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RFID Systems, an Introduction

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RFID Technology

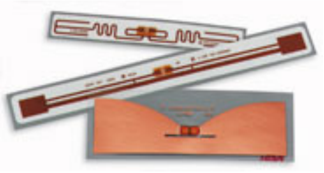
- **RFID** - **R**adio **F**requency **Id**entification

Technology enabling automatic object identification

- The shopping today
  - Goods are identified (reading their barcode) one at a time
- The shopping tomorrow
  - You can check out without emptying your cart, receiving the bill in seconds

No need for line of sight as in the case of barcodes

What is an RFID system?



RF Tags

Radio frequency labels store a unique identifier (ex. 96 bits) and consist of an antenna integrated on a microchip.

They are attached to objects to be identified

Interrogators

and Antennas

The reader queries tags to get their IDs

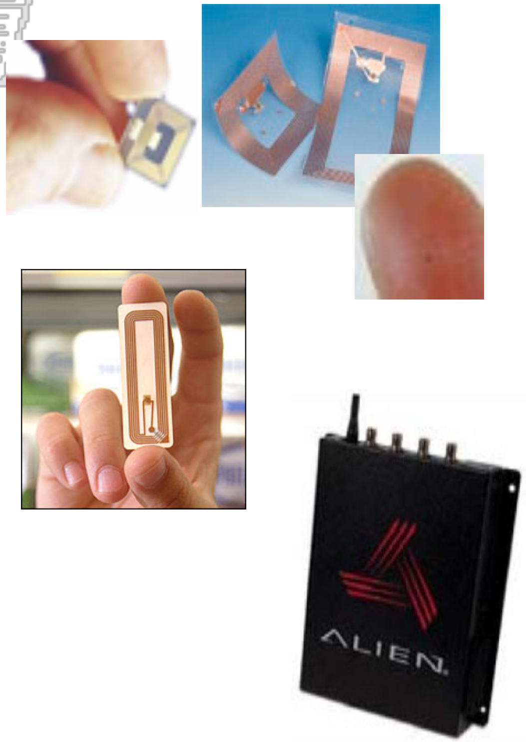
Server

& Data repositories

A server handles the data received by the reader and processes it based on the application requirements.

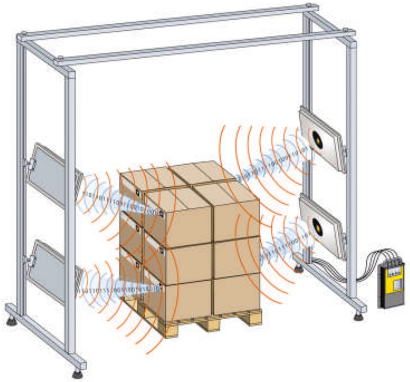
Passive tags

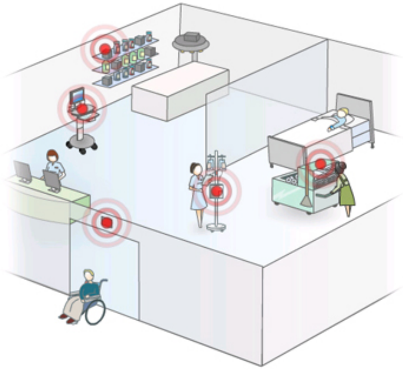
- Small, cheap, long lasting
- No power source (battery)
- Transmission through back-scattering:
  - Tags are energized by the transmission power emitted by the reader antenna
- Active tags: powered by batteries, can be smarter tags and can have a longer transmission range
  - Much more expensive!

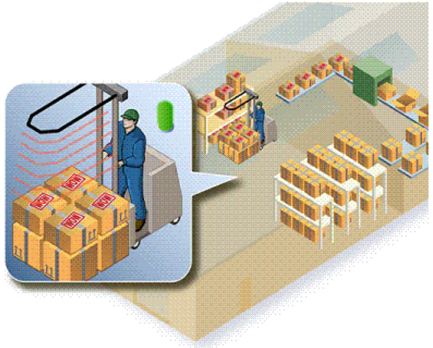


Applications

- Inventory and logistics (supply chain)
- Access control & object tracking
  - Libraries
  - Airport luggages
- Domotic and Assisted Living
  - Intelligent appliances
  - Daily assistance to people with disabilities

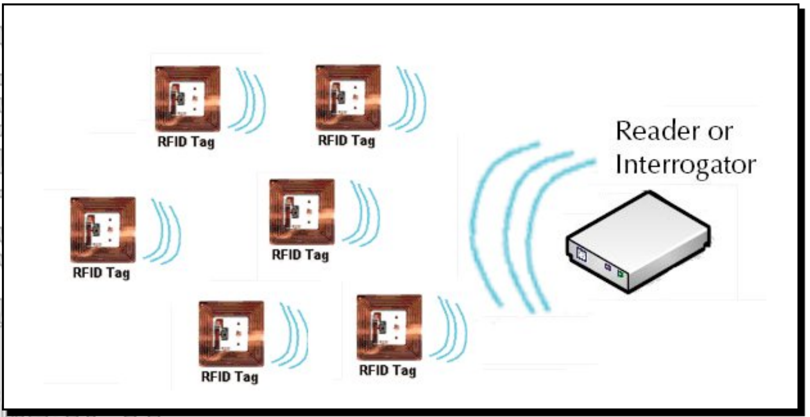






An RFID system is a network

- Single reader system with passive tags
- Communication
  - The reader queries tags
  - Tags reply by sending their IDs



Key aspects

- Multiple tags answering together cause collisions
- Tags cannot perform collision detection
- Channel access must be arbitrated by the reader

Effective and efficient identification of labeled objects

To identify tags = to avoid collisions

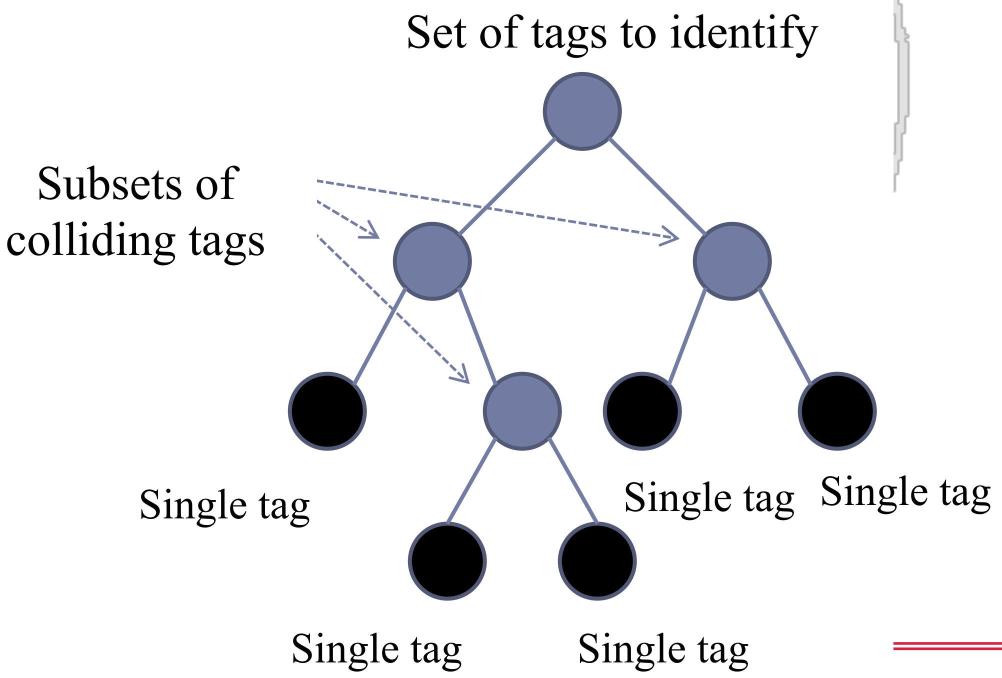
- An identification protocol has to
  - Identify tags so as to optimize single tag responses (identifications)
  - Minimize concurrent responses (or collisions that prevents identifications)
- Identification protocol ⇒ anticollision or medium access protocol (MAC)

Anti-collision protocols

- Two approaches
  - Tree based protocols
    - ✓Query – response
    - ✓Deterministic (actually one of them is randomic)
  - Aloha based protocols
    - ✓Time is slotted
    - ✓Randomic

Tree based protocols

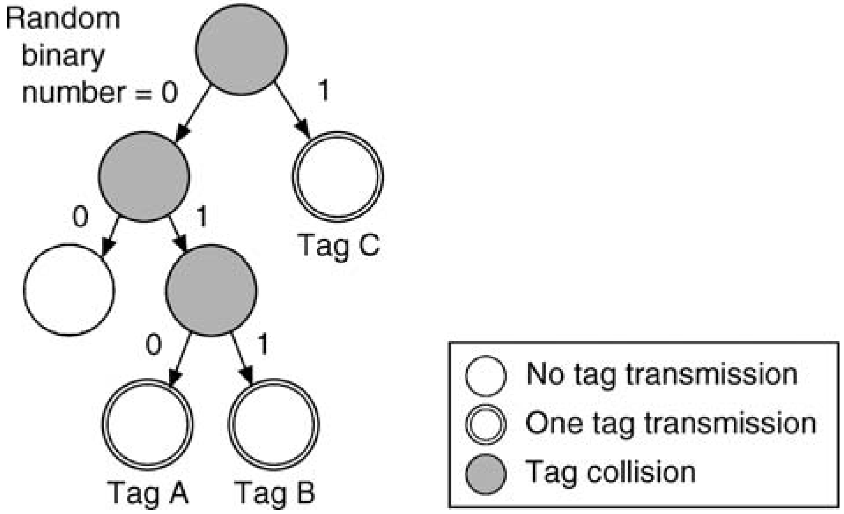
- To search unique tag ID (EPC) tree based protocols follow a binary tree structure
  - Root node: Initial set of tags (to be identified)
  - Intermediate nodes: groups of colliding tags
  - Leaf nodes: identified tags



Subsets queried depend on the specific anticollision protocol adopted

Tree based: Binary splitting (BS)

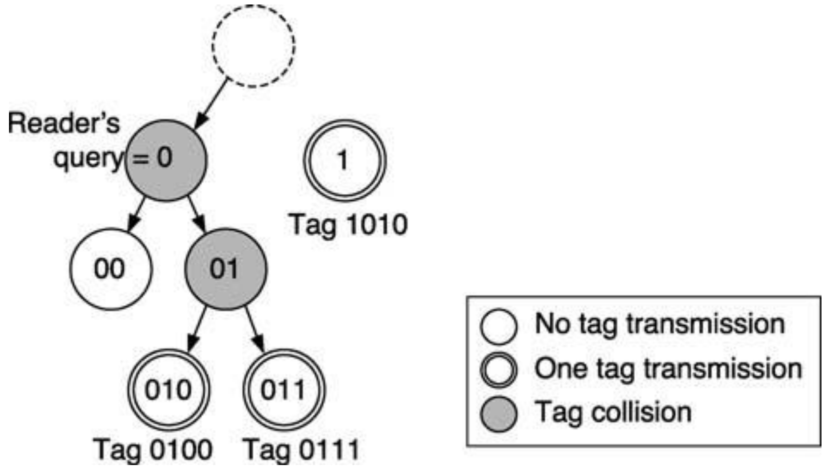
- Tags are grouped based on the generation (inside tags) of a random binary number



- Tags have a counter initialized to 0
- Tags transmit when their counter is 0
- The reader notifies the tags about the query outcome (identification, collision, no answer)
- Tags update their counter based on the query outcome
  - Collision: silent tags increase their counter by 1 while transmitting tags generate a random binary number (0,1) and sum it to the counter
  - No collision (identification or empty): every tags decrease the counter by 1

Tree based: Query Tree (QT)

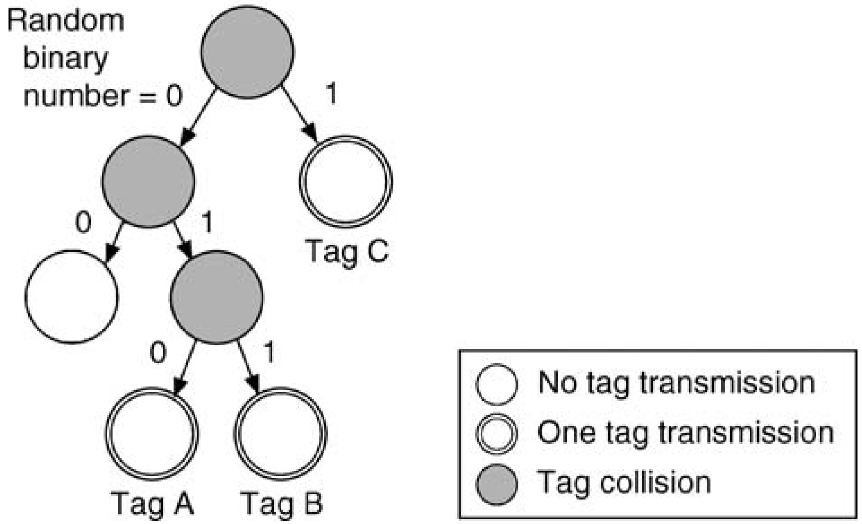
– Tags are queried based on their ID



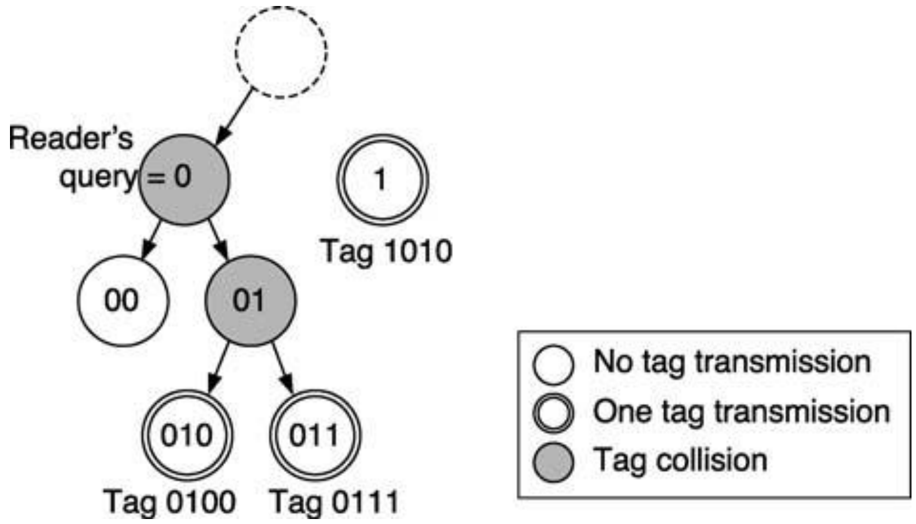
- The reader sends a query containing a binary string
- The tags whose prefix ID matches the string reply with their ID
- If there is a collision on the string $q_1q_2\ldots q_x$ (q_i ε{0,1}), $1 \le x < b$, and b is the number of bits in the ID, the reader appends one bit (0 and 1) to the string and sends two new queries $q_1q_2\ldots q_x0$ and $q_1q_2\ldots q_x1$
- Colliding tags are then splitted into two subsets

Binary Splitting vs Query Tree

- Identification trees are similar
- The assignment of random IDs to tags is similar to the generation of random bits based on BS queries



Binary Splitting (BS)



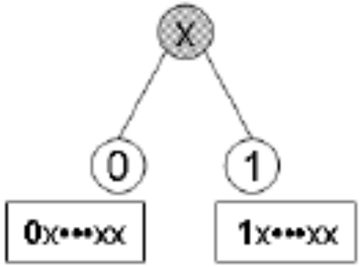
Query Tree (QT)

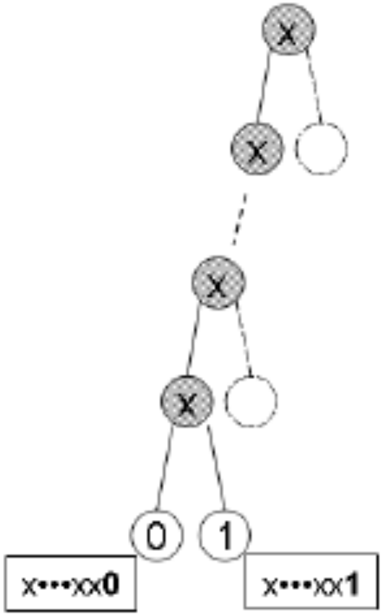
Query Tree Improved (QTI)

