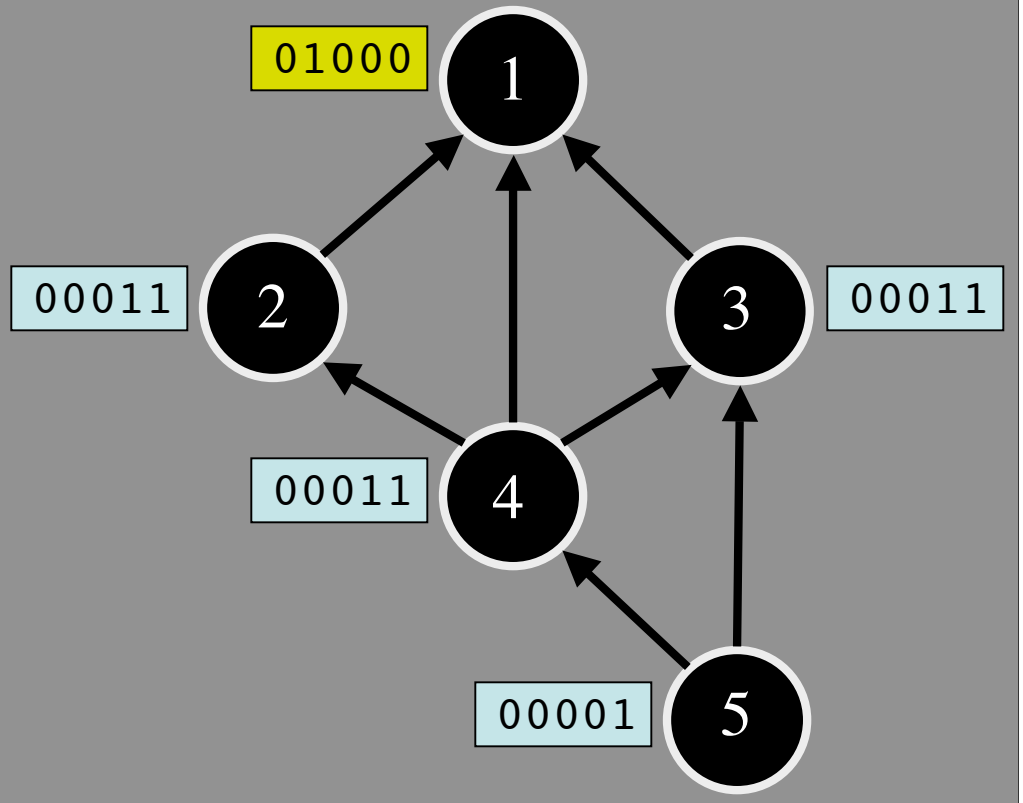


Count Example

- Three functions:
  - Generate initial sketch
  - Merge sketches (ODI)
  - Compute aggregate from complete sketch
  - 8/1.556 = 5.14

