ECE 5990

Note 9
RFID Air Protocols

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Outline

- Overview of anti-collision algorithms
- Aloha-based protocols to resolve tag collision
- Tree-based protocols to resolve tag collision
- Problems of moving tags and reader collision
- EPC and IP-X protocol and commands
- Comparison of RTF (EPC) and TTF (IP-X) protocols

Quotable Quotes

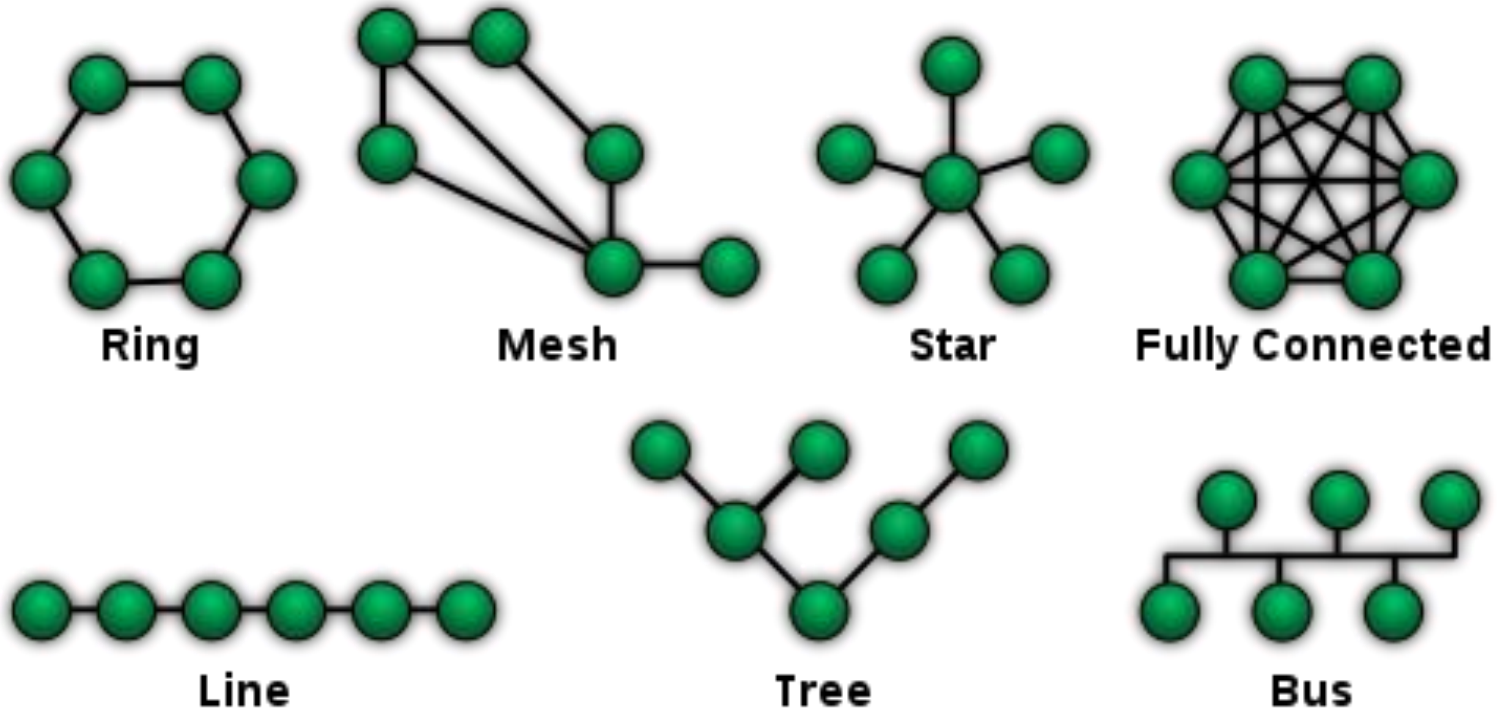
“Everyone seems to think that the D.N.S. system is a big deal, but it's not the heartbeat of the Internet. Who controls the flow of the ocean? Nobody controls it, and it works just fine. There are some things that can't be controlled and should be left distributed.”

— Leonard Kleinrock (1934 - present)

Open Systems Interconnection (OSI) Model

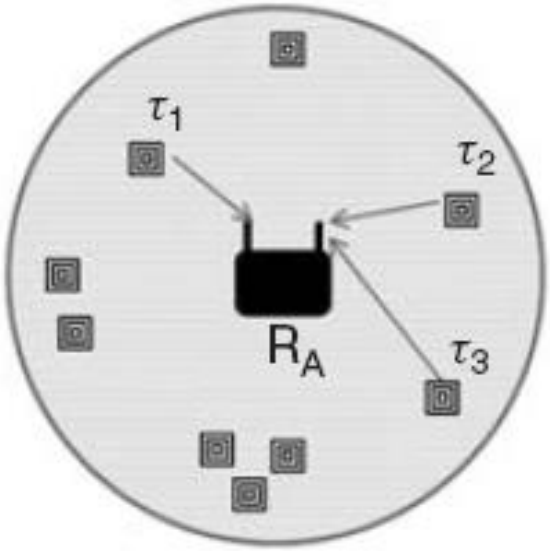
Layer	Example
Application	FTP, HTTP, NFS, DHCP
Presentation	MIME, XDR
Session	Named pipe, SAP, RTP, SOCKS
Transport	TCP, UDP, DCCP
Network	IP, AppleTalk, X.25
Data link	ATM, IS-IS, HDLC, SLIP, IEEE 802.2, MAC
Physical	DSL, IEEE 802.3, USB, Bluetooth, RS-232

Local Area Network (LAN) Topology: IEEE 802

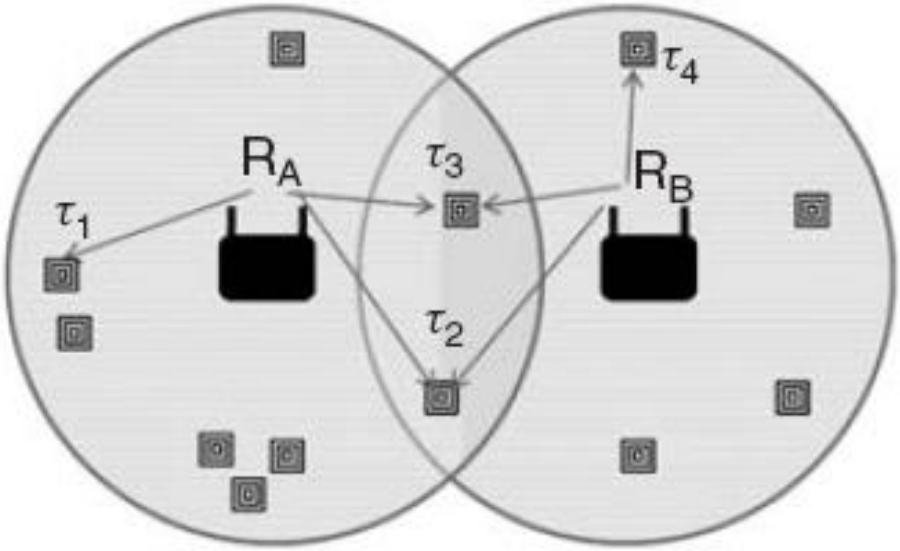


- Star network: RFID, Ethernet, Wifi
- Network Interface Card (NIC)
- IEEE 802 LAN/MAN standards

Signal Collisions from Tags and Readers



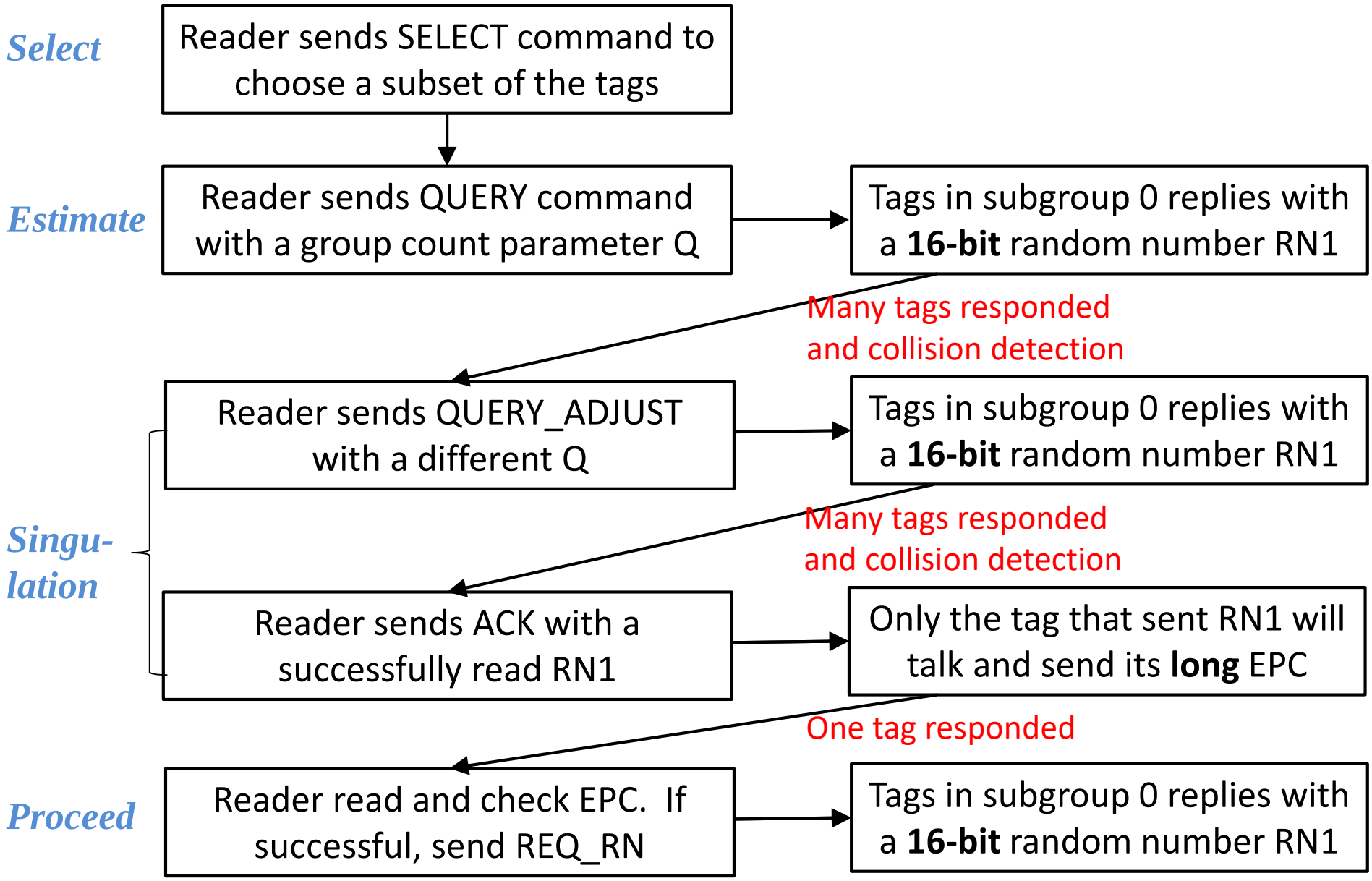
Tag Collision



Reader Collision

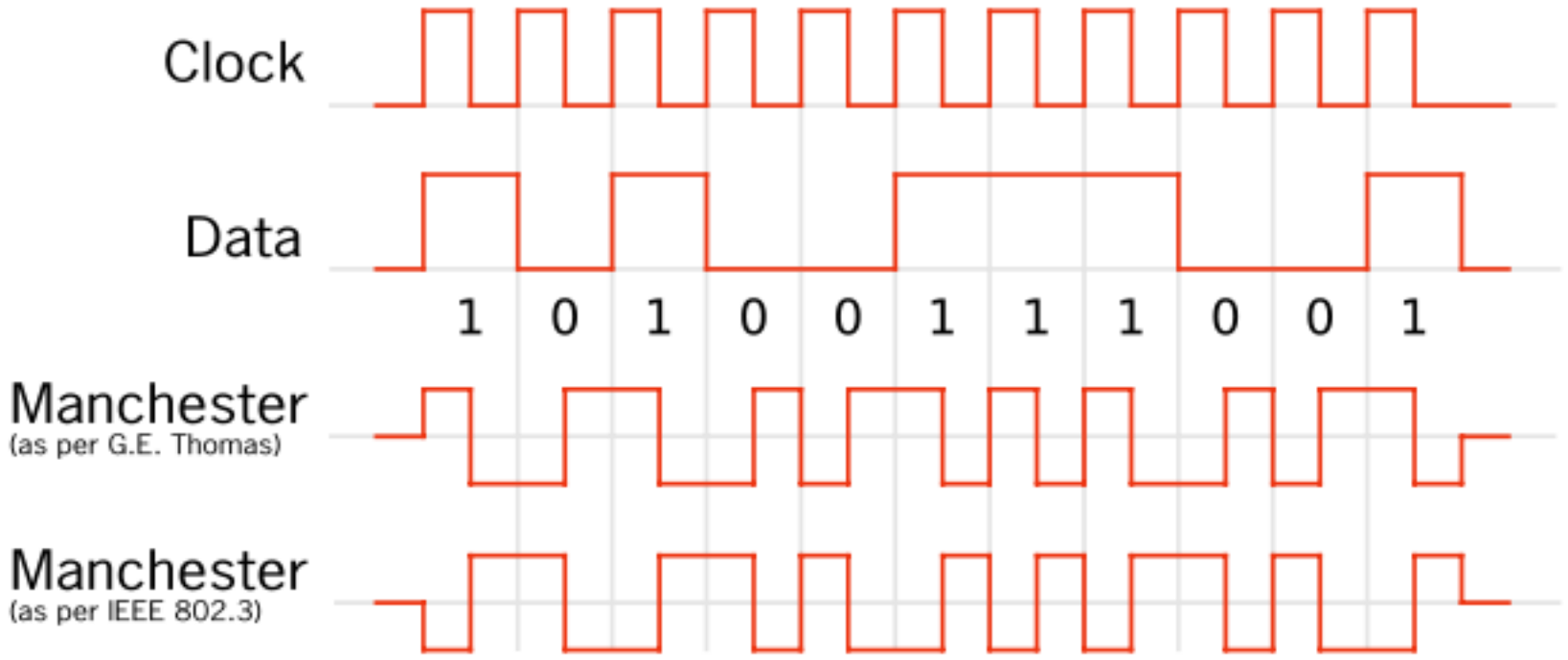
Both collisions need to be resolved by readers!!!

General Handshake Procedures



Handshake Properties

- 16-bit header is used for easier pooling, estimation, verify, and collision detection
- Header is often Manchester coded to facilitate collision detection: Man_code = clock ⊕ data



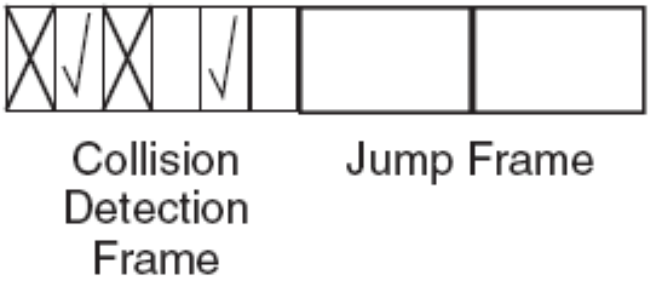
Collision Detection by Cyclic Redundancy Check

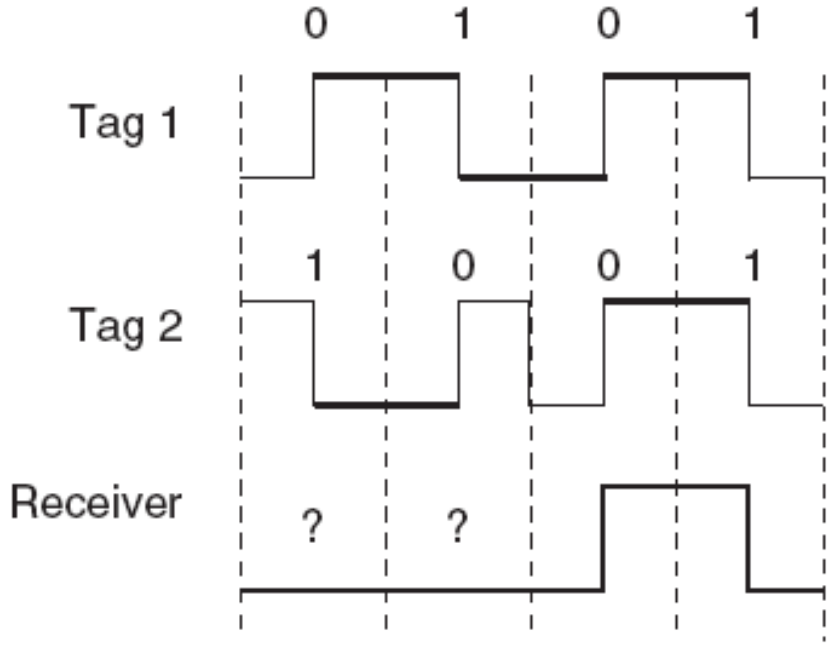
```
11010011101100 000 <--- input right padded by 3 bits
1011               <--- divisor
01100011101100 000 <--- result
 1011              <--- divisor ...
00111011101100 000
  1011
00010111101100 000
   1011
00000001101100 000
       1011
00000000110100 000
        1011
00000000011000 000
         1011
00000000001110 000
          1011
00000000000101 000
           101 1 ----------------
00000000000000 100 <--- remainder (3 bits)
```

Cyclic Redundancy Check (CRC): Very good in detecting errors; but less efficient in error correction.

Collision Detection in Fixed Time Slots

- Dedicated the initial frames for pooling, and then decide the jump frame sizes.
- Collision detection from Manchester coding (as one possibility)





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Tag Pooling to Prepare for Singulation

- Similar to ad hoc LAN, within the read range, there is an unknown number of tags.
- If all backscattering is added together, it is highly possible that the inter-tag interference is so high that BER is unbearable.
- A checksum or cyclic redundancy check (CRC) is used to see if a correct message (header or ID) is heard by reader.
- If the tags are pre-known (but have additional info), then a simple TDMA or CDMA (small number) is enough.
- The RFID bandwidth is far from sufficient for ID-coded o CDMA (96-bit or even 16-bit code injection will cause a broad BW not accommodate in RFID bands)

Aloha and Tree Air Protocols

- Aloha protocols
  - Simpler reader design
  - Low protocol complexity
  - Smaller bandwidth
  - Smaller instruction set
  - Dynamically adapt to varying tag population within range
- Tree protocols
  - Deterministic but complex hardware needed
  - Need large amount of memory and expanded instruction set
- EPC Global Class 1 and IP-X are two popular Aloha air protocols
- Aloha protocols are also used in Ethernet in similar ways (Alohanet is originally from U. Hawaii).

Heritage from Ethernet

- An invention by Robert Metcalfe in 1974 in Harvard (almost flunked) and then Xerox.
- In 1979, Metcalfe formed 3Com and developed Ethernet with Digital, Intel and Xerox (called DIX).
- 3Com developed Network Interface Card for all later computers including Apple and PC.
- Communication markets shift quickly, and 3Com has tried Chinese market (Huawei), but eventually purchased by HP in 2010.

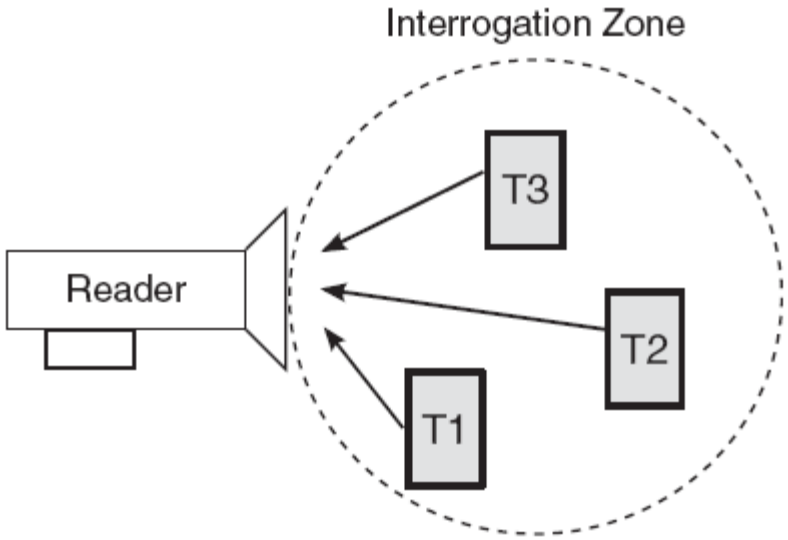
"Every success takes a unique combination of timing, invention, talent, and effort. Failure, it just needs one thing terribly wrong."

--- Adapted from Sun Tze.

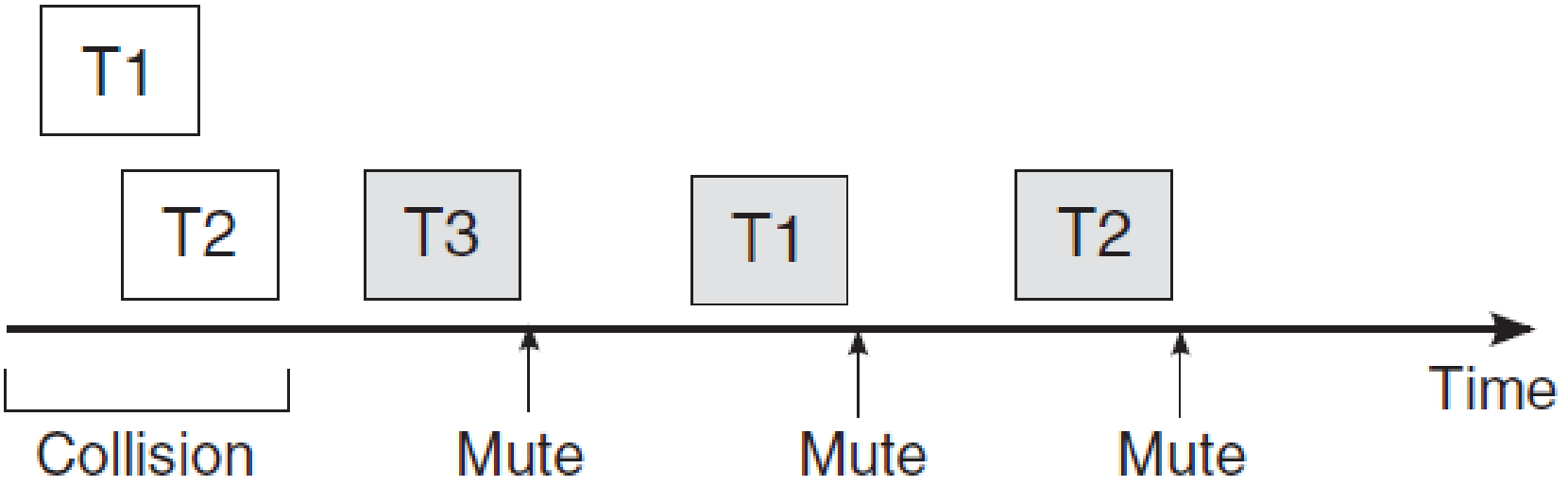
Bob Metcalfe
National Medal, 2003

Pure Aloha

- When tags are energized, they respond a random header after receiving a read request from reader
- If the reader reads a tag header correctly, it sends ACK
- If the reader detects a collision, it sends NACK, and tags transmit headers again after a random delay.

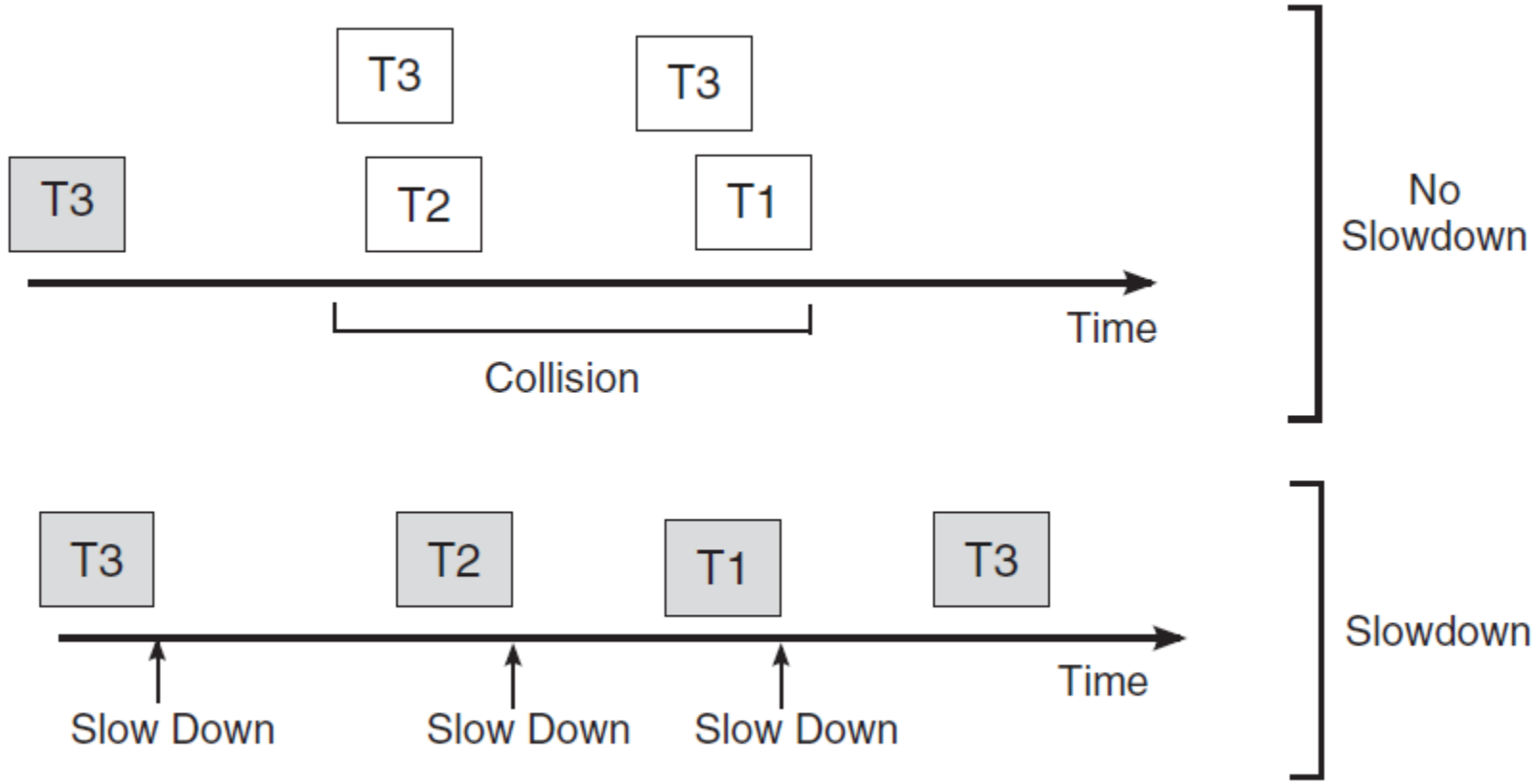


Pure Aloha with Muting



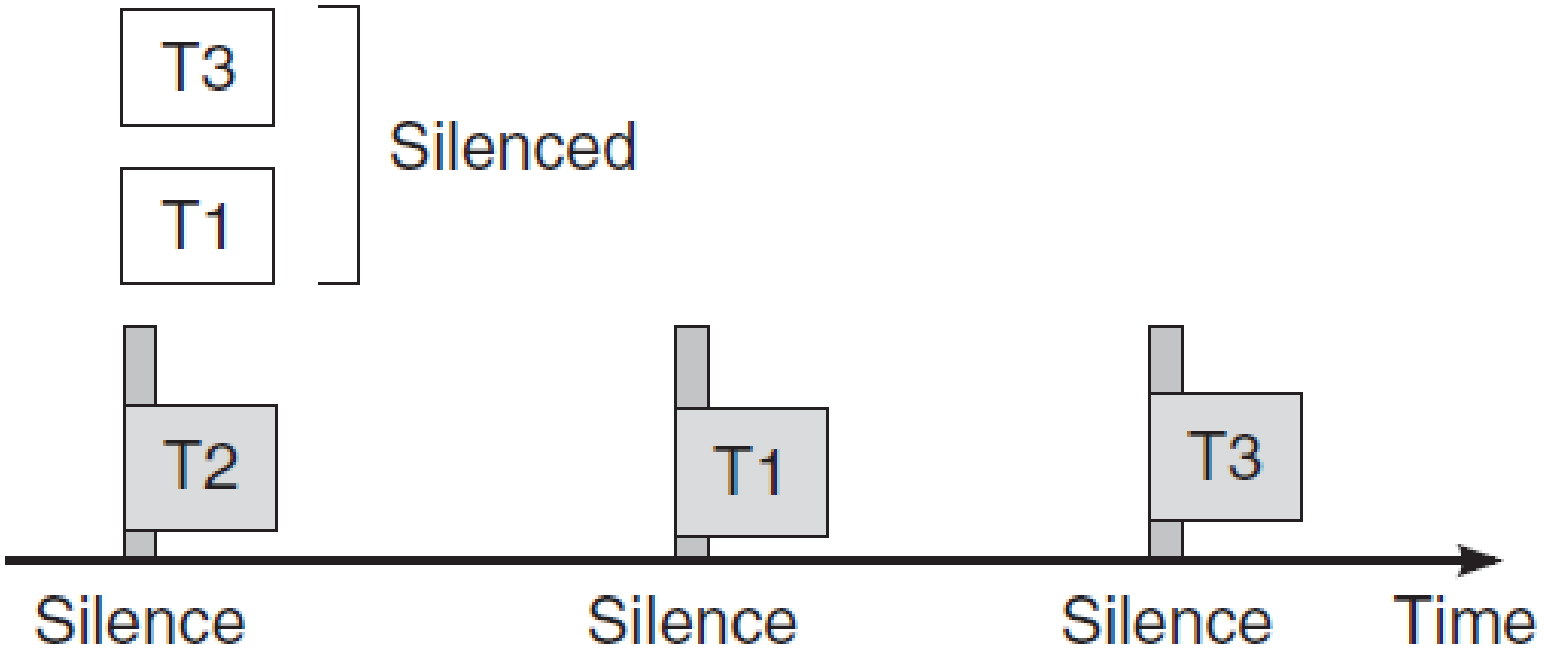
- Tags still respond with a random delay
- Each tag that is successfully read (defined by checksum or CRC during handshaking) will be muted until reset.
- Successfully read tag will not cause further collision

Pure Aloha with Slow Down



- Successfully read tags will not report again before a pre-determined period.
- Without slow down or muting, successfully read tags can continue to cause collision

Pure Aloha with Fast Mode

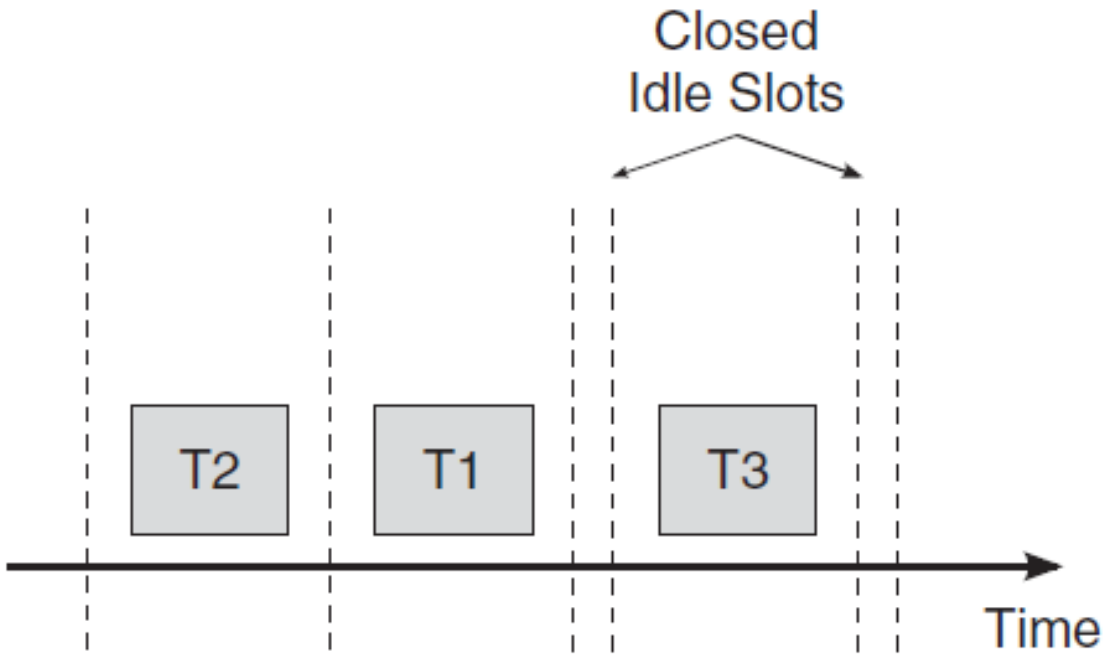


- When the tag header is read successfully, a silence command is given to other tags by a different channel.
- Tags that were silenced will transmit after receiving an ACK from reader, or after the waiting expired (then it chooses a random delay to send headers again).

Hybrid Pure Aloha

- Pure Aloha with fