Design and Development of IoT Applications

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  - Multi-hop communication
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  - IPv6 addressing
  - Fragmentation
  - 6LoWPAN Header compression
  - Bootstrapping
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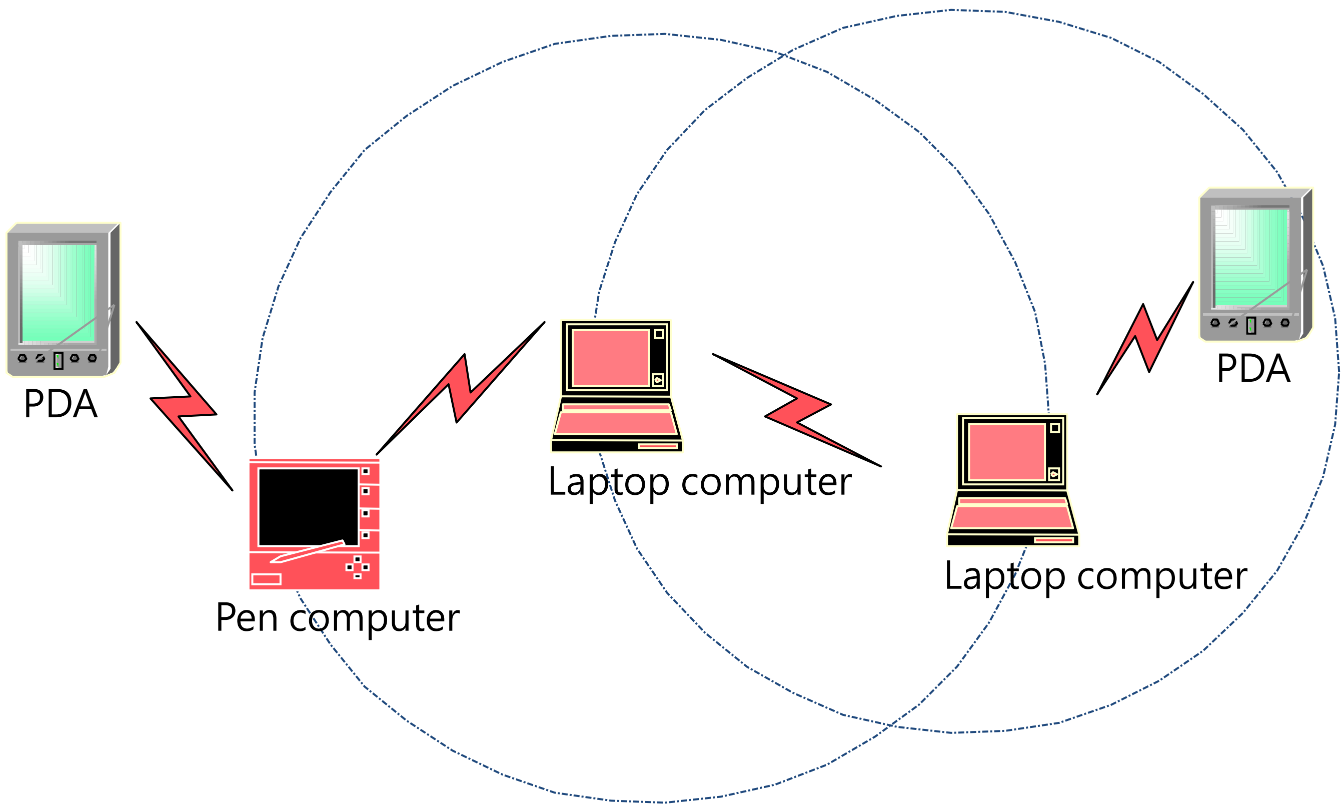
Wireless Ad-hoc Networks

Two types of wireless network:

- Infrastructured (WLAN)
    - the mobile node can move while communicating
    - the base stations are fixed
    - as the node goes out of the range of a base station, it gets into the range of another base station
- Infrastructureless or ad-hoc
    - the mobile node can move while communicating
    - there are no fixed base stations
    - all the nodes in the network need to act as routers
- In Latin “ad-hoc” literally means “for this purpose only”. Then an ad-hoc network can be regarded as “spontaneous network”

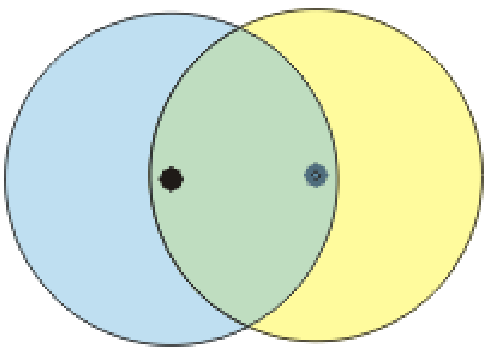
MANET

- Infrastructurless (ad-hoc) network or MANET (Mobile Ad-hoc NETwork)

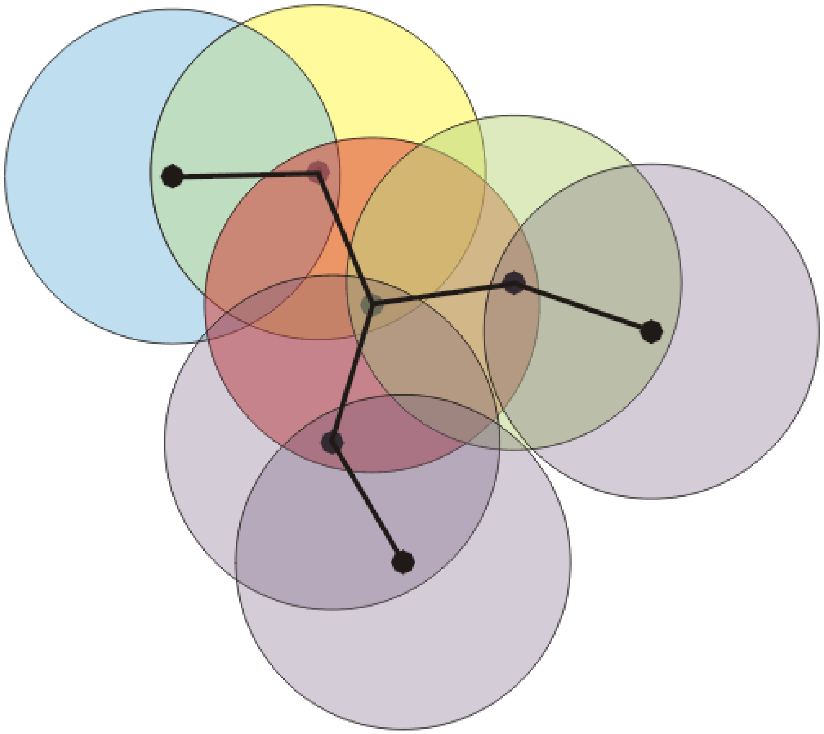


Classification of ad-hoc networks

- **Single hop** – nodes are in their reach area and can communicate directly

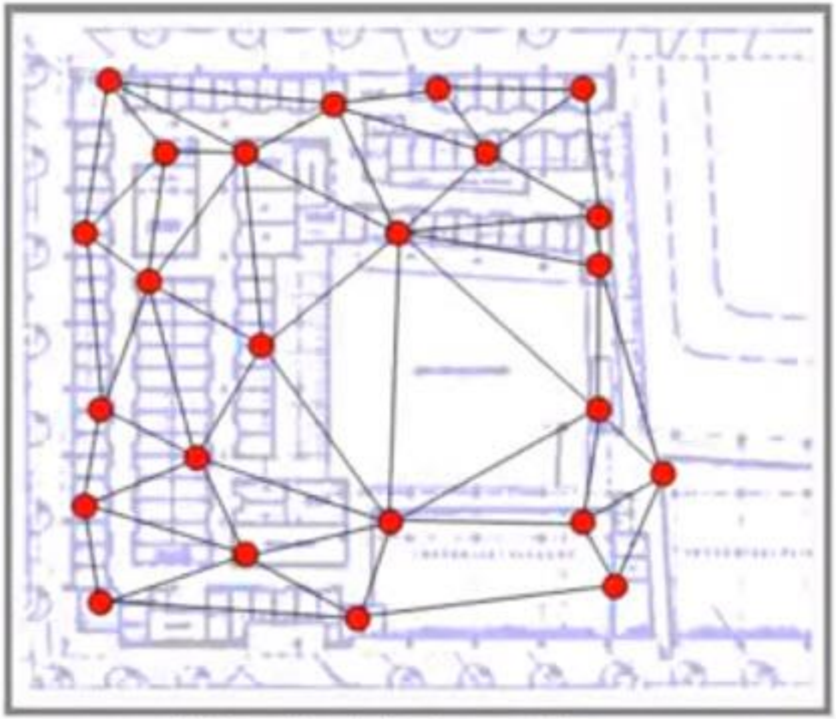


- **Multi hop** – some nodes are far and cannot communicate directly. The traffic has to be forwarded by other intermediate nodes.



Multi-hop network

Star Network
(e.g. 802.11)



Mesh Network
(e.g. ZigBee)

Characteristics of an ad-hoc network

- Collection of mobile nodes forming a temporary network
- Network topology changes frequently and unpredictably
- No centralized administration or standard support services
- Each host is an independent router
- Hosts use wireless RF transceivers as network interface
- Number of nodes 10 to 100 or at most 1000
- Nodes/host are powerful and focus on how to keep the mobile connection; high computation and high power consumption may be acceptable

Classical View of Routing

- Connectivity between nodes defines the network graph.
  - Topology formation
- A Routing algorithm determines the sub-graph that is used for communication between nodes.
  - Route formation, path selection
- Packets are forwarded from source to destination over the routing sub-graph
  - At each node in the path, determine the recipient of the next hop
- The selection at each hop is made based on the information at hand
  - Sender address, current address, destination address, information in the packet, information on the node.
  - Table-driven, source based, algorithmic, …
  - Who knows the route? Do you determine it as you go?

Classification of the Routing Protocols

- Link state
  - Nodes shout (send) and listen (receive) to determine neighbor connectivity.
  - Each floods this information throughout (Link State Advertisement) so every node has a map (Link state data base) of the network.
  - Any node can determine the path or the next hop.
  - management protocol deals with changes in connectivity
  - Classic Example: OSPF
- Distance vector
  - Nodes maintain routing information about “distance” and “direction” to destinations
  - Choose next hop by comparing the cost of routing through neighbors
  - Cost(dest D, neighbor b) = linkCost(b) + pathCost(b,D)
  - Management propagates routing information
  - Sequence numbers, etc.
  - Classic Example: RIP

Classification of the Routing Protocols

- Proactive (table driven)
  - Require each node to maintain one or more tables to store routing information
  - Each node responds to changes in network topology by propagating updates throughout the network in order to maintain a consistent network view
  - DSDV, OLSR (Optimized Link State Protocol)
- Reactive protocols (source initiated)
  - Creates routes only when desired by the source node
  - Once a route has been established, it is maintained by a route maintenance procedure until either the destination becomes inaccessible along every path from the source or until the route is no longer desired
  - DSR, AODV (Ad-hoc On-demand Distance Vector)

Classification of the Routing Protocols

- Various simulation studies have shown that reactive protocols perform better in mobile ad hoc networks than proactive ones.
  - However, no single protocol works well in all environments.
  - Which approach achieves a better trade-off depends on the traffic and mobility patterns.

	Proactive Approach	Reactive Approach
Route Latency	**Lower** ▪A route is kept at all times	**Higher** ▪A route is never kept when not used
Routing Overhead	**Higher** ▪A frequent dissemination of topology information is required	**Lower** ▪Fewer control packets in general

Classification of the Routing Protocols

- Other classification
  - Proactive protocols:
    - DSDV, STAR, WRP, ...
  - Reactive protocols:
    - AODV, DSR, TORA, ...
  - Hierarchical/Clustering protocols:
    - CGSR, ZRP, CBR, FSR, LANMAR, ...
  - Position aware protocols:
    - GPSR, LAR, GRA, ABR, ...

Problems with Routing

- Distance-vector protocols
  - Slow convergence due to “Count to Infinity” Problem
  - Creates loops during node failure, network partition or congestion
- Link state protocols
  - Use flooding technique and create excessive traffic and control overhead
  - Require a lot of processor power and therefore high power consumption
- Limitations of the Wireless Networks
  - packet loss due to transmission errors
  - variable capacity links
  - frequent disconnections/partitions
  - limited communication bandwidth
  - Broadcast nature of the communications
- Limitations Imposed by Mobility
  - dynamically changing topologies/routes
  - lack of mobility awareness by system/applications
- Limitations of the Mobile Computer
  - short battery lifetime
  - limited capacities

Leading Routing Protocols

- Leading protocols chosen by MANET
  - DSR: Dynamic Source Routing
  - AODV: Ad-hoc On-demand Distance Vector Routing

- Both are “on demand” protocols: route information discovered only as needed

MANET vs WSNs

- ❑ WSN nodes have less power, computation and communication compared to MANET nodes
  - ❖ MANET protocols require significant amount of routing data storage and computation
- ❑ MANETs have high degree of mobility, while sensor networks are mostly stationary mostly stationary
  - ❖ Topology changes in WSNs due to nodes dying in the network (due to energy dissipation or due to lossy links)
- ❑ MANET protocols are not being optimized to cater for duty cycles
- ❑ WSNs may be considered a subset of MANET
  - ❖ Routing in WSNs should not necessarily be complex as in MANET