- Optimization of the number of queries, avoiding queries whose result can be deduced based on previous outcomes
- Example:
  - Query with prefix "p" causes collision
  - Query with prefix "p0" results in no answer
  - Query with prefix "p1" is skipped because it will cause a collision, and "p10" and "p11" are queried next

Effect of ID distribution on QT (1/3)

- Best ID distribution: the idea is to minimize the number of collisions (shortest common prefix).
  - In the case of two tags: if their IDs differ for the most significant bit
    - ✓ < **0**0000 >
    - ✓ < **1**0000 >
  - the inventory will result in only one collision (which is the minimum number of collisions to identify two tags).
- Worst ID distribution: the idea is to maximize the number of collisions (longest common prefix)
  - In the case of two tags: if they differ for the least significant bit
    - ✓ < 0000**0** >
    - ✓ < 0000**1** >
- The inventory will result in as many collisions as the common bits in the IDs





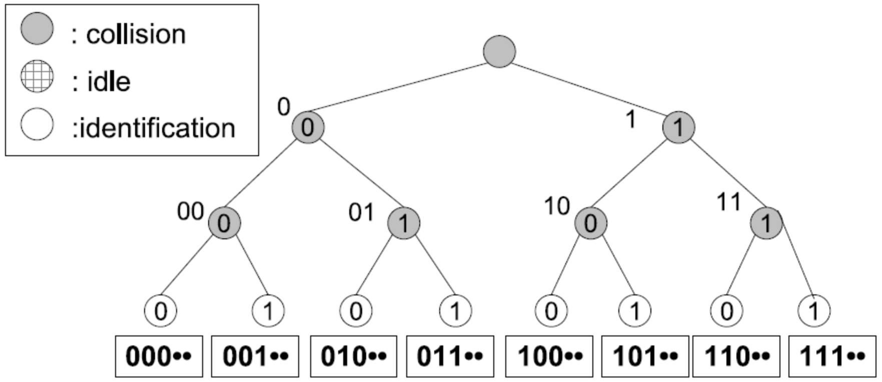
Effect of ID distribution on QT (2/3)

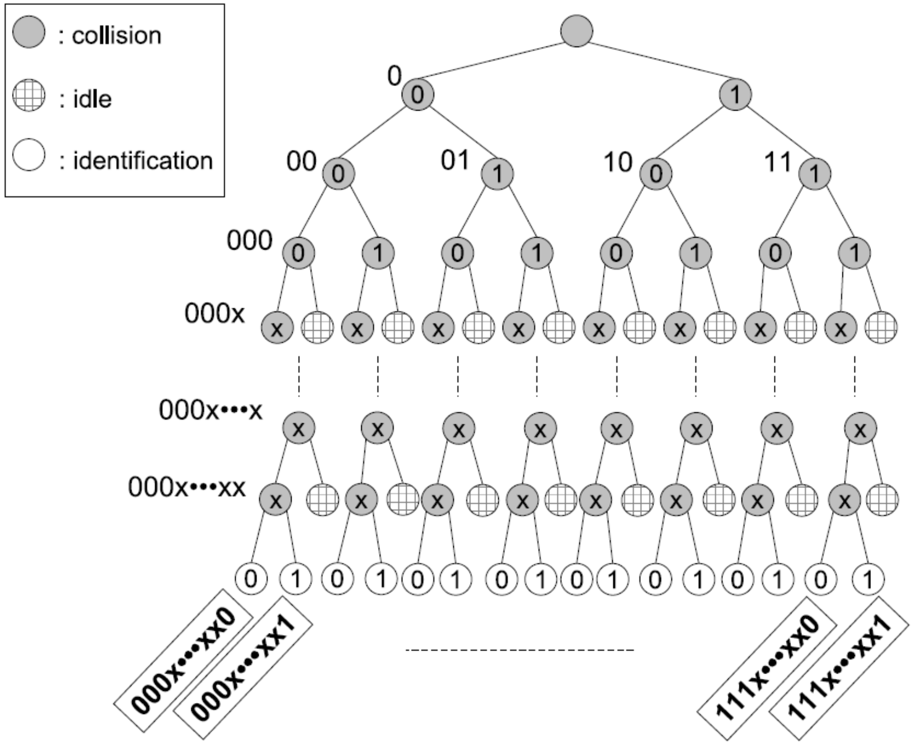
Optimal distribution

- Is it unique?

Worst distribution

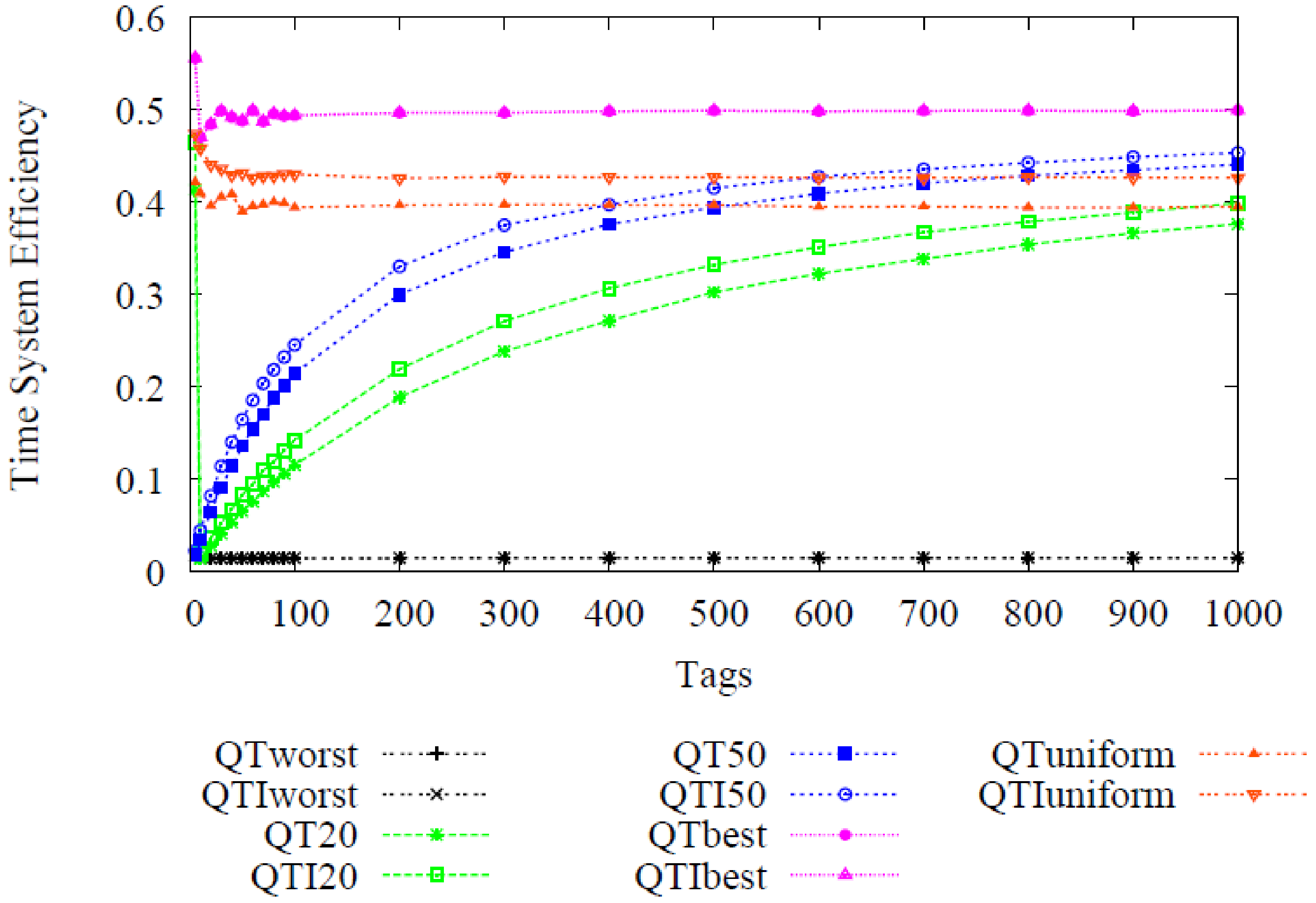
- Is it unique?





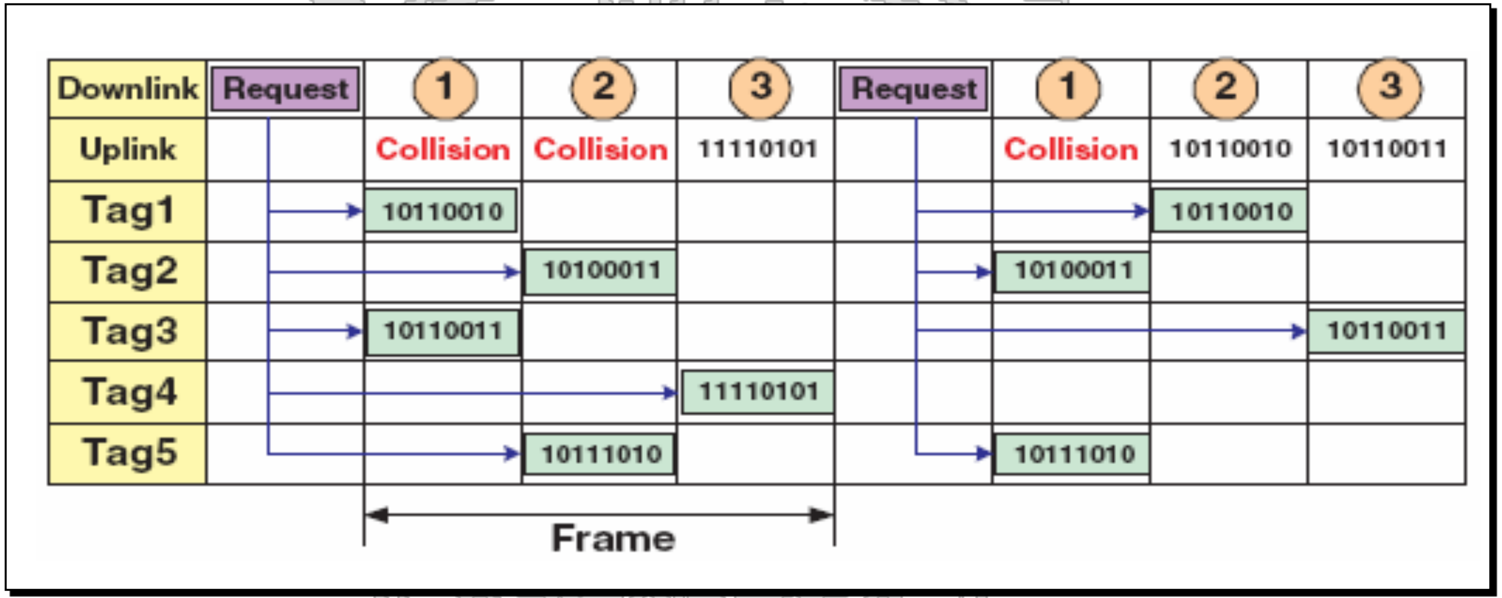
Effect of ID distribution on QT (3/3)

- Temporal efficiency with various ID distributions



Framed Slotted Aloha

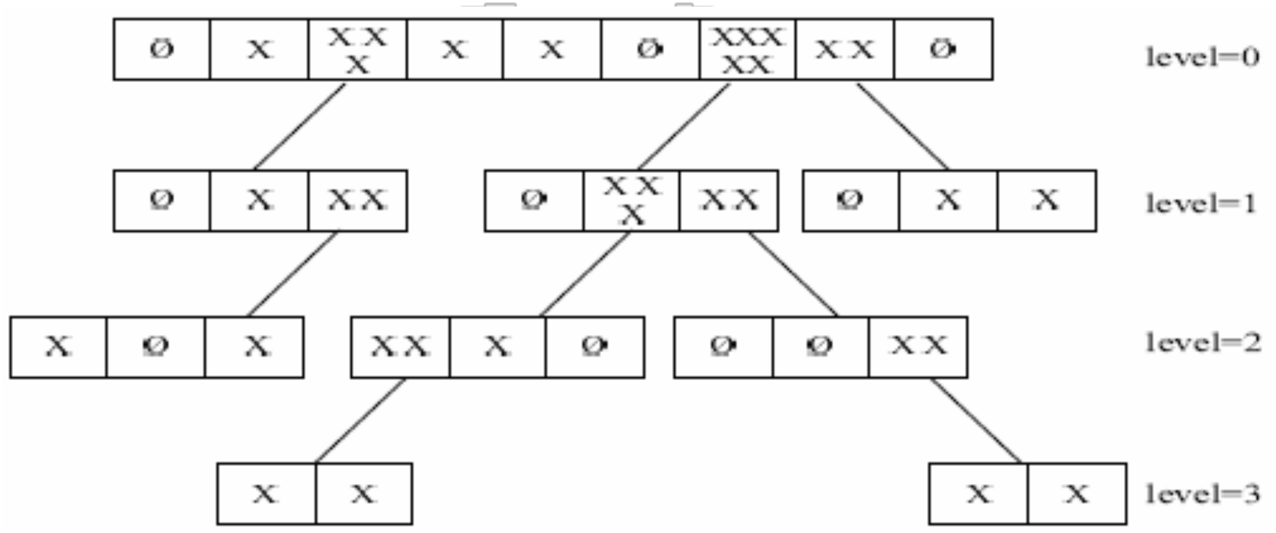
- Slotted Aloha (random selection of slots)



Downlink	Request	1	2	3	Request	1	2	3
Uplink		Collision	Collision	11110101		Collision	10110010	10110011
Tag1		10110010					10110010	
Tag2			10100011			10100011		
Tag3		10110011						10110011
Tag4				11110101				
Tag5			10111010			10111010		

- 6 slots: 3 collisions + 3 identifications
- Protocol efficiency = # identifications / #slots = 50%
- In general
- 37% of identifications
- The remaining 63% is wasted in collisions and idle queries

Tree Slotted Aloha (TSA)



- A new *child* frame is issued for each collision slot: only tags replying to the same slot participate
- Child frames should be sized properly according to the number of colliding tags

Main Issue

Estimating tag population to properly tune frame sizes

Tag estimation issues

- How to set the initial frame size (the number of tags is unknown)

- How to estimate the number of tags that collide in the same slot and properly tune the following frames
  - True in any Aloha protocol

Estimating tag population

- The number of tags to be identified is not known
  - The initial frame size is set to a predefined value (i.e., 128)
  - The size of the following frames is estimated

$$\text{tags per collision slot} = \frac{(\text{estimated total num of tags}) - (\text{identified tags})}{\text{collision slots}}$$

  - The total number of tags is estimated according to the outcome of the previous frame (based on Chebyshev's inequality)

$$\varepsilon(N, c_0, c_1, c_k) = \min_n \left| \begin{pmatrix} a_0^{N,n} \\ a_1^{N,n} \\ a_k^{N,n} \end{pmatrix} - \begin{pmatrix} c_0 \\ c_1 \\ c_k \end{pmatrix} \right|$$

- N: size of completed frame
- $<c_0, c_1, c_k>$ triple of observed values
- $<a_0, a_1, a_k>$ triple of estimated values

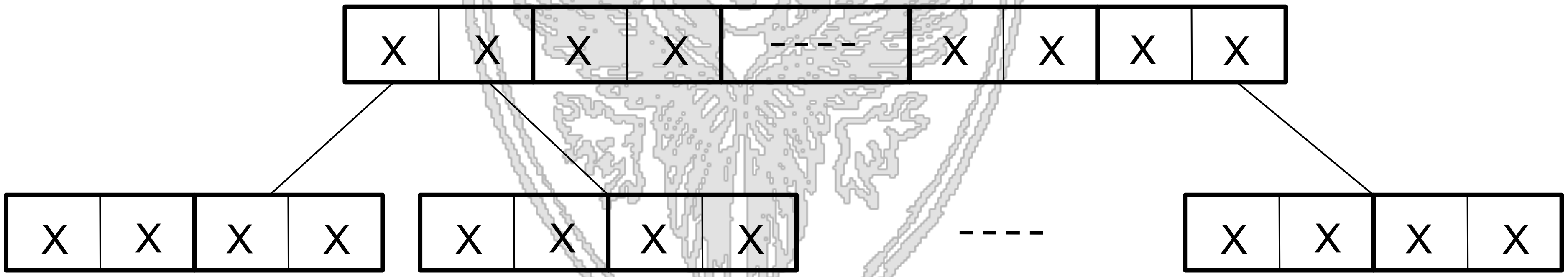
- Given *N* and a possible value of *n*, the expected number of slots with *r* tags is estimated as

$$a_r^{N,n} = N \times \binom{n}{r} \left(\frac{1}{N}\right)^r \left(1 - \frac{1}{N}\right)^{n-r}$$

Inaccuracy of tag estimation for large networks

- The estimator does not capture the possibly high variance of the number of tags
- The minimum is computed over *n* ranging in $[c_1 + 2c_k, 2(c_1 + 2c_k)]$
- The upper bound $2(c_1+2c_k)$ is not adequate for network composed of thousands of nodes
  - Example: 5000 tags, N=128, it is highly likely that $c_1=0$

    n is estimated $2(c_1+2c_k) = 512$ → definitively too small



Only 4 slots for an expected number of colliding tags around 40!