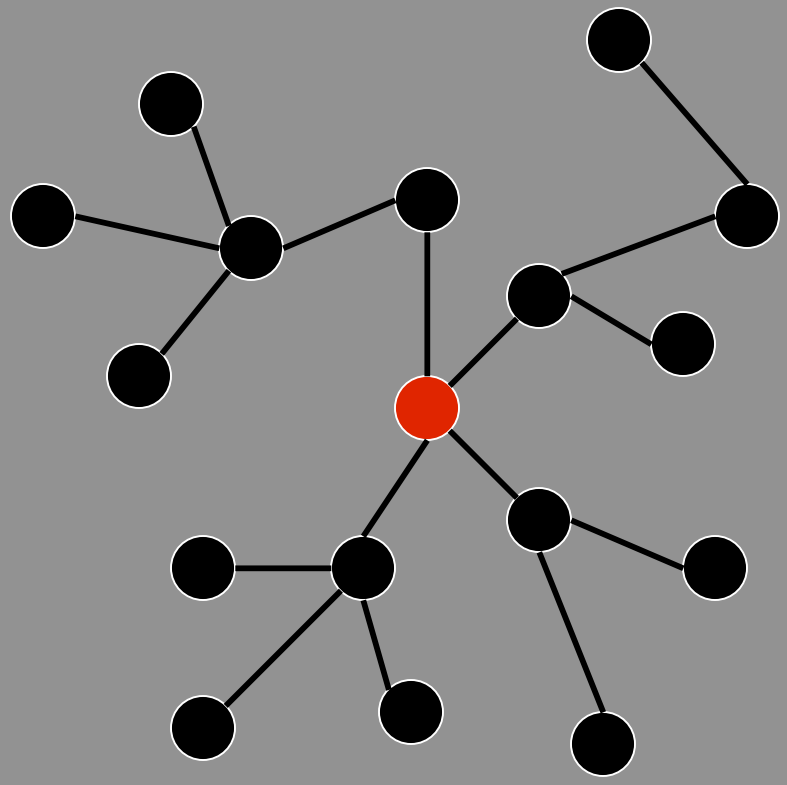


ODI Issues

- Sketches are robust, but are inaccurate estimates.
  - Standard deviation of error is 1.13 bits
- Many sketches are needed for an accurate result
  - Compute many (e.g., 12) in parallel
  - Generate a stream of sketches

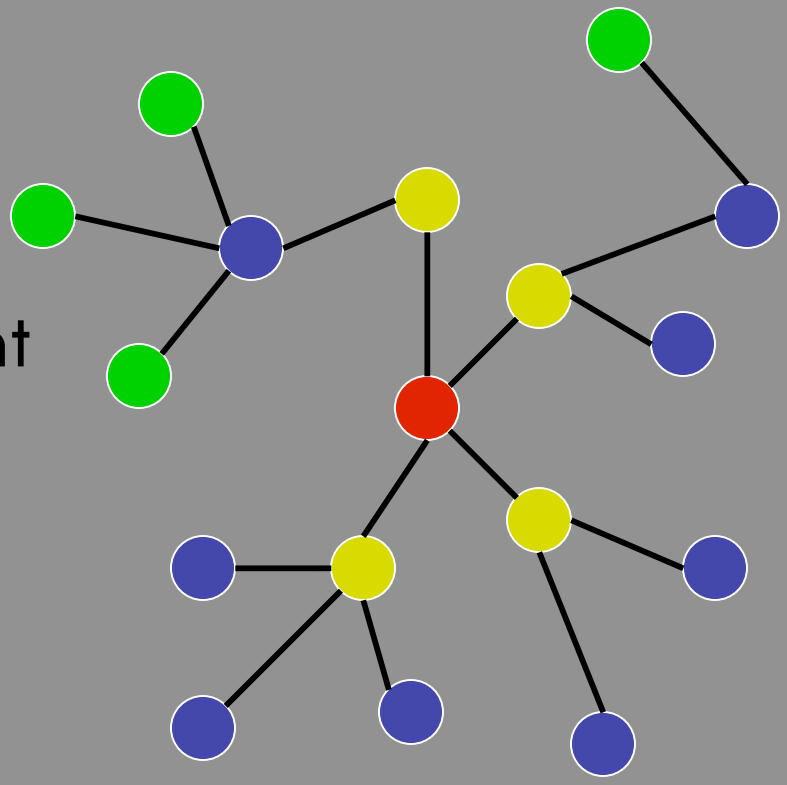
A Stream of Sketches

- ODI rings
- Only merge in lower rings



A Stream of Sketches

- ODI "rings"
- Only merge in lower rings
- Example: hop count



Arbitrary Network Layers

- ODI aggregates can be computed with Trickle
  - Two trickles: ODI sequence number, ODI sketches
  - When *you* hear a new sequence number, generate a new local sketch, reset both trickles
  - Delivers aggregate to ever*y* node in the network
- ODI aggregates require a *gradient*
  - Gradient determines what values can be merged
  - Prevents a sketch persisting forever
  - Gradient through time (seq no.), or through space (hops)

TAG vs. ODI

- TAG: computes exact value, bound to a specific routing layer that is vulnerable to loss and requires complex synchronization
  - If it works right once, you get the precise answer.
  - Really hard to get to work right.
- ODI: computes estimate, decoupled from network layer, multipath makes it more resistant to loss, requires simple synchronization
  - Simple implementations can accurately compute estimate, many estimates needed for a precise answer.

Implementation Experience

- TAG: implemented in TinyDB system
  - Two months of work to get TinyDB to work in deployment.
  - Very low data yield, no-one has been able to get it to work again (TASK project).
- ODI: a count query is 30 lines of code
  - A few tricks: coarse time synchronization needed.
  - Hasn't been tested to the same degree as TAG.

Design Considerations

- Uncontrolled environment: simplicity is critical.
  - The world will find *y*our edge conditions for *y*ou.
  - Simplicity and fault tolerance can be more important than raw performance.
- Wireless channel: cheap broadcast primitive.
  - Protocols can take advantage of spatial redundancy.
- Redundancy requires idempotency
  - But we have limited state.

Questions