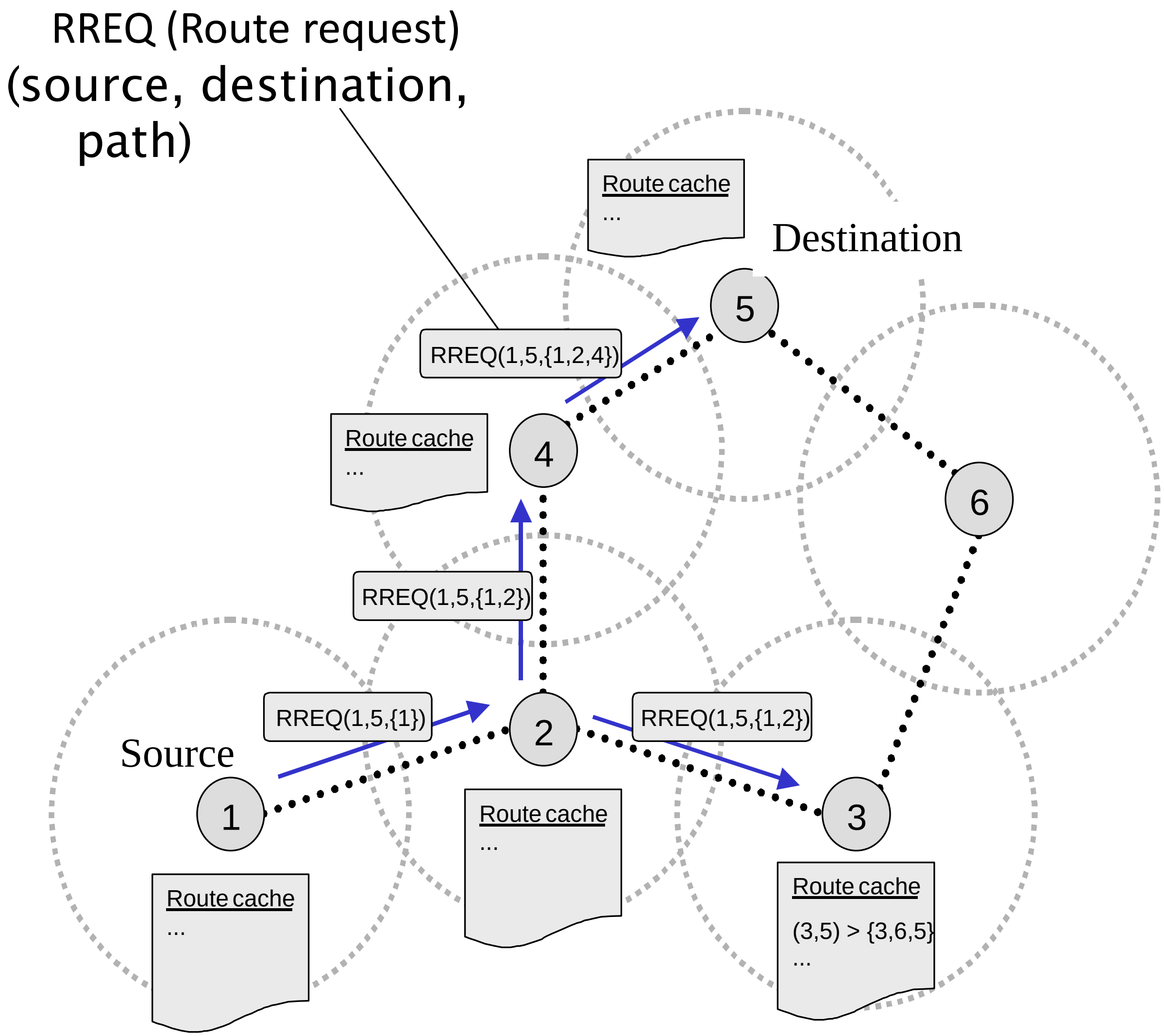
Dynamic Source Routing

- DSR (Dynamic Source Routing)
  - Similar to the source routing in traditional networks
  - A node maintains route cache containing the routes it knows
  - Includes route discovery on request and route maintenance when needed
  - Reactive routing

DSR

- Route discovery
  - The source sends a broadcast packet which contains source address, destination address, request id and path.
  - If the host receiving this packet, saw this packet before, discards it.
  - Otherwise, it looks up its route caches to look for a route to destination. If a route is not found, it appends its address into the packet and rebroadcasts it.
  - If the route is found, it sends a reply packet to the source node.
  - The route will be eventually found when the request packet reaches the destination

DSR


RREQ (Route request)
(source, destination,
path)
Route cache
...
Destination
5
RREQ(1,5,{1,2,4})
Route cache
...
4
6
RREQ(1,5,{1,2})
RREQ(1,5,{1})
2
RREQ(1,5,{1,2})
Source
1
3
Route cache
...
Route cache
...
Route cache
(3,5) > {3,6,5}
...

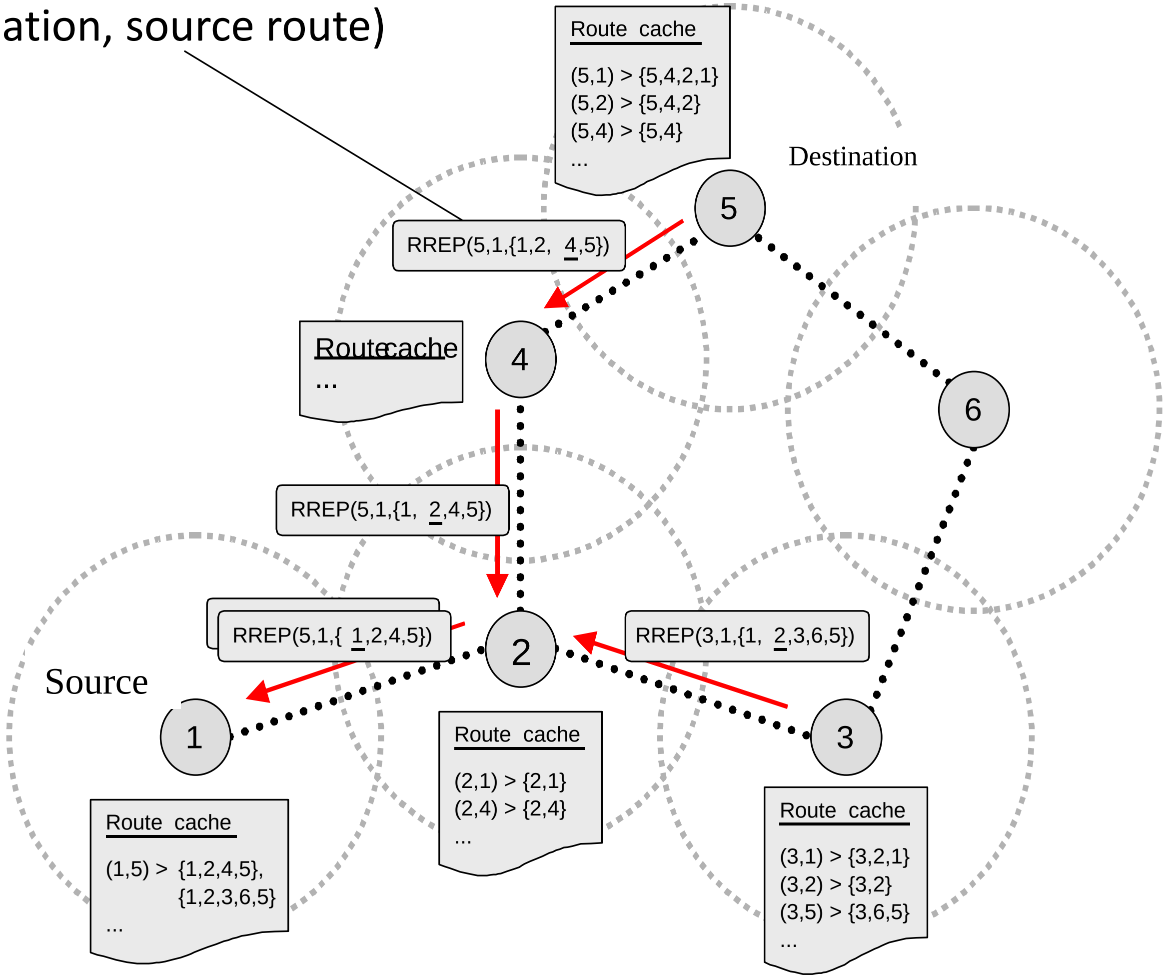
DSR

- How to send a reply packet?
  - If the destination has a route to the source in its cache, use it
  - Else if symmetric links are supported, use the reverse of the route record
  - Else, if symmetric links are not supported, the destination initiate route discovery to source

DSR

RRREP (Route reply)

Source, destination, source route)



DSR

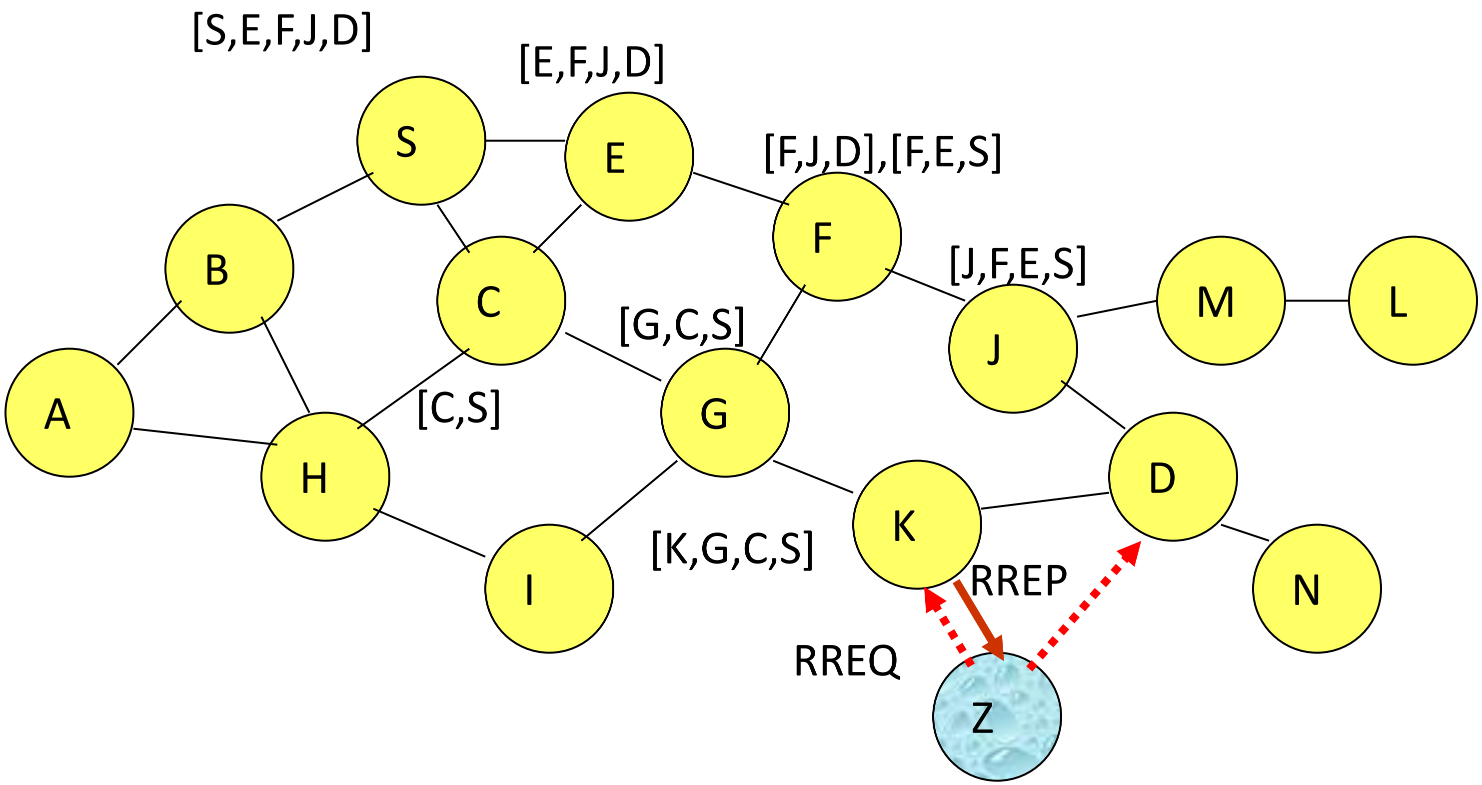
❑ Route maintenance

- ❖ Whenever a node transmits a data packet, a route reply or a route error, it must verify that the next hop correctly receives the packet.
- ❖ If not, the node must send a route error to the node responsible for generating this route header.
- ❖ The source restarts the route discovery

❑ Route caching

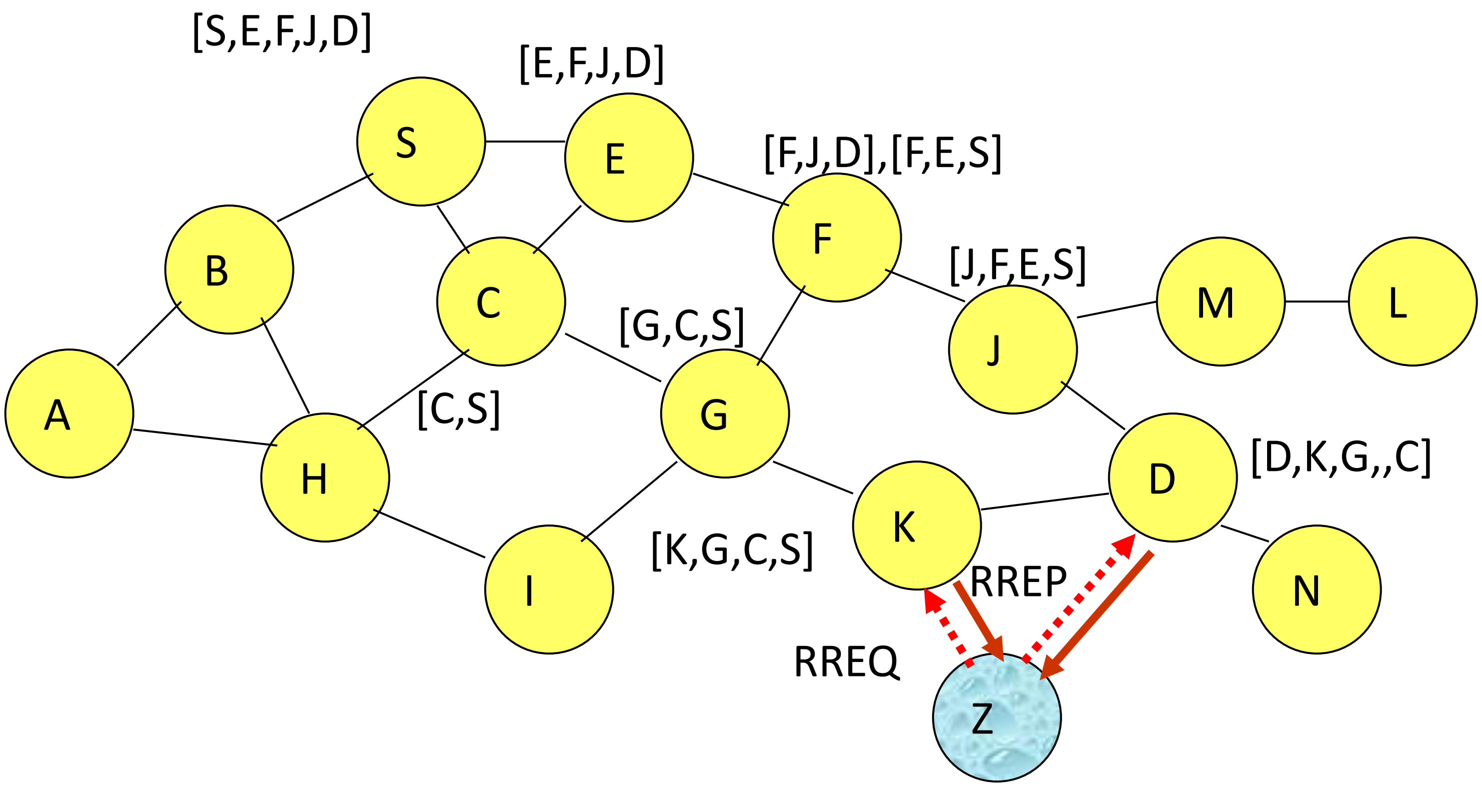
- ❖ When S finds route [S,E,F,J,D] to D, S also learns route [S,E,F] to F
- ❖ When K receives Route Request [S,C,G] destined for some node D, K learns route [K,G,C,S] to S if links are bi-directional
- ❖ F forwards Route Reply RREP [S,E,F,J,D], F learns route [F,J,D] to D
- ❖ When E forwards Data [S,E,F,J,D] it learns route [E,F,J,D] to D

Can Speed up Route Discovery



- When node Z sends a route request for node C, node K sends back a route reply [Z,K,G,C] to node Z using a locally cached route

Reduce Propagation of Route Requests



- Route Replies (RREP) from node K and D ***limit flooding*** of RREQ

DSR

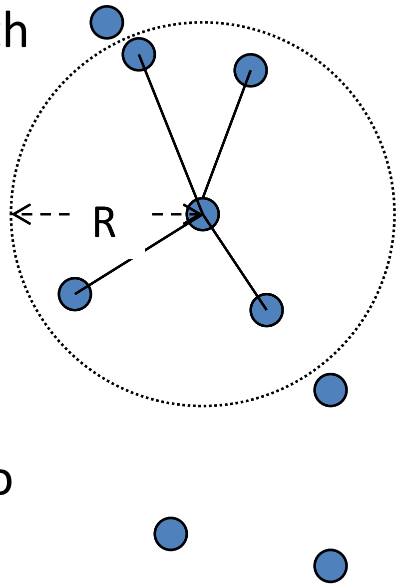
- Advantages
  - Routes are discovered only they are needed: Reduces overhead of route maintenance
  - Route caching reduce the cost of route discovery
  - A single route discovery may yield many routes to the destination, due to intermediate nodes may reply route request from local caches
  - Does not require symmetric links
- Disadvantages
  - Packet header size grows with route length due to source routing: Inefficiency
  - Route request packet may potentially reach all nodes in the network: RREQ flooding
  - Route requests may collide at the targeted node: Pay so much but get nothing
  - Every node needs to turn on its receiver all the time: No energy saving
  - Increased contention if too many route replies come back: Route Reply Storm
  - An intermediate node may send Route Reply using a stale cached route, thus polluting other nodes' caches: Mess up routing and forwarding

What's different in WSN?

- There is no a priori network graph
  - It is discovered by sending packets and seeing who receives them.
  - The link relationship is not binary.
  - pairs of nodes communicate with some probability that is determined by many of factors.
  - It is not static.
- The embedding of the "network" in space is important.
  - Need to get information to travel between particular physical places.
  - But the "communication range" is not a simple function of distance.
- addressing & naming
  - Flat EUID? Hierarchical IP? Topologically meaningful? Spatially meaningful?

Topology Formation

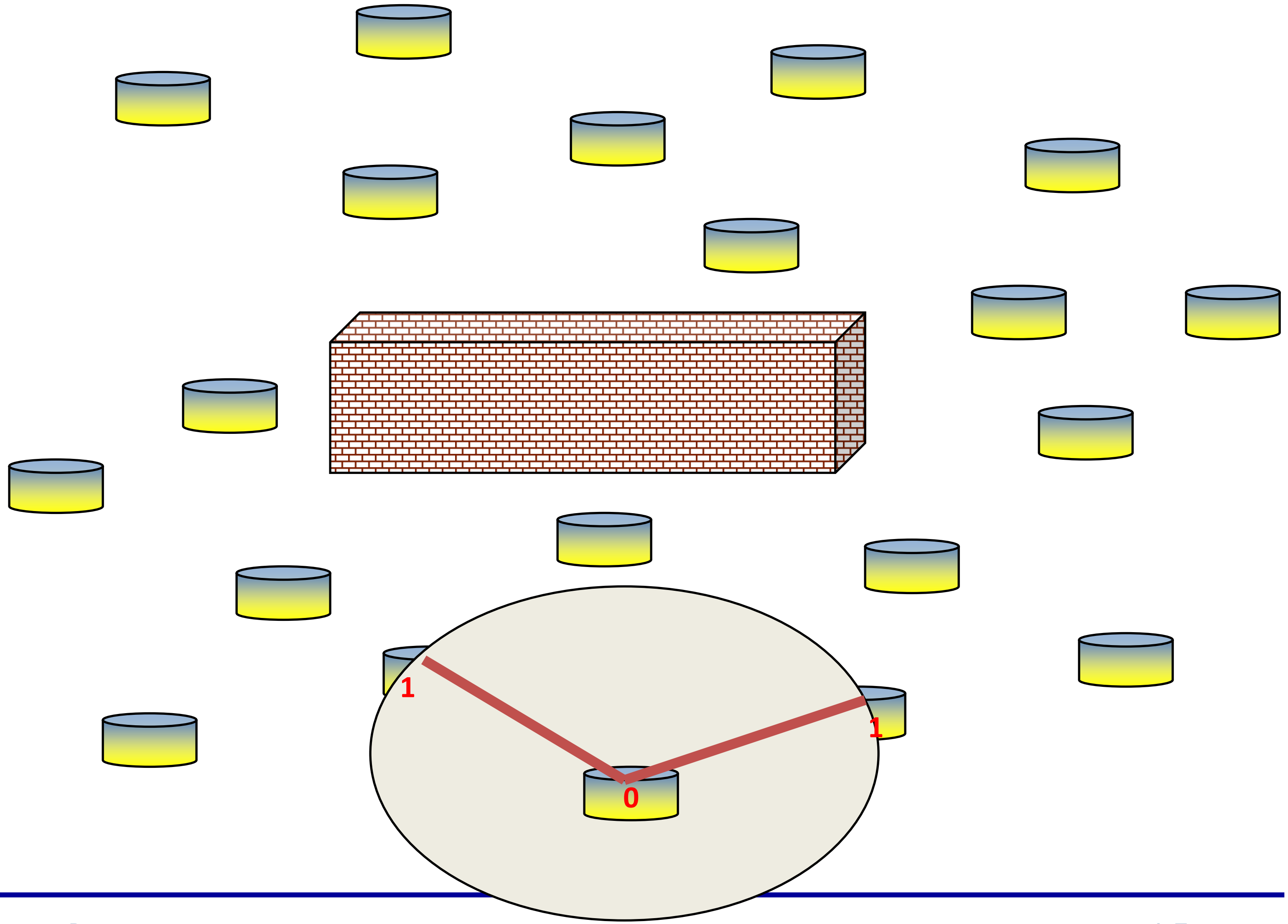
- Much of the "paper protocols" define connectivity graph with unit disk model
  - Link(A,B) if dist(A,B) ≤ R
- OK for rough calculations, but not for protocol design
  - Nearby nodes may not be able to communicate.
  - Far away nodes may be able to communicate.
  - Nodes that communicated in the past may not be able to communicate in the future.
  - Nodes may have intermittent communication depending on external factors.
- Connectivity is determined by communication
  - If B receives packet reasonably reliably from A, then A → B
  - If A receives packet reasonably reliably from B, then A ← B
  - And if both are true, A ←→ B



Wireless Routing Protocols

- Many wireless protocols in the IP context have been development in the IETF MANET (Mobile Ad Hoc Networking) working group in the context of 802.11 links carrying traditional TCP/IP point-to-point traffic.
  - AODV – ad hoc on-demand distance vector
  - OLSR – Optimized link state Routing
  - DSDV - Destination Sequenced Distance Vector
  - DSR – Dynamic Source Routing
  - TDRPF - Topology Dissemination Based on Reverse-Path Forwarding
- Assume a fairly “classic” view of connectivity
  - Naïve radio
- Routing protocols for MANET require high computation, powerful MCU, which are not satisfied in sensor nodes

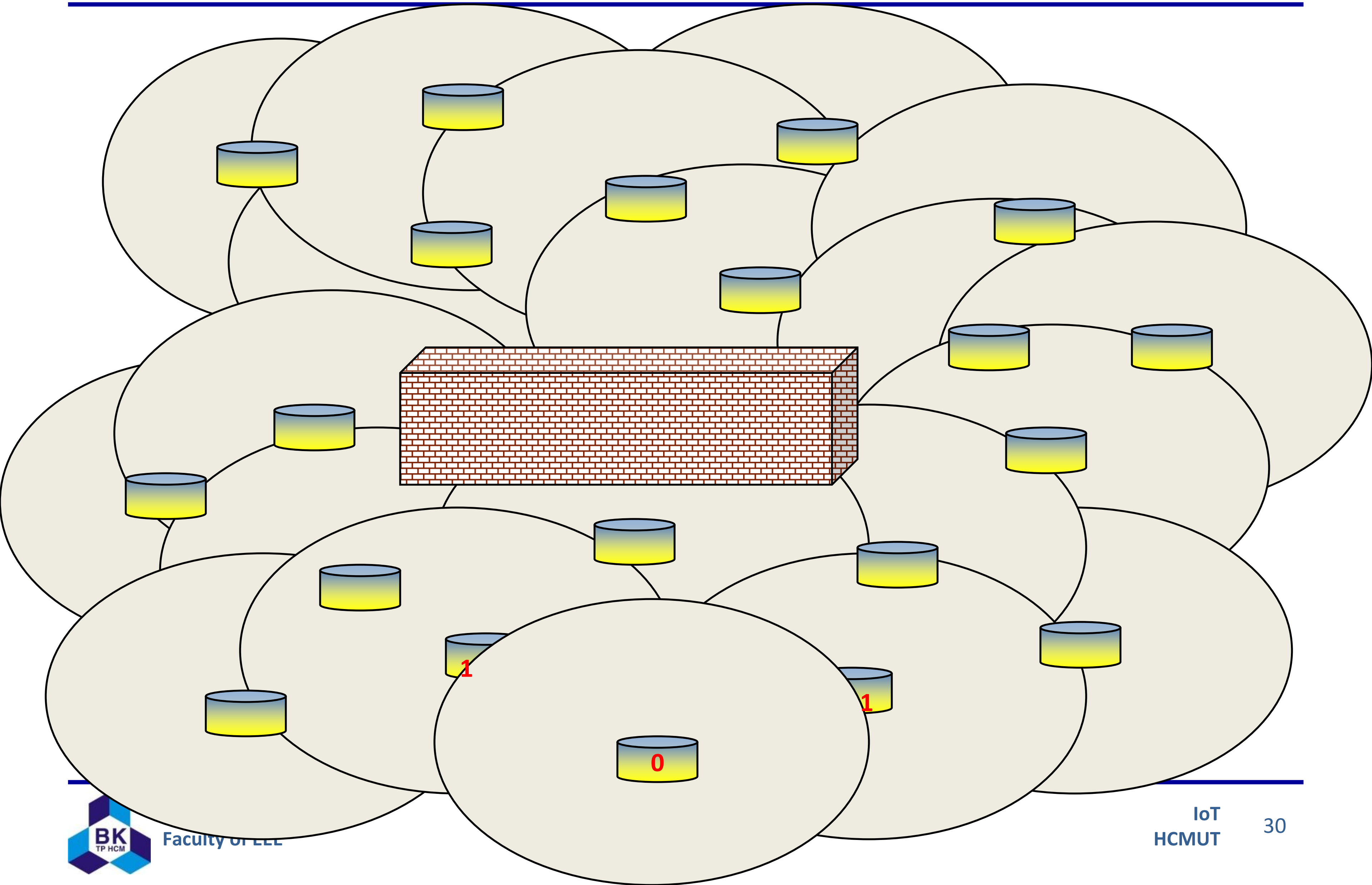
Neighbor Communication



Fundamental Primitive

- Transmit to whatever receivers happen to hear it
- This is the fundamental primitive that is buried underneath complex protocols like Bluetooth, but not made available.
- It is what make it possible to build higher level protocols on the link, especially IP.
- To determine connectivity,
  - Local broadcast
  - Respond
  - on-going protocol to estimate quality of the link
    - Packet reliability (sequence numbers, acks)
    - Note 802.15.4 acks only from a specific destination
    - RSSI, LQI, …

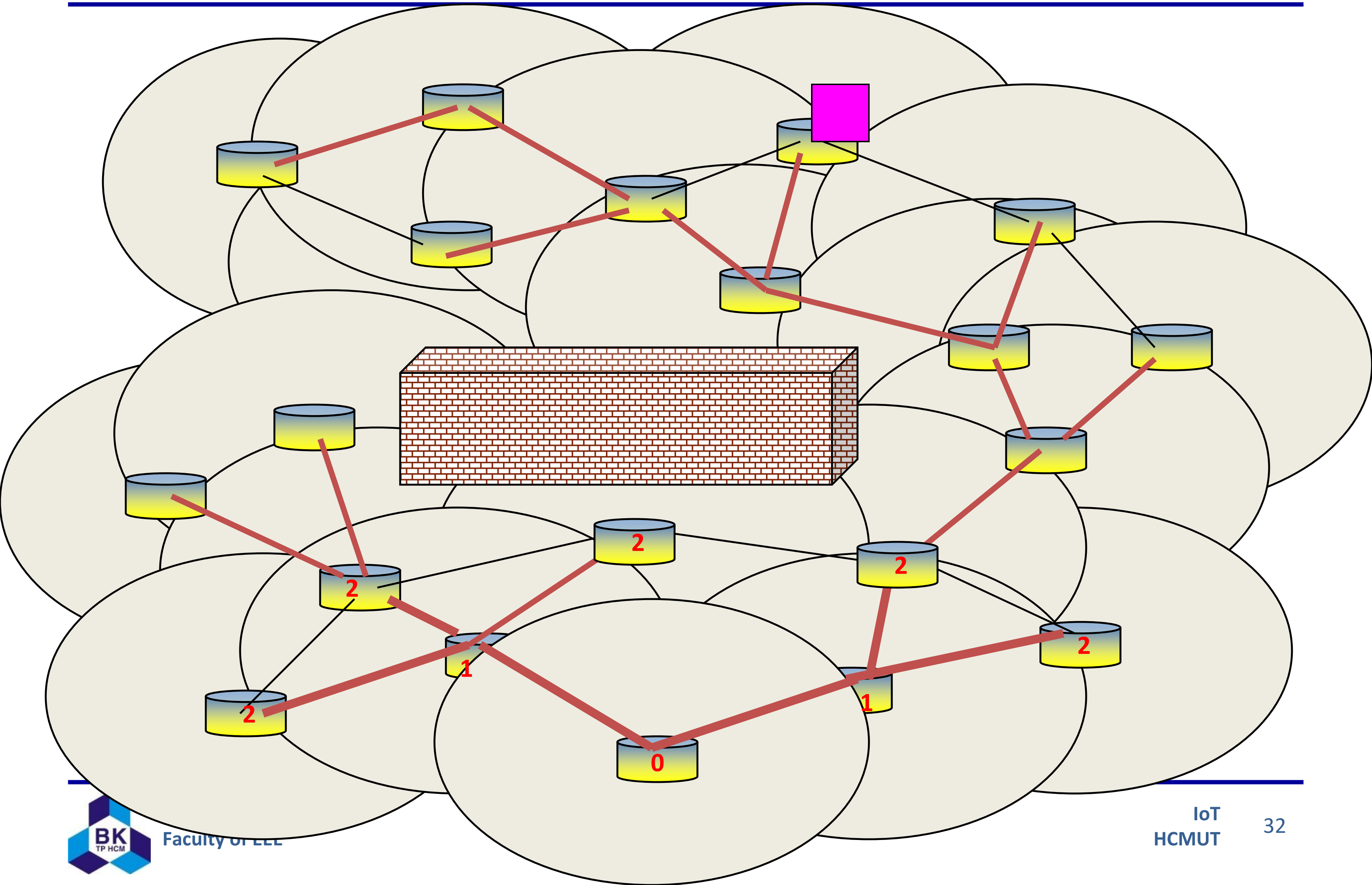
Route-Free “Flood”



"Flooding"

- Route free dissemination is extremely useful in its own right
  - Disseminate information
    - Router advertisements, solicitations, …
  - Network-wide discovery
  - Join, …
- It is also the network primitive that most "ad hoc" protocols used to determine a route
  - Flood from source till destination is reached.
  - Each node records the source of the flood packet
    - This is the parent in the "routing tree"
  - Reverse the links to form the path back

Data Collection in concept



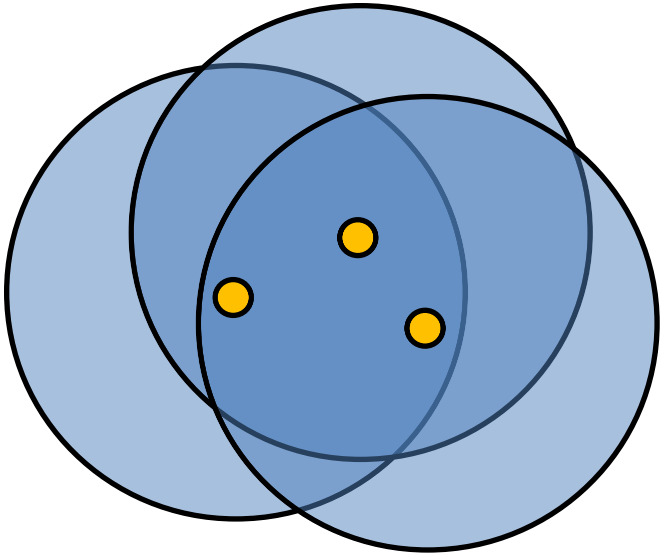
The Problems

- Flood causes tremendous contention
  - Many good links missed because of collisions
  - Huge amount of noise
- Many links are not symmetric

Trickle – better than flood

- Want the communication rate per unit area to be constant, regardless of the density of nodes
  - Lots of nodes, transmit infrequently
  - Few node, transmit more frequently
- Nodes listen before transmitting
- Estimate density based on how many nodes you hear from
  - Arrival during timer wait extends timer
- If new value is disseminated by others, no need for you to transmit it.
- Increase delay over time so ambient rate approaches zero.
- Shorten delay when new epoch appears.

Trickle



- ❑ Concerns
  - ❖ Broadcast is expensive
  - ❖ Wireless channel is a shared, spatial resource
- ❑ Idea
  - ❖ Dynamic adjustment of transmission period
  - ❖ Suppress transmissions that may be redundant

Trickle

- "Every once in a while, broadcast what data you have, unless you've heard some other nodes broadcast the same thing recently."
- 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.
- As long as each node communicates with others, inconsistencies will be found
- Either reception or transmission is sufficient

Algorithm

- Define a desired detection latency, ***t***
- Choose a redundancy constant k
  - (receptions + transmissions) <= ***k***
  - In an interval of length ***t***
- Trickle keeps the rate as close to ***k/t*** as possible

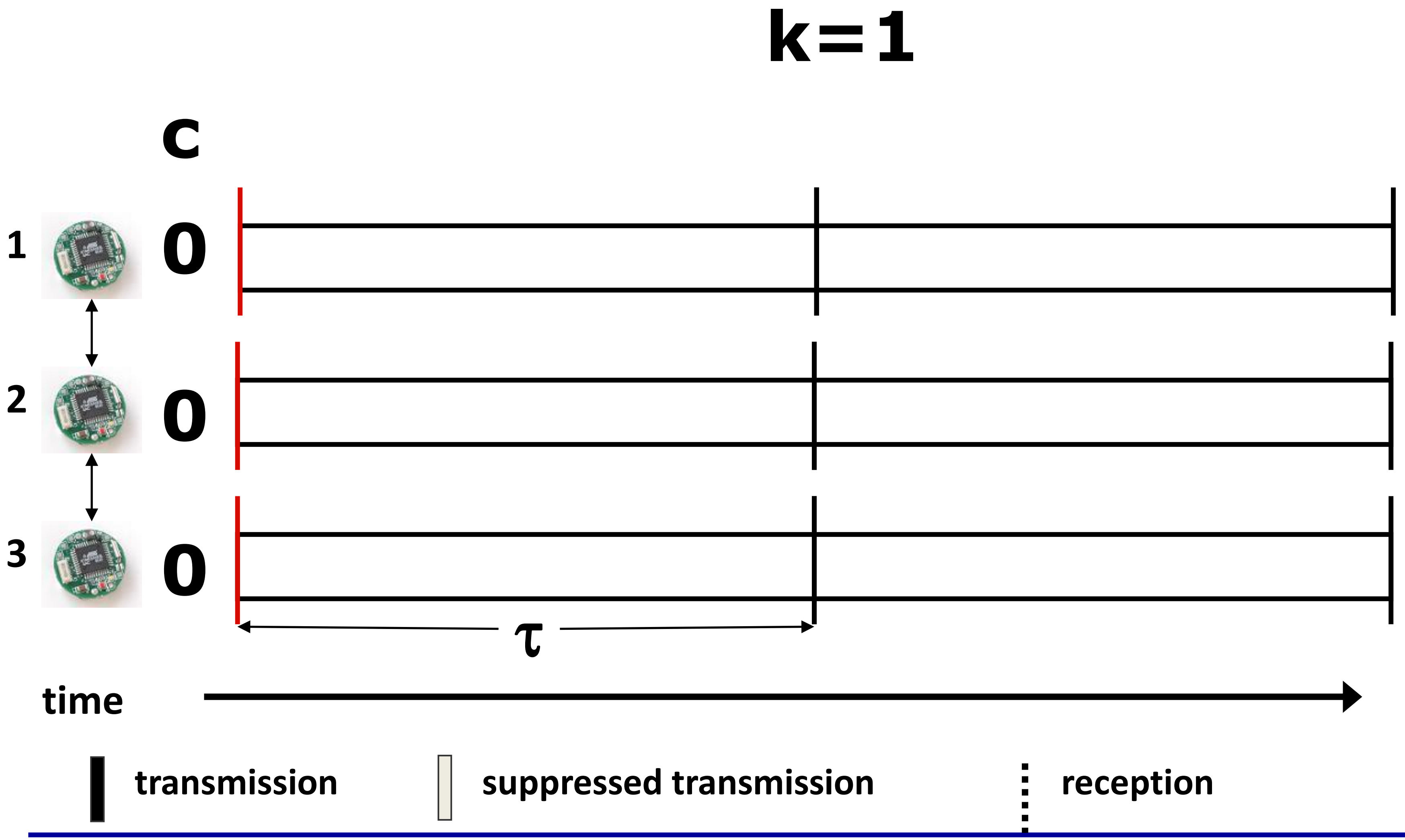
- Choose timer ***t*** random in (t/2, t]
- If inconsistent broadcast is heard before ***t***, reset t to t_{min}.
- If ***c*** < ***k*** consistent broadcasts are heard by ***t***, broadcast
- Otherwise suppress and double t up to t_{max}.

- When there is nothing new to say, stay quiet

Trickle Algorithm

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

Example Trickle Execution



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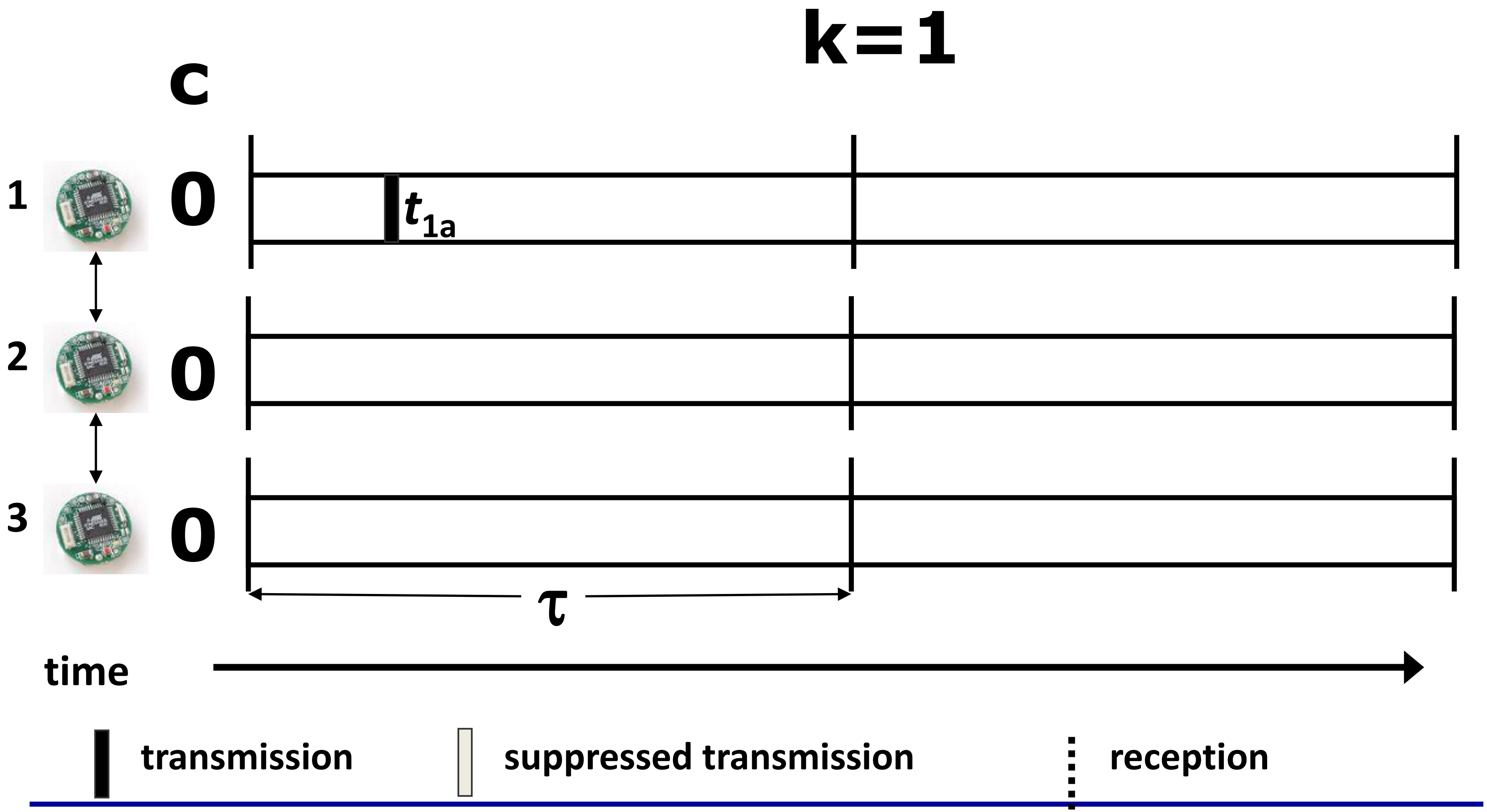

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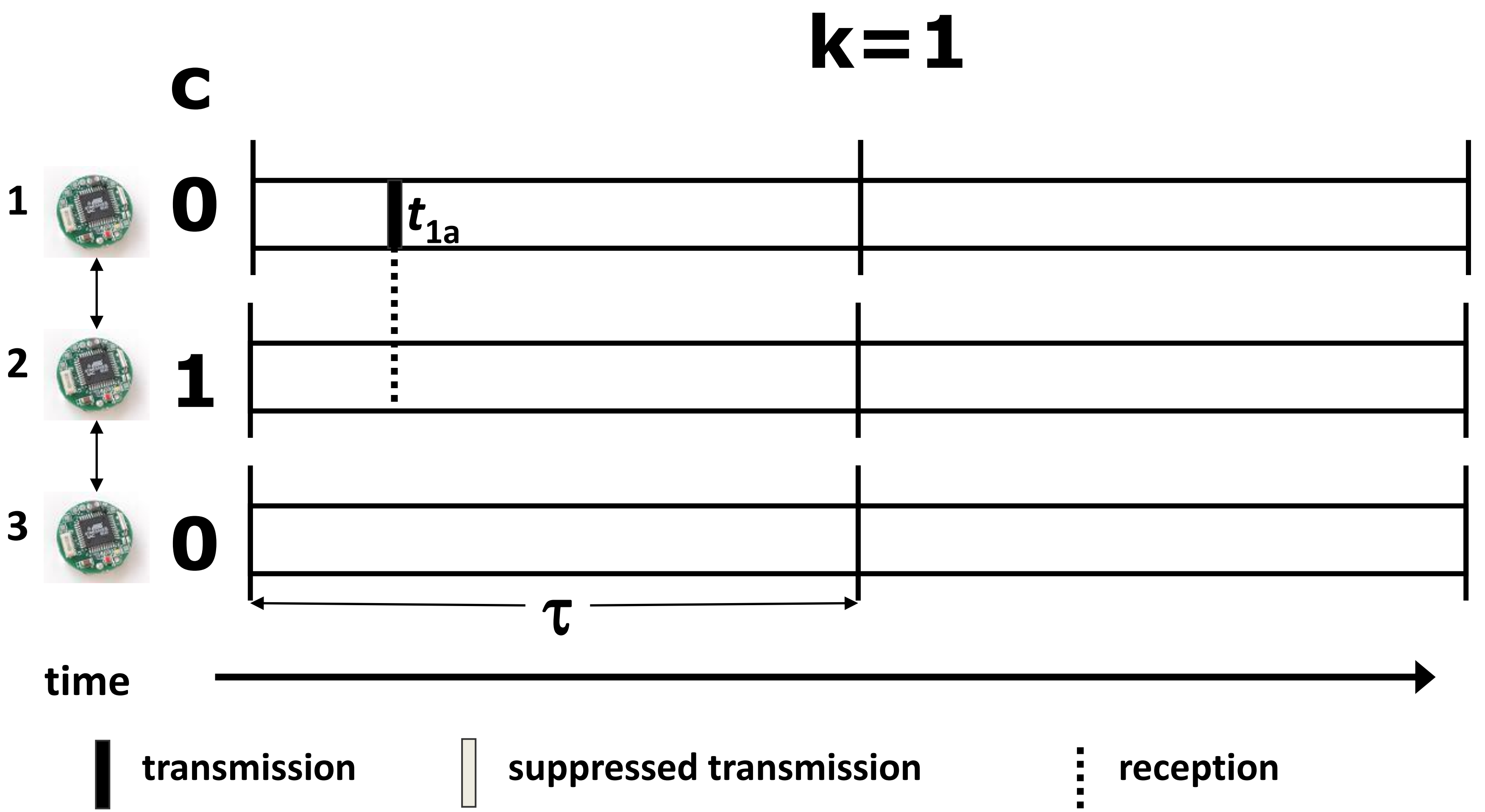

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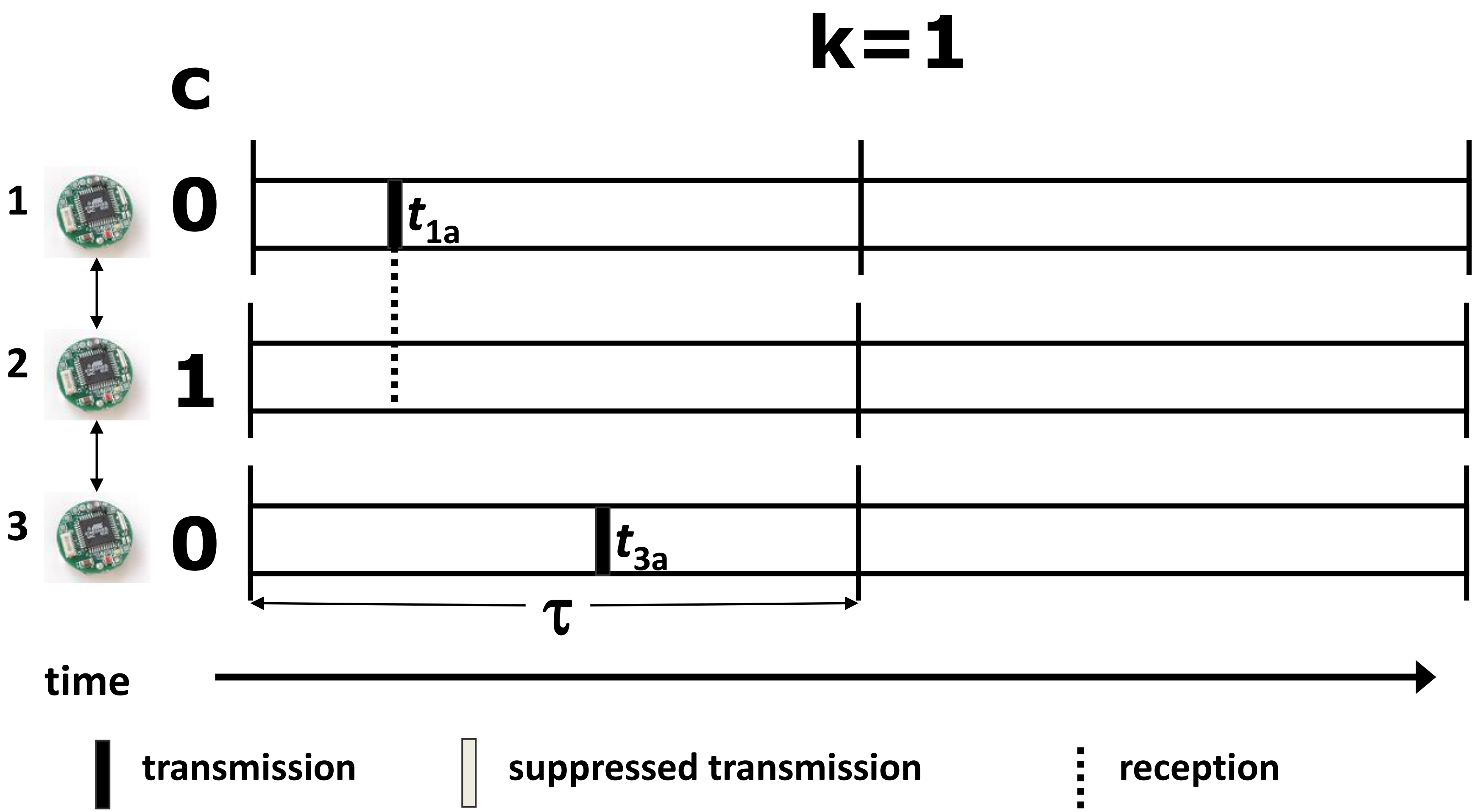

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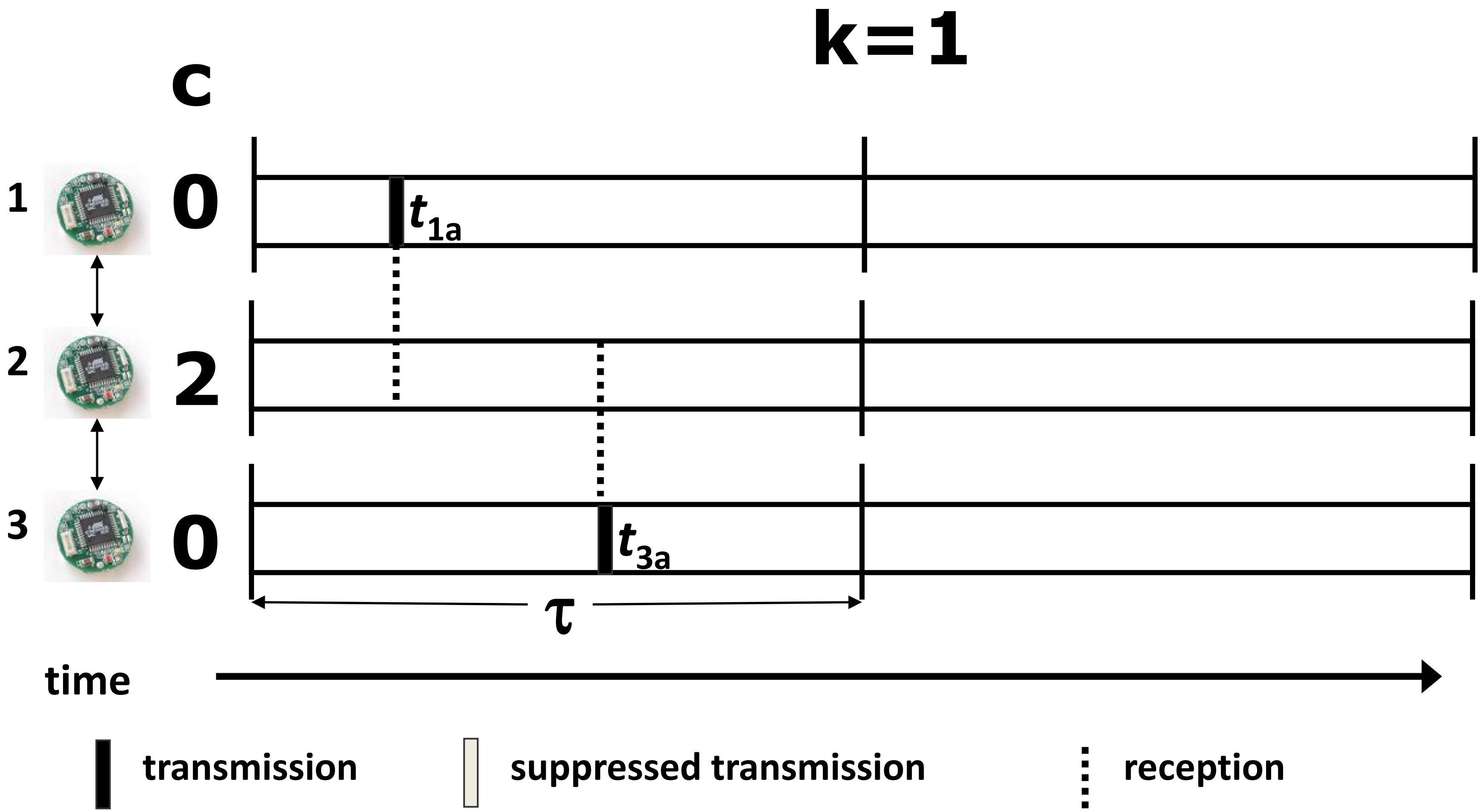

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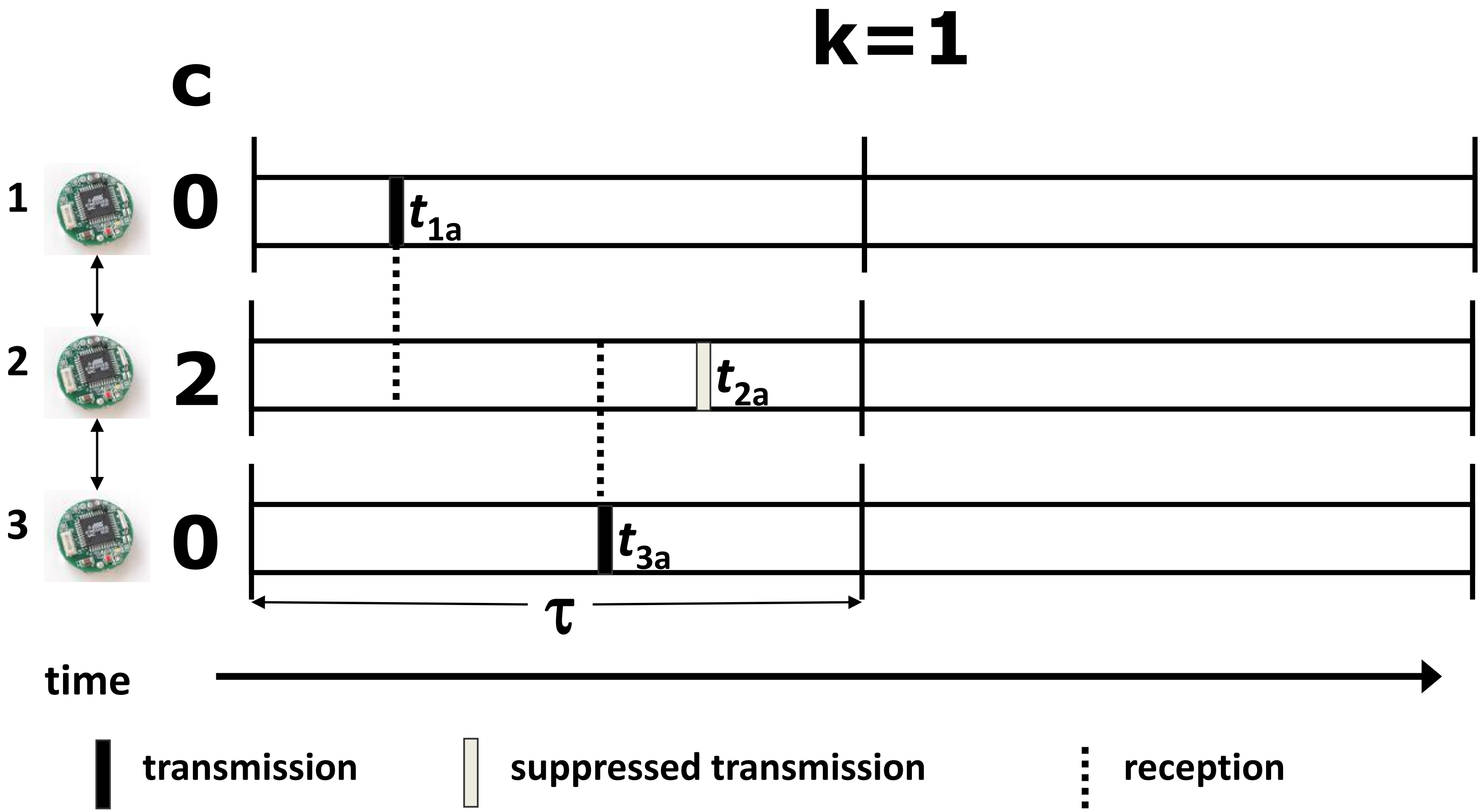

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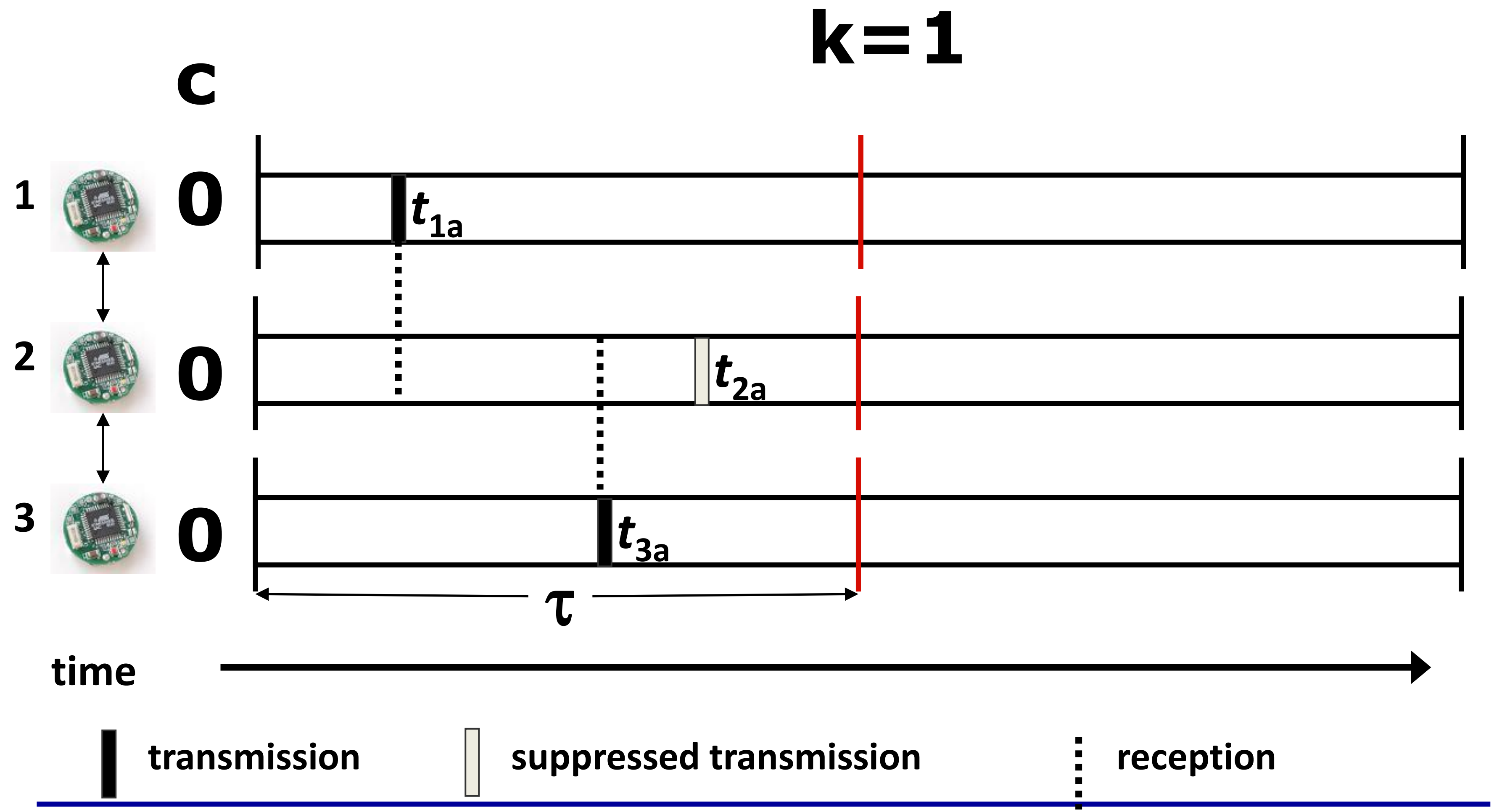

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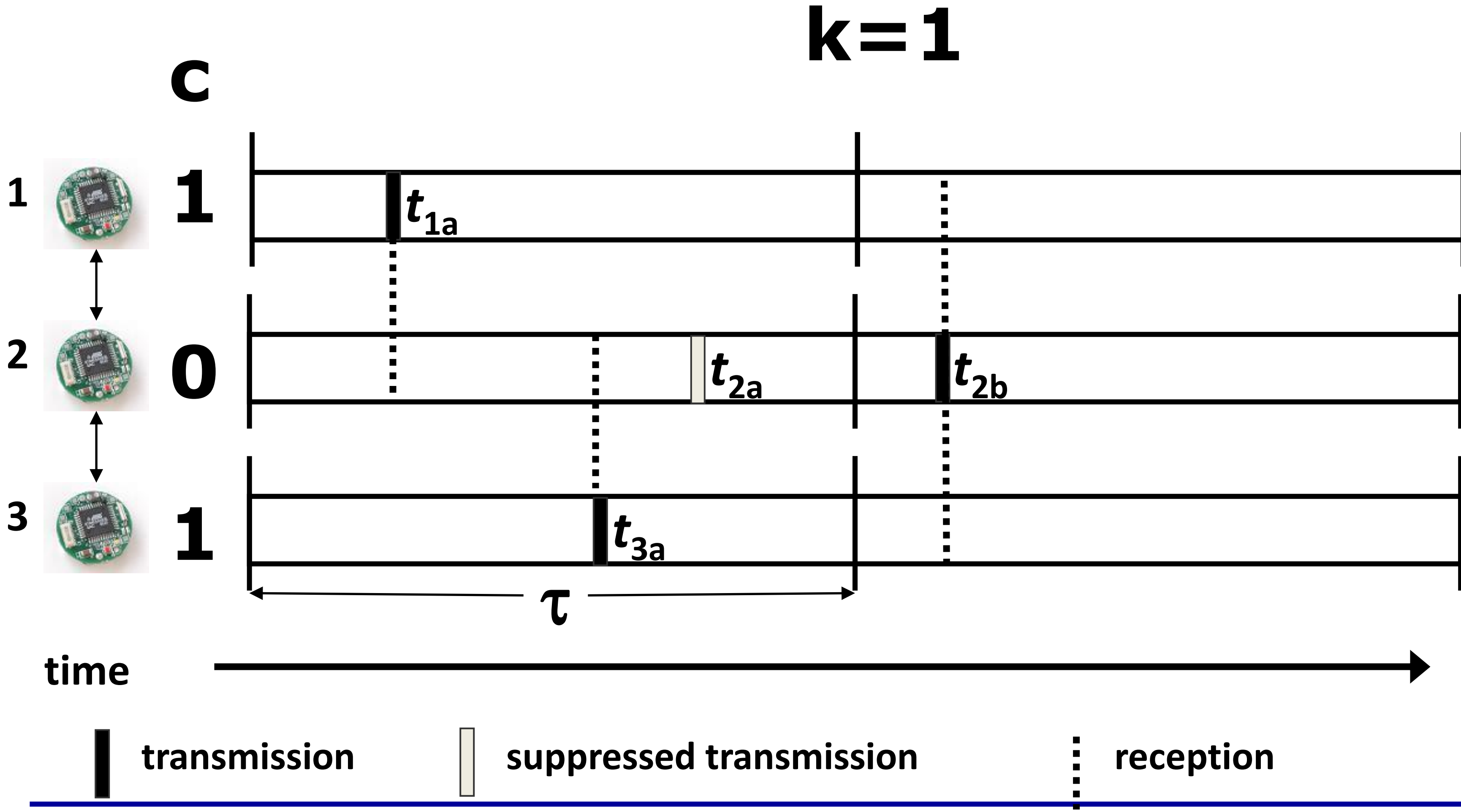

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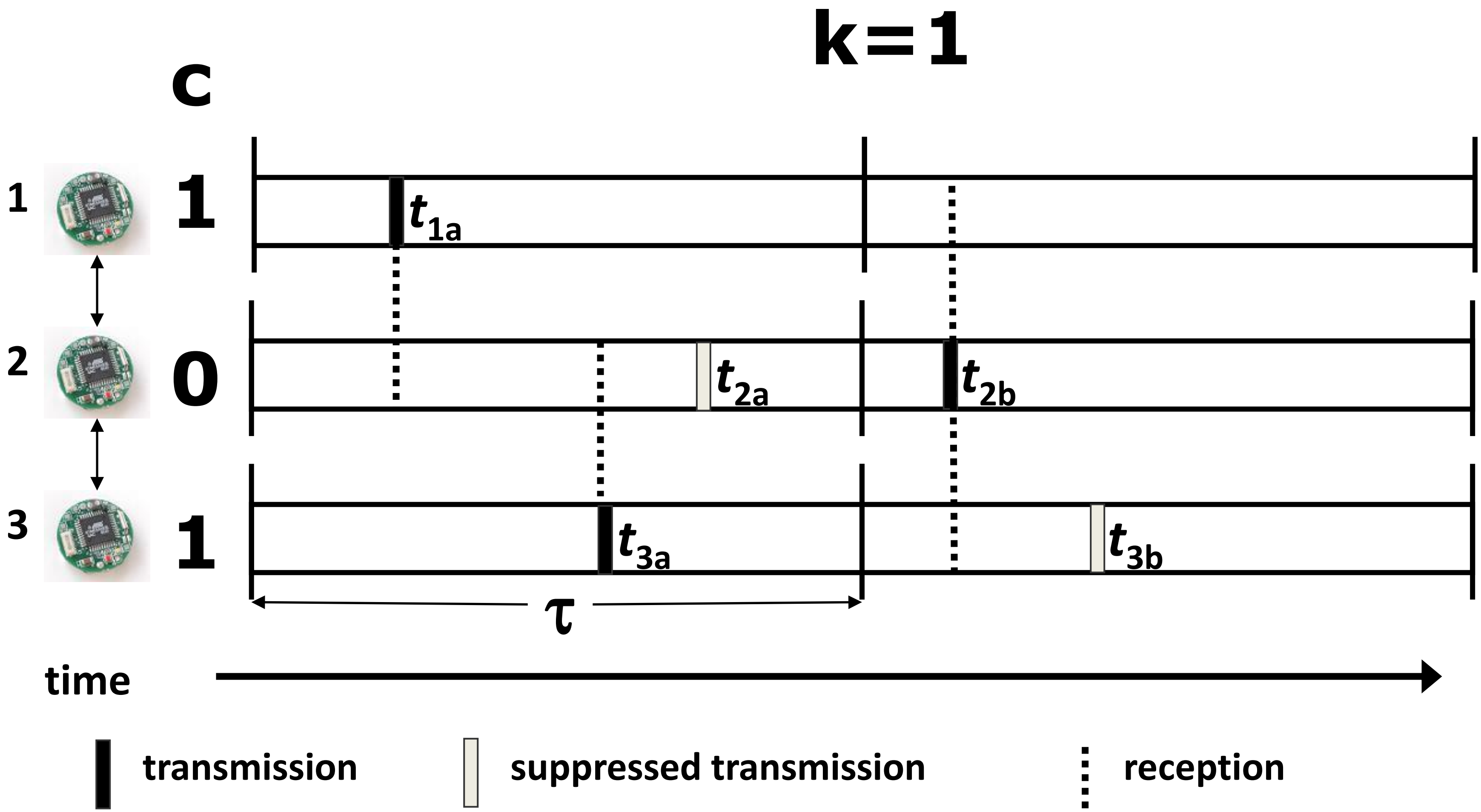

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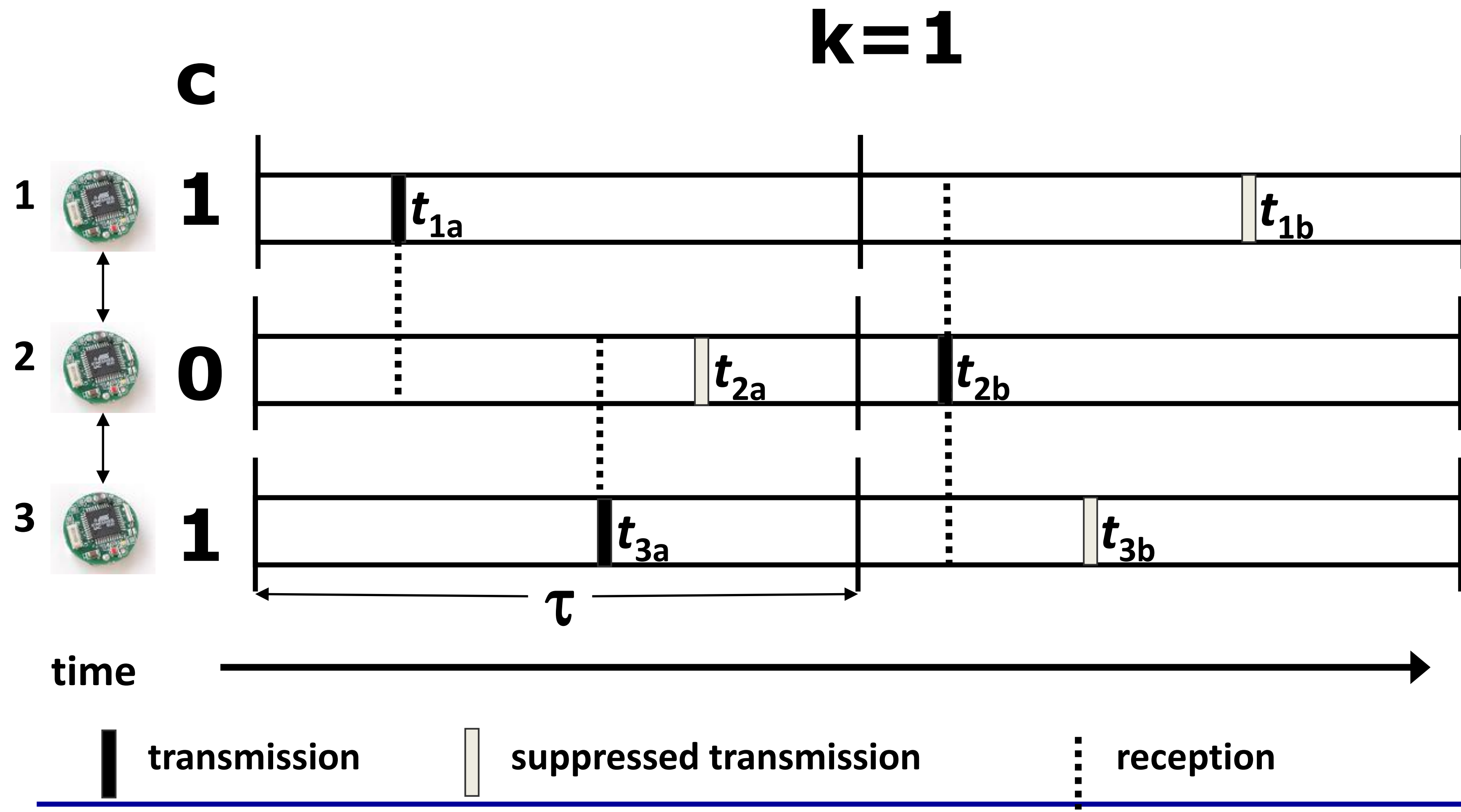


Ideal case

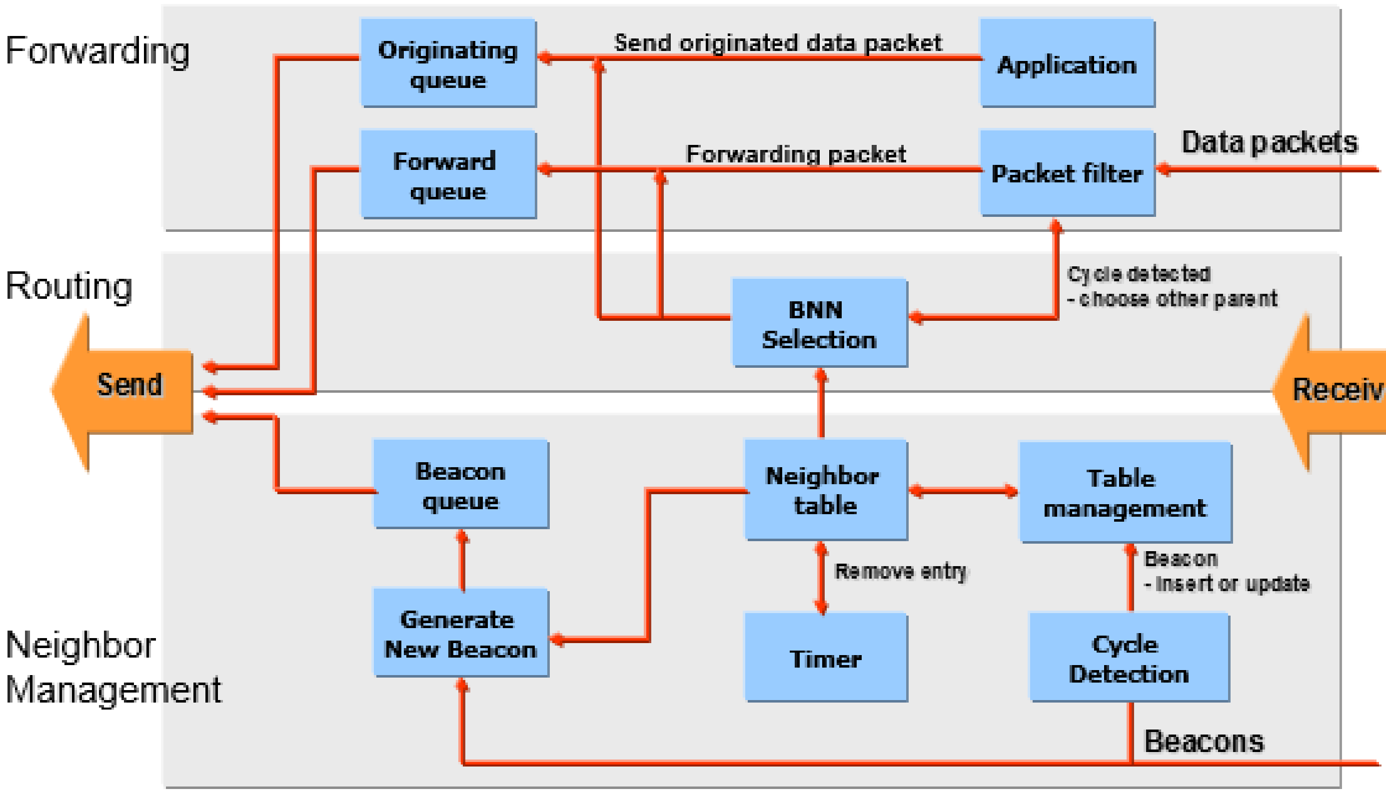
- ***k*** transmissions per interval
- First ***k*** nodes to transmit suppress all others
- Independent of density

Link Characteristics

- RSSI/LQI given by hardware
- How can we consider a link good or bad?
  - Based on RSSI/LQI?
  - Based on PRR?
- Neighbor Management
  - Policy: Add/Remove
  - Information Exchange: Link Estimation Exchange Protocol (LEEP): measure the link quality based on number of receiving:
    - Data Packet
    - Beacon

Routing Design

- ❑ Including 3 sub-layers: Neighbor Management, Routing and Forwarding



Simple Address-Free Flooding Protocol

- Root broadcasts a "new" message to local neighborhood
- Each node performs a simple rule

```
if ("new" incoming message) then {
      take local action
      retransmit modified message
}
```

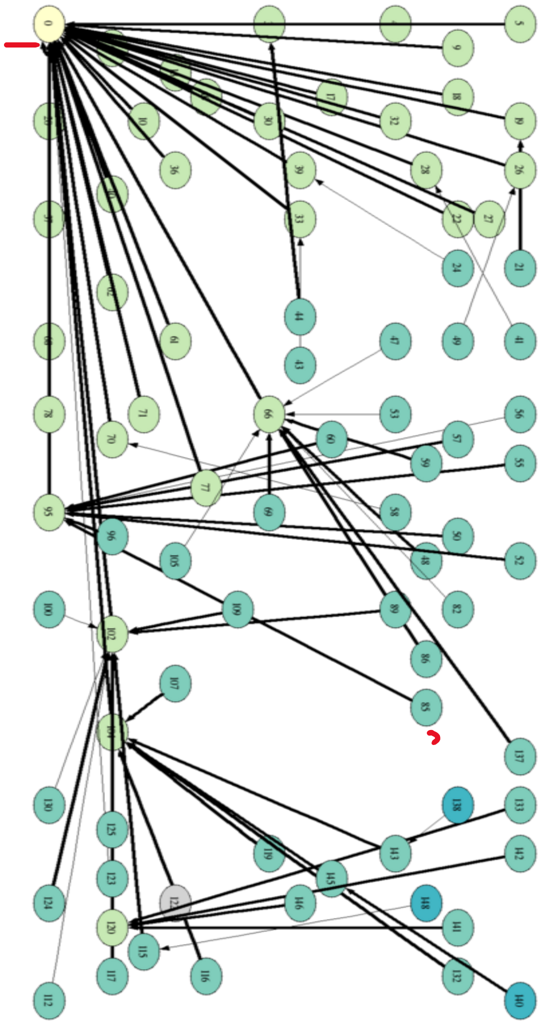
- No underlying routing structure required
  - The connectivity over physical space determines it.

CTP: Collection Tree Protocol (TEP123)

- The Collection Tree Protocol (CTP) is a tree-based protocol with some tree root nodes
- CTP is address free
- Proactive Routing & Distance Vector
- Nodes generate routes to root using rooting gradient
- CTP assumes that the data link layer provides:
  - efficient local broadcast address
  - synchronous ACKs for unicast packets
  - protocol dispatch field (support higher-level protocols)
  - single-hop source and destination fields

CTP: Collection Tree Protocol

- CTP assumes that it has link quality estimates of some number of nearby neighbors
- CTP has several mechanisms in order to improve delivery reliability (not promise 100%)
- CTP designed for relatively low traffic



CTP: Routing metric

- ETX (*Expected number of transmission*): measure each link's delivery probability with broadcast probes (& measure reverse)

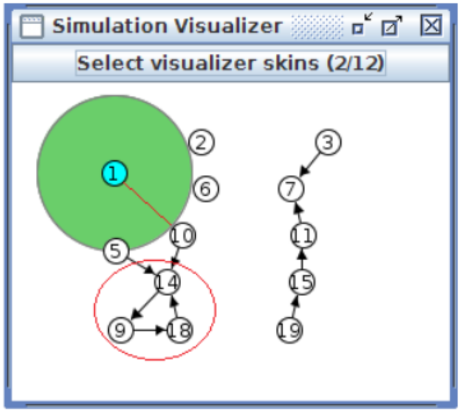
$$P_{delivery} = P_{data} * P_{ACK}$$

$$ETX_{link} = 1 / P_{delivery}$$

$$ETX_{route} = \Sigma (ETX_{link})$$

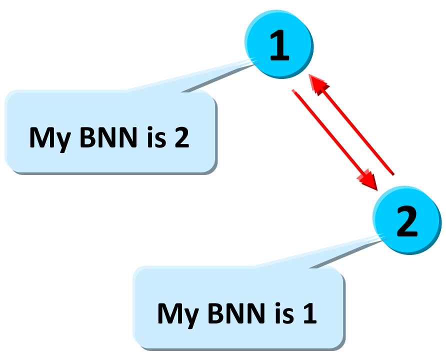
- CTP uses Expected Transmissions (ETX) as a routing metric
  - $ETX_{root} = 0$ and $ETX_{node} = ETX_{parent} + ETX_{link\text{-}to\text{-}parent}$
  - CTP should choose the route with the lowest Route-ETX (routing metric)
  - CTP represents ETX as 16-bit fix-point real number with precision of hundredths

- Main problems
  - Routing loops
  - Packet duplication
  - Network partitioning

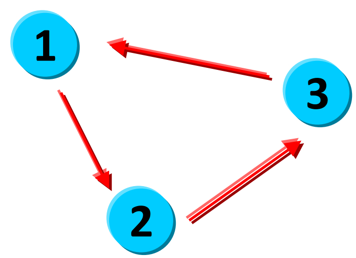


Loop – Duplication Problems

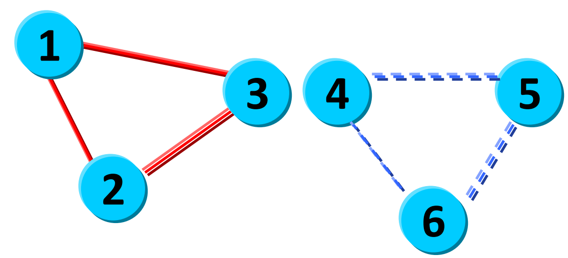
- **Beacon frame**
  - Loop: using **Sender** field to avoid. If a node receives a Beacon with **Sender** field equals to its ID: a loop occurs.
  - Duplicate: using **Sequence** field to suppress. If a node receives a Beacon with lower **Sequence** value -> not rebroadcast this beacon
- **Data frame**
  - Duplicate: using **Sequence** field in header of Data packet
  - Loop: two-hop, multi-hop and network partitioning. So, each node will have 2 BNNs if possible



If **Sender** field in packet and node's BNN are equal, try to use another BNN



If a mote receives its own packets, tries another BNN

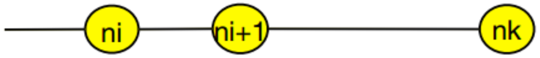


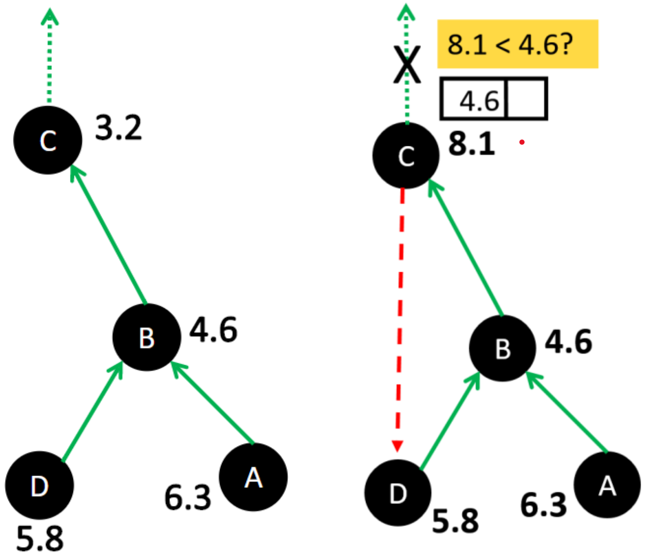
If TTL equals to a max value, discards packets because of network partitioning

CTP: Routing loop

- Occur when a node choose a new route with higher ETX than its old one
- Two mechanisms to address this problem:
  - CTP packet contains a node's current cost
    - the data frame with lower cost indicates inconsistency
    - Do not drop packets
    - try to solve inconsistency by broadcasting a beacon frame
  - Not consider routes with an ETX higher than a reasonable constant
- Data path validation
  - Cost in the packet
  - Receiver checks

$$\forall i \in \{0, k-1\},\ ETX(n_i) > ETX(n_{i+1})$$





CTP: Packet Duplication

- Occurs when a node receives a packet successfully, but the ACK is not received by the sender
- The sender retransmits the packet and the receiver receives it a second time
- The duplication is exponential
- CTP data frames have Time Has Lived (THL) field which was incremented by routing layer

CTP Data Frame

- **P** (Routing Pull)
  - allows nodes to request routing information
  - if **P** is set the node should transmit a routing frame
- **C** (Congestion notification)
  - if a node drops a CTP data frame it must set the **C** bit field on the next data frame
- **THL** (Time Has Lived)
  - if a node generates a CTP data frame, it must set THL to 0
  - if a node receives a CTP data frame must increment the THL

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
P	C	reserved						THL							
ETX															
origin															
seqno								collect_id							
data...															

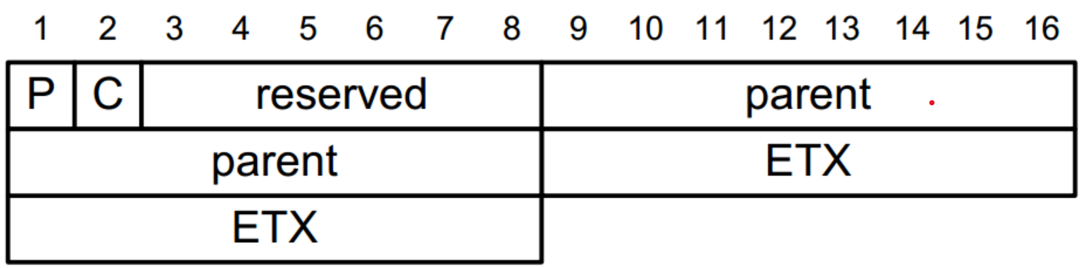
CTP Data Frame

- **ETX** (Expected Transmissions)
  - the ETX is the routing metric of the *single-hop* sender
  - node send a CTX data frame must put the ETX of its routes
  - node receives a packet with lower gradient must schedule a routing frame
- **Seqno**
  - origin sequence number
- **Collect_id**
  - Higher-level protocol identifier
- **Data**
  - the data payload, of zero or more bytes

<table>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td></tr>
<tr><td>P</td><td>C</td><td colspan="6">reserved</td><td colspan="8">THL</td></tr>
<tr><td colspan="16">ETX</td></tr>
<tr><td colspan="16">origin</td></tr>
<tr><td colspan="8">seqno</td><td colspan="8">collect_id</td></tr>
<tr><td colspan="16">data...</td></tr>
</table>

CTP Routing frame (beacon)

- **P** (Routing Pull): same as data frame
- **C** (Congestion Notification): same as data frame
- **Parent**: the node's current parent
- **Metric** (ETX): the node’s current routing metric value

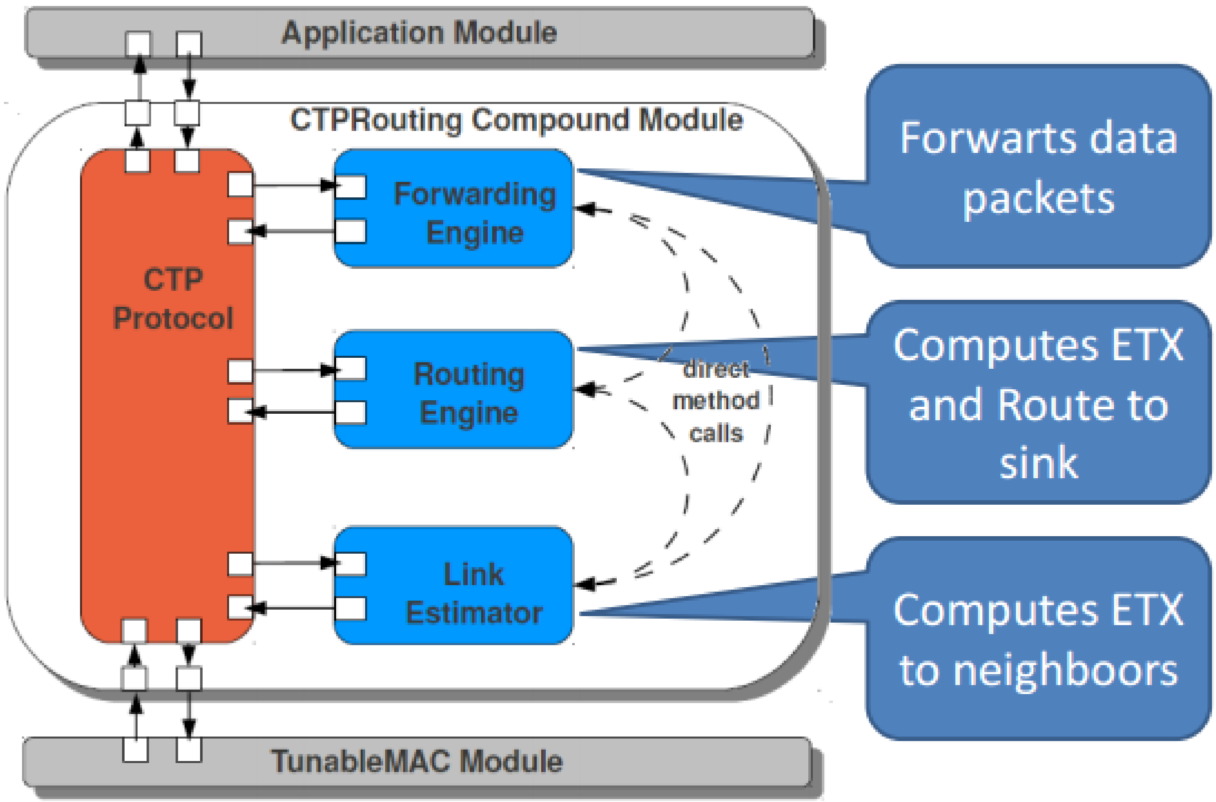


CTP: Operation

- After a node hears a routing frame (beacon), it must update its routing table
- If a node ETX value changes significantly, should transmit broadcast/beacon frame to notify other nodes
- The parent can detect when a child ETX is significantly below its own
  - parent must schedule a routing frame

CTP: Architecture

- Enable control and data plane interaction
- Two mechanisms for efficient and agile topology maintenance
- Data path validation



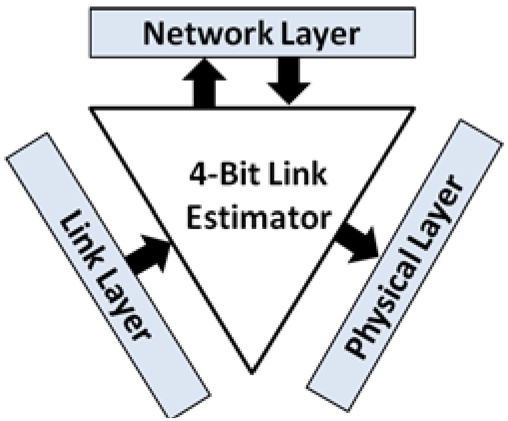
CTP: Implementation

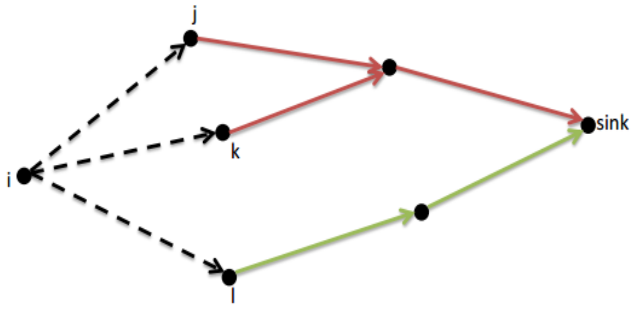
- Three major subcomponents
  - ***link estimator***
    - responsible for estimating the single-hop ETX of communication with single hop neighbors
  - ***routing engine***
    - uses link estimates to decide which neighbor is the next hop routing hop
  - ***forwarding engine***
    - maintains queue of packets to send
    - decides when and if to send them

CTP: Link Estimator

Two mechanism to estimate the link quality

- ❑ Periodic Link Estimation Extension Protocol (LEEP) packets.
  - ❖ sends routing beacons as LEEP seeds the neighbor table
  - ❖ similar to Trickle based dissemination
- ❑ Data packets
  - ❖ direct measure of ETX
  - ❖ estimator produces ETX estimate after 5 successfully acknowledged packet transmission





- $ETX_{1hop}(i,j)$
- $ETX_{1hop}(i,k)$
- $ETX_{1hop}(i,l)$

CTP: 4B Link Estimator

The ETX values are separately calculated for the sent unicast packets and received beacons

- The unicast ETX value is updated every k_{uw} **unicast packets**. k_{uw} is called the unicast update window.
  If a out of k_{uw} packets are acknowledged by the receiver, the unicast ETX estimate is:

$$\boldsymbol{ETX_u = \frac{k_{uw}}{a}}$$

- The beacon ETX value is updated every k_{bw} **beacons** (of which some might be missed). k_{bw} is called the beacon update window. The calculation is similar but involves an extra step. First the packet reception ratio (PRR) is calculated based on the number of received beacons R_b and failed beacons F_b:

$$\boldsymbol{PRR_{last} = \frac{R_b}{R_b + F_b}}$$

" Four Bit Wireless Link Estimation " by Rodrigo Fonseca, Omprakash Gnawali, Kyle Jamieson, and Philip Levis. In *Proceedings of the Sixth Workshop on Hot Topics in Networks (HotNets VI)* , 2007.

CTP: 4B Link Estimator

This instantaneous PRR value is dampened using an exponentially weighted moving average (EWMA) function:

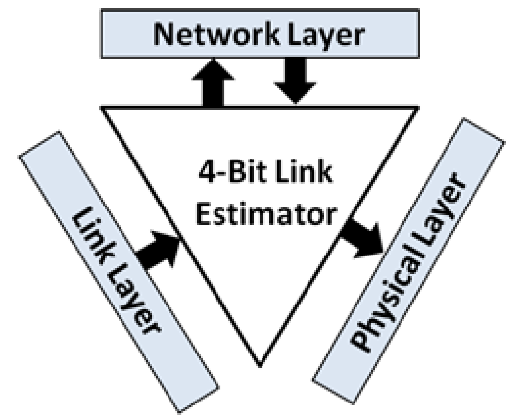
$$PRR_{new} = \alpha\, PRR_{old} + (1-\alpha)\, PRR_{last}$$

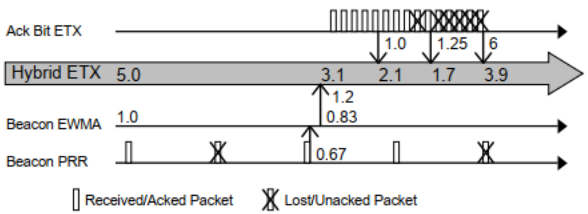
with α being a weighting factor between 0 and 1.
The resulting PRR value is then inversed to turn it into an ETX value:

$$ETX_b = \frac{1}{PRR}$$

These two streams of ETX values are combined in a second EWMA:

$$ETX_{hybrid} = \alpha\, ETX_u + (1-\alpha)\, ETX_b$$





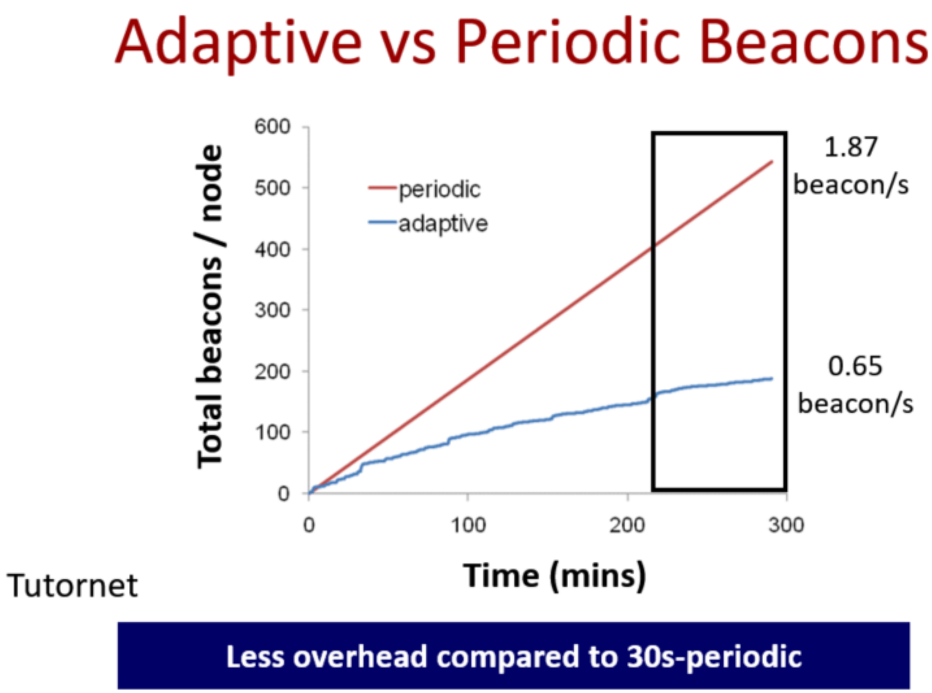
When there is heavy data traffic, unicast estimates dominate.
When the network is quiet, broadcast estimates dominate

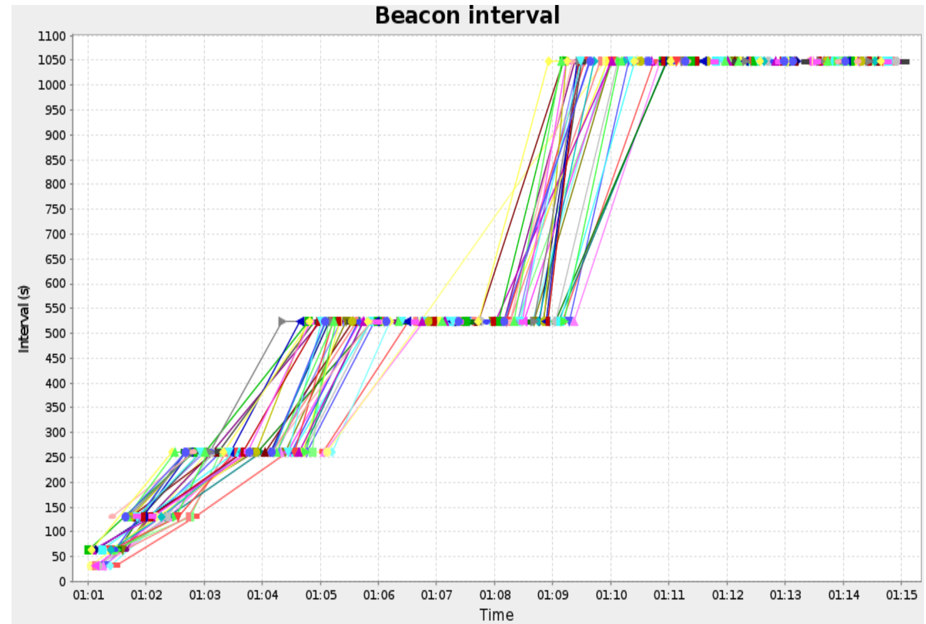
" Four Bit Wireless Link Estimation " by Rodrigo Fonseca, Omprakash Gnawali, Kyle Jamieson, and Philip Levis. In *Proceedings of the Sixth Workshop on Hot Topics in Networks (HotNets VI)* , 2007.

CTP: Adaptive Beaconing

- **Adaptive Beaconing:** Routing protocols typically broadcast control packets at a fixed interval (e.g., every 30 seconds). This interval poses a basic tradeoff.
- A small interval, i.e., frequent beacons, makes the protocol more responsive to the changes in the network, but uses more bandwidth and energy. A large interval uses less bandwidth and energy but can let topological problems persist for a long time.
- CTP uses adaptive beaconing to break this tradeoff. When the topology is inconsistent and has problems, it sends beacons *faster*. Otherwise, it *decreases* the beaconing rate exponentially. Thus, CTP can quickly respond to adverse wireless dynamics while incurring low control overhead in the long term

CTP: Adaptive Beaconing



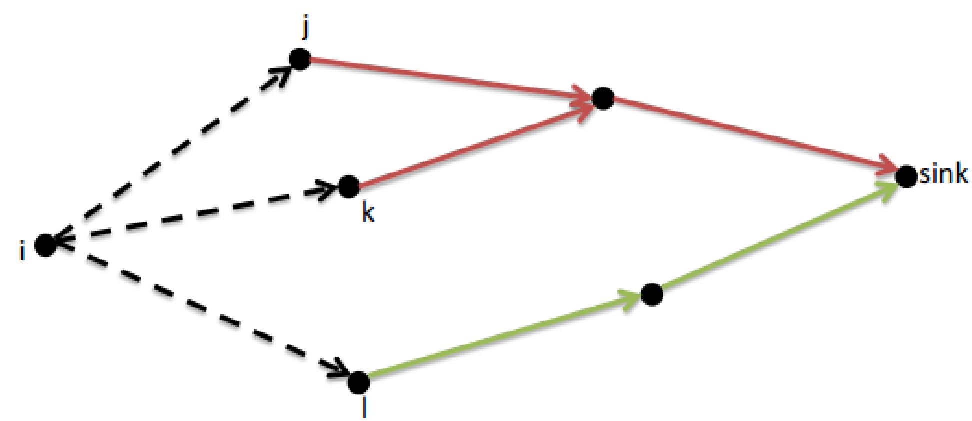


Routing Engine

- Picking the next hop for data transmission
- Keeps track of the path ETX of the subset of the nodes
- The minimum cost route has the *smallest sum*
    - the path ETX from that node
    - the link ETX of that node

Link estimator:

- $ETX_{1hop}(i,j)$
- $ETX_{1hop}(i,k)$
- $ETX_{1hop}(i,l)$



Routing Engine:

- $ETX_{multihop}(i,j) = ETX_{1hop}(i,j) + ETX_{multihop}(j)$
- $ETX_{multihop}(i,k) = ETX_{1hop}(i,k) + ETX_{multihop}(k)$
- $ETX_{multihop}(i,l) = ETX_{1hop}(i,l) + ETX_{multihop}(l)$

➡ **Choose the route having min $ETX_{multihop}$**

Forwarding Engine

- Transmitting, retransmitting packets to the next hop and passing ACK based information to the link estimator
- Deciding when to transmit packets to the next hop
- Detecting routing inconsistencies and informing the routing engine
- Maintaining a queue of packets to transmit (local and forwarded)
- Detection singe-hop transmission duplicates

Data Plane Design

- Per-client Queuing
  - One single outstanding packet per client (process)
- Hybrid Send Queue
  - Route through- and locally-generated traffic buffer
- Transmit Timer
  - Wait two packet times between transmissions
- Transmit Cache
  - Avoid duplicates

CTP: Summary

- Advantages
  - Consistent routing
  - Suitable for many-to-one application
  - High PRR
  - Evaluation:
    - CTP delivers >90% of packets (usually 99.9%)
    - CTP sends 73% fewer beacons than others
    - CTP reduces topology repair latency by 99.8%
- Disadvantages
  - Do not support any-to-any routing (e.g. IP application)