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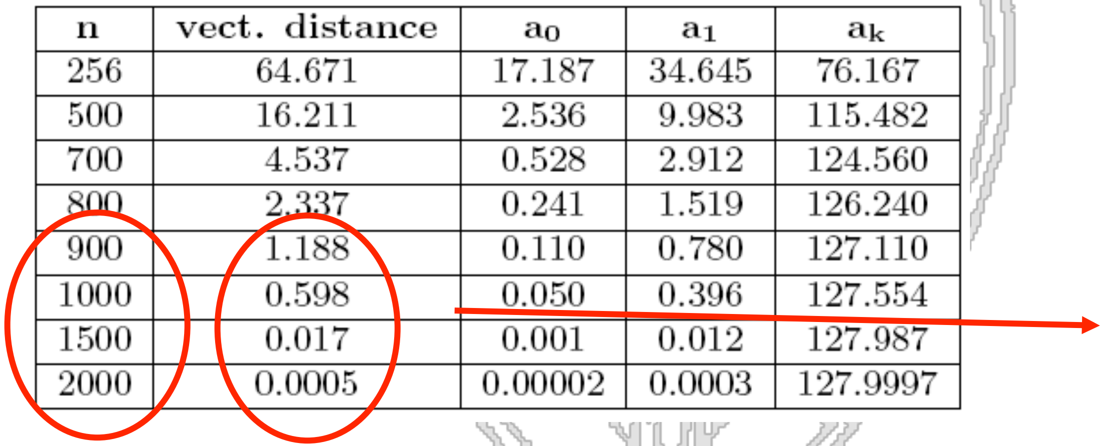
Unbounded estimator

- Let’s search for a better upper bound
- Let’s not stop at $2(c_1+2c_k)$
- For N=128 and $<c_0,c_1,c_k> = <0,0,128>$, the table shows the triple of estimated values and their distance from the observed values by varying *n*

Varying n



n	vect. distance	a_0	a_1	a_k
256	64.671	17.187	34.645	76.167
500	16.211	2.536	9.983	115.482
700	4.537	0.528	2.912	124.560
800	2.337	0.241	1.519	126.240
900	1.188	0.110	0.780	127.110
1000	0.598	0.050	0.396	127.554
1500	0.017	0.001	0.012	127.987
2000	0.0005	0.00002	0.0003	127.9997

still not accurate!

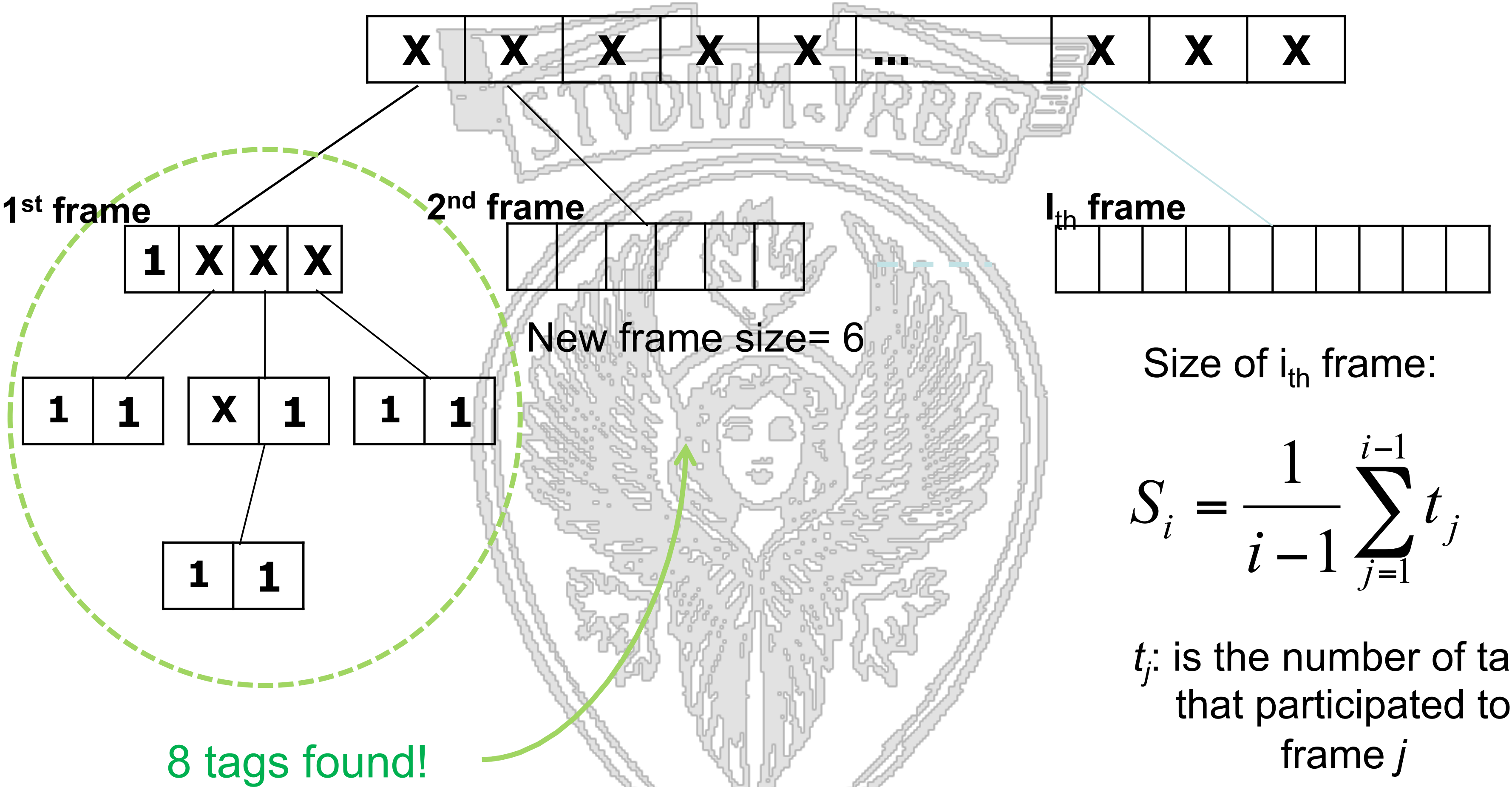
Dynamic Tree Slotted Aloha (Dy_TSA)

- **Dynamic** tag estimation that exploits the knowledge gained during previously completed frames
- Assumption: tags are uniformly distributed among all slots
  - The expected number of tags in a slot is

$$E[X] = \frac{n}{N}$$

  - Satisfied for when $n >> N$

Dy_TSA
dynamic tag estimation



New frame size= 6

8 tags found!

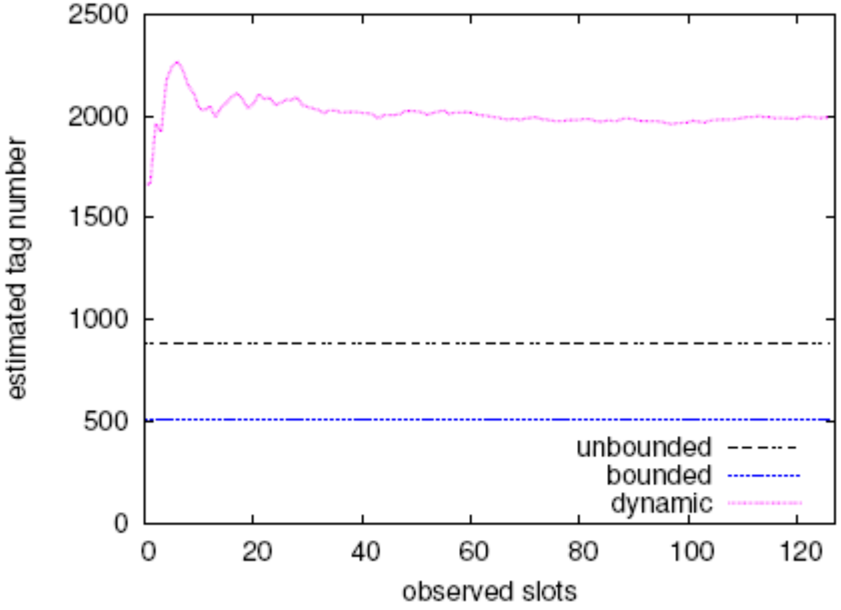
Size of i_{th} frame:

$$S_i = \frac{1}{i-1}\sum_{j=1}^{i-1} t_j$$

t_j: is the number of tags that participated to frame j

- As TSA proceeds in depth-first order, the estimation method can be recursively applied on deeper levels of the tree

Accuracy of dynamic tag estimation



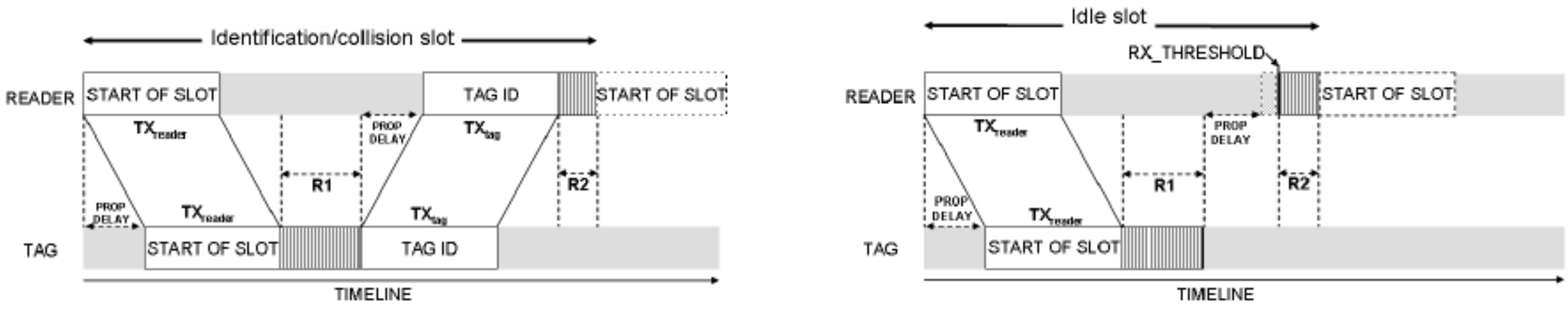
Estimated number of tags as slots of the first frame are resolved (n=2000)

Performance evaluation

- Implementation of RFID framework within Network Simulator *ns*2 (v. 2.30)
- Simulated protocols: QTI, BS, TSA, Dy_TSA
- Metrics
  - **Latency:** protocol execution time defined as the time (in seconds) for identifying all tags.
  - **System efficiency:** the fraction of rounds or time spent by the various protocols identifying tags.
    - ✓ In terms of *rounds* $\mathbf{SE_r = R_{id}/R_{tot}}$
      where $\mathbf{R_{id}}$ is the amount of identification rounds (which is equal to the number of tags), and $\mathbf{R_{tot}}$ is the total number of rounds.
    - ✓ In terms of *time* $\mathbf{SE_t = T_{id}/T_{tot}}$
      where $\mathbf{T_{id}}$ is the time spent in identifying tags, and $\mathbf{T_{tot}}$ is the total protocol execution time.

Transmission time model

- Derived from EPCglobal Specification Class 1 Gen 2



(a) Identification or collision slot.

(b) Idle slot.

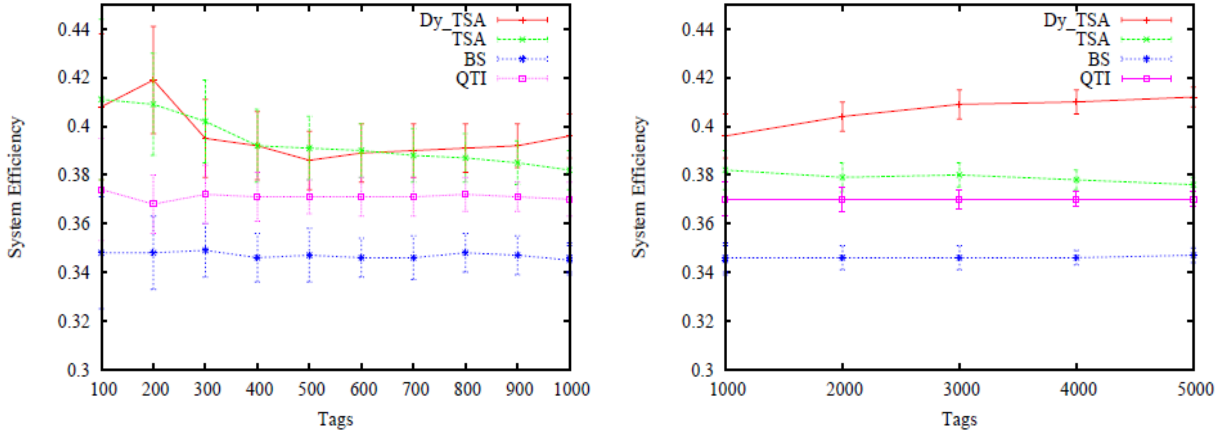
Fig. 1. Link timing for reader-to-tag and tag-to-reader transmission during a slot.

- R1: tag reaction time
- R2: reader reaction time
- RX_threshold: time at which the reader should receive the first bit of tag transmission

Scenarios

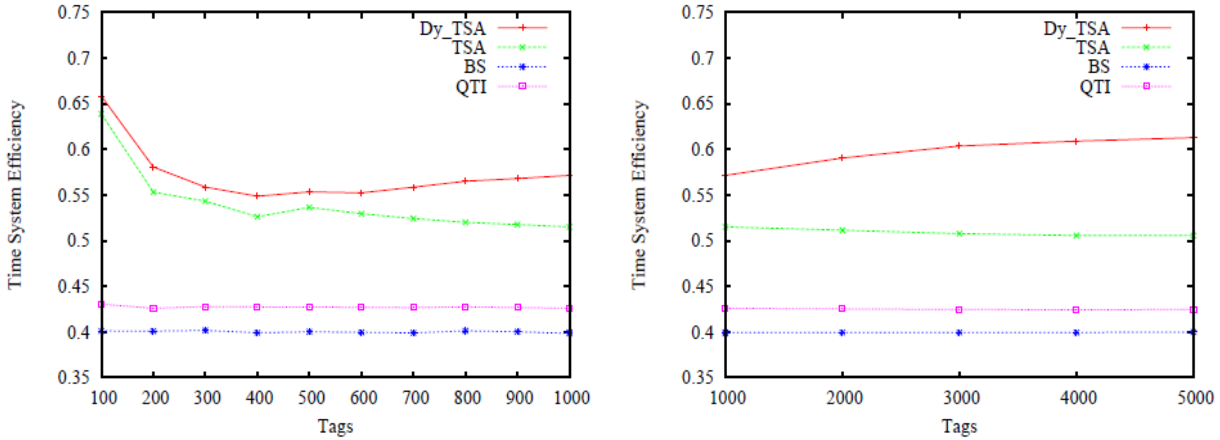
- Network size *n* = 100, ..., 5000 tags
- Channel data rate: 40 Kbps
- Tag ID length: 96 bits
- Initial frame size for Aloha-based protocols is set to 128 slots
- Uniform distribution of tag IDs
- Results have been obtained by averaging over 100 runs

Results: Round vs. Time System Efficiency



(a) System efficiency: 100-1000 nodes.

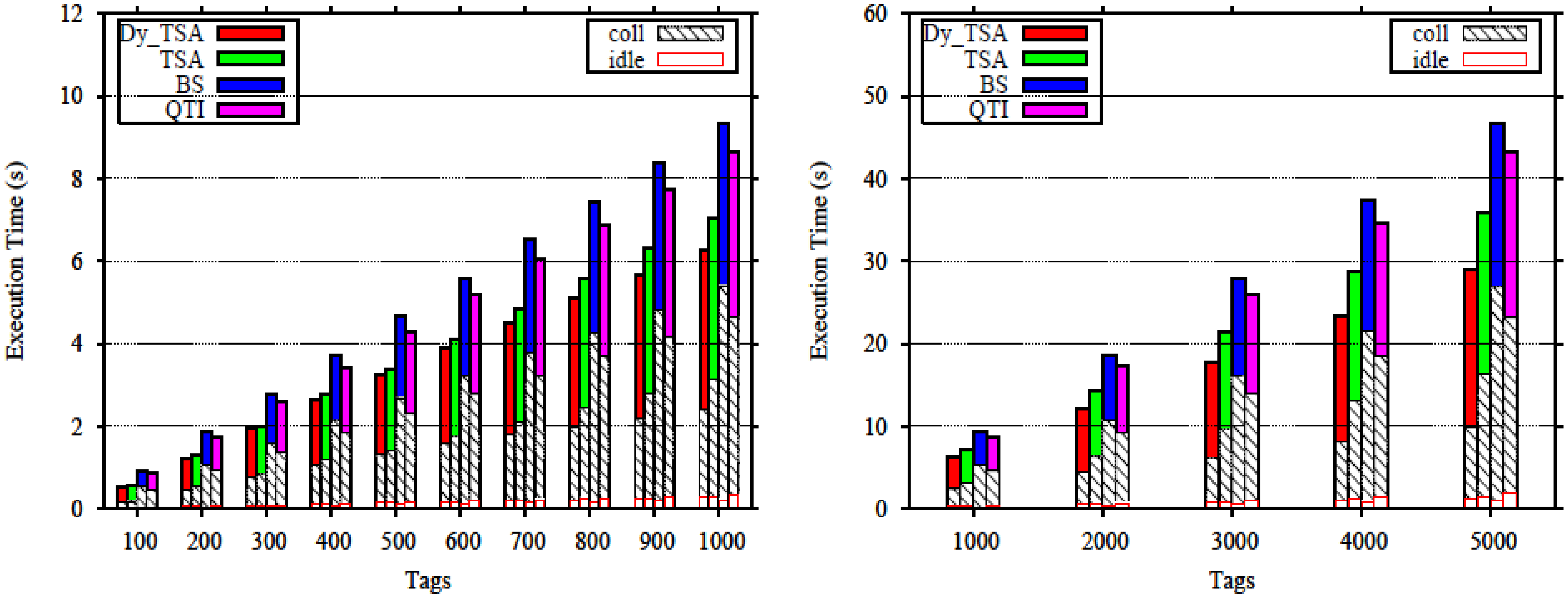
(b) System efficiency: 1000-5000 nodes.



(c) Time system efficiency: 100-1000 nodes.

(d) Time system efficiency: 1000-5000 nodes.

Results: latency



(a) Execution time: 100-1000 nodes.

(b) Execution time: 1000-5000 nodes.

Binary Splitting Tree Slotted Aloha (BSTSA)

- Combination of BS and TSA
  - BS is used to divide tags into groups whose size can be easily estimated
  - TSA is used to identify tags
- Optimal frame sizing is adopted for each frame
  - We derive (and use for sizing each frame) the frame size which maximizes the time system efficiency of Framed Slotted Aloha protocols

Time system efficiency

- Let R_{ident}, R_{coll}, and R_{idle} be the number of identification, collision and idle rounds during the tag identification process
- In Framed Slotted Aloha protocols in which n tags randomly select the slot to answer among N slots the probability that r tags answer in the same slot is given by the binomial distribution
- $R_{idle} = N \times (1 - 1/N)^n$
- $R_{ident} = n \times (1 - 1/N)^{n-1}$
- $R_{coll} = N - R_{idle} - R_{ident}$
- System efficiency in case of rounds of the same duration (weight) is 36%
- If idle rounds last a ß fraction of identification and collision round:

$$Time\_SE = \frac{R_{ident}}{\beta R_{idle} + R_{ident} + R_{coll}} = \frac{n\left(1-\frac{1}{N}\right)^{n-1}}{(\beta-1)N(1-\frac{1}{N})^n + N}$$

Optimal frame tuning

- To obtain the optimal frame size *N* for a given number of tags, we compute the maximum value of *Time SE* by deriving it, and posing

$$\frac{\delta Time\_SE}{\delta N} = 0$$

  - The maximum is achieved when

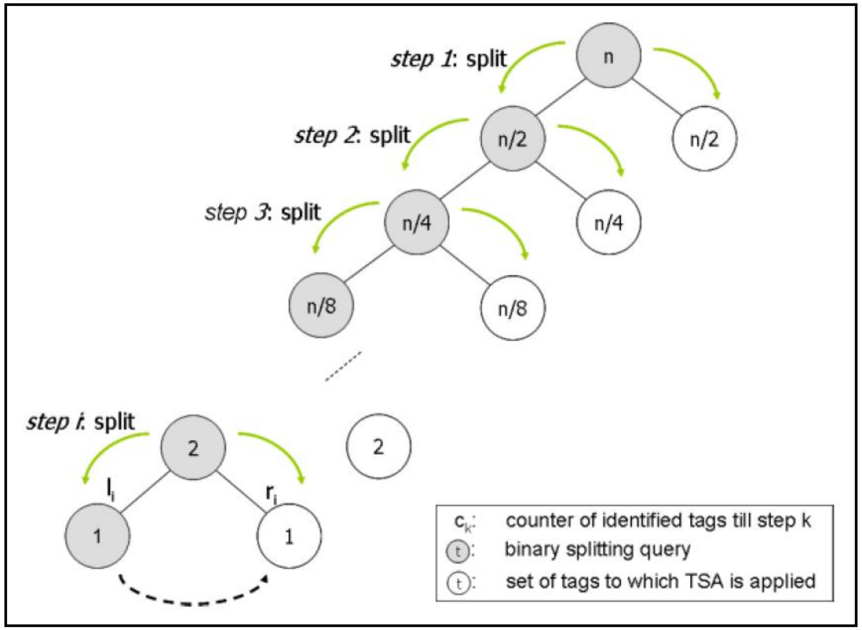
$$(\beta - 1)\left(1 - \frac{1}{N}\right)^{n} + 1 = \frac{n}{N}$$

  - Studying the two functions we have found that the Time_SE is maximum (upper bounded by 80%) when

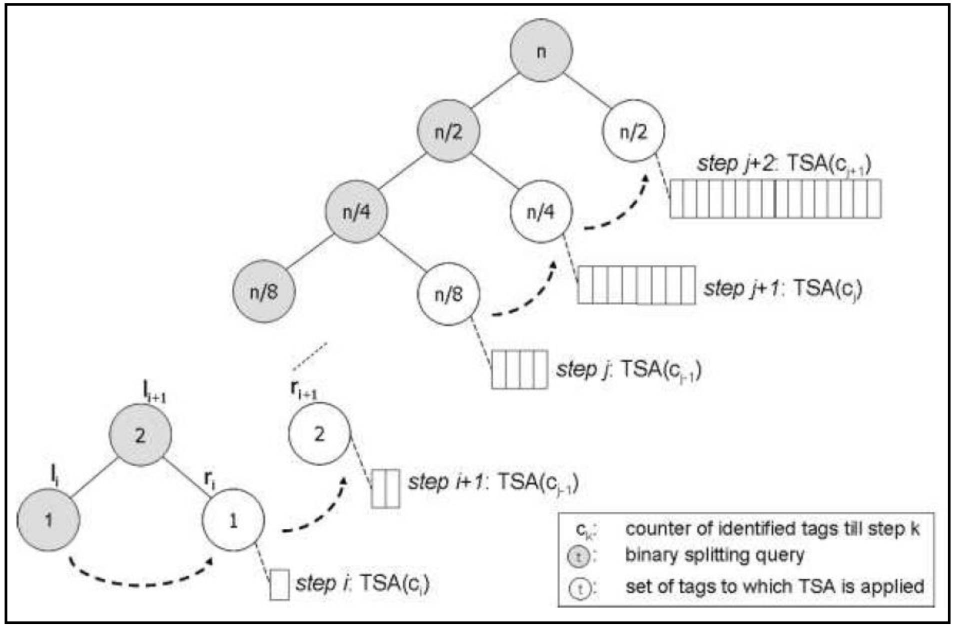
Optimal frame size

$$\boxed{N = 4.406 \times n - 1}$$

BSTSA protocol description

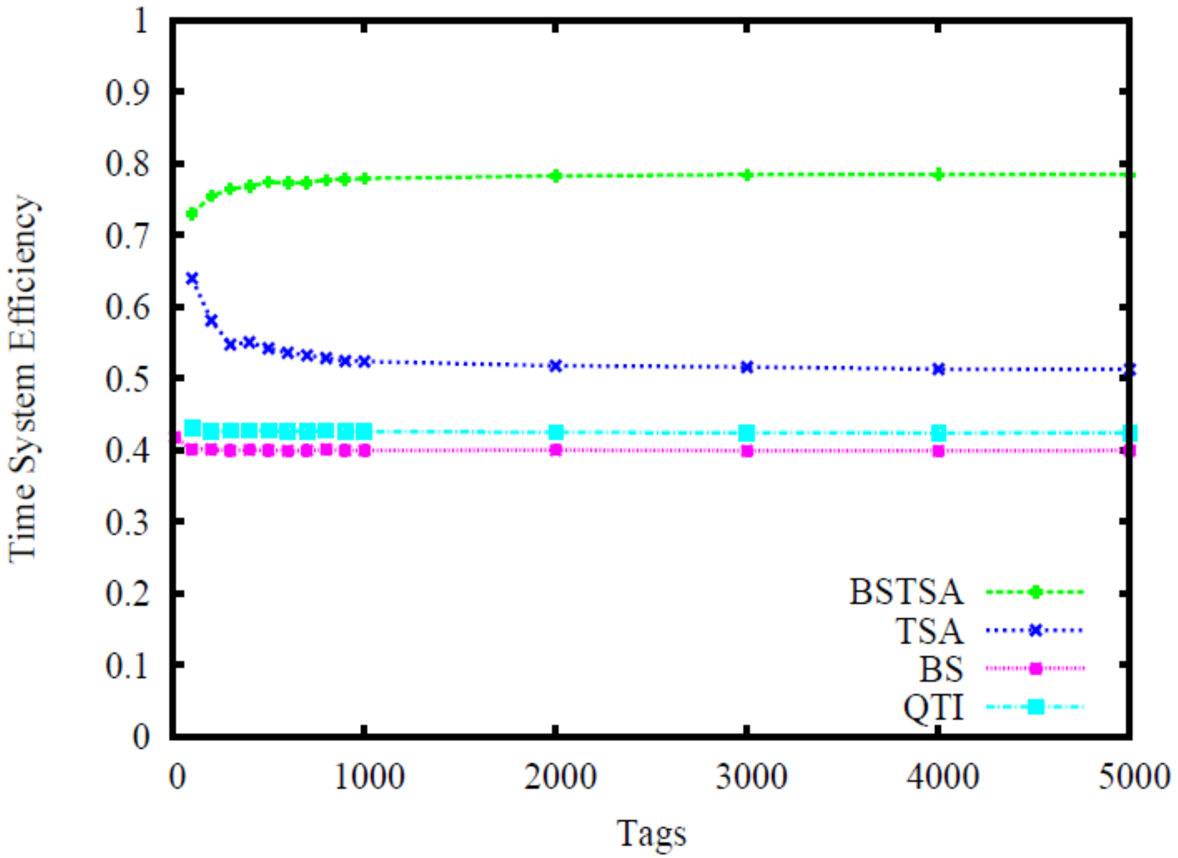


Binary Splitting phase

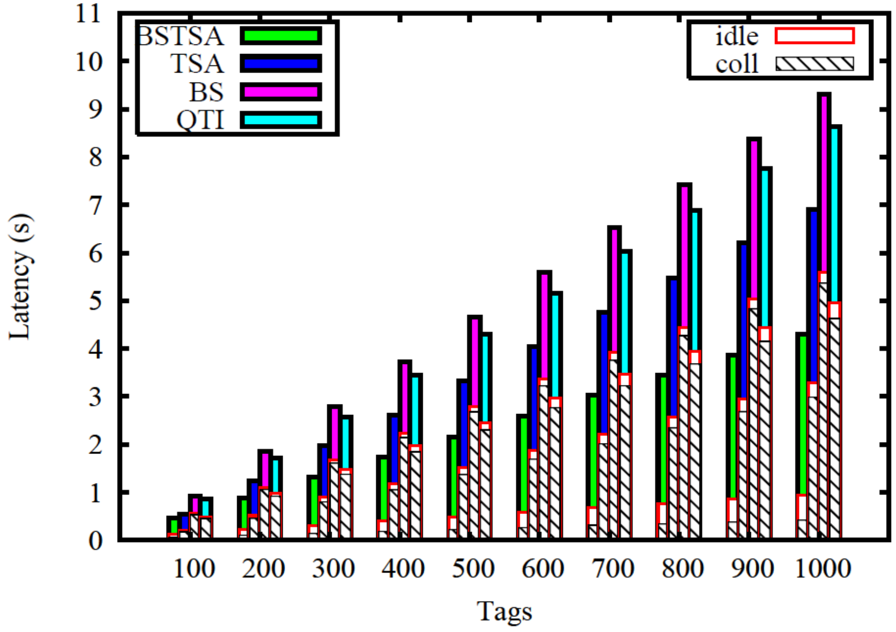


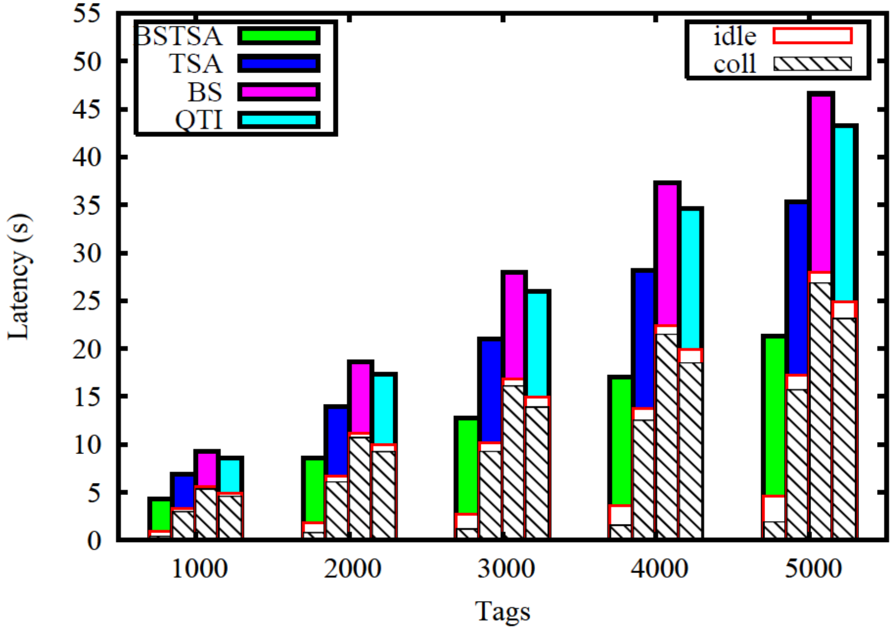
Tree Slotted Aloha phase

Results: Time system efficiency



Results: Latency





Possibilità di tesi con borsa

- Development of RFID based systems for high data rate BAS
  - Collaboration with: Prof. Gaetano Marrocco
  - Collaboration with: Prof. Deepak Ganesa, UMASS
- Development of novel energy neutral Internet of Things platforms
  - WSENSE S.r.l
  - Collaboration with ETHZ
- Development of Internet of Things technologies for monitoring the conservation status of cultural heritage
  - WSENSE S.r.l
- Underwater sensor networks
  - WSENSE S.r.l
    - ✓ development and support of SUNSET
    - ✓ development of the front end of underwater monitoring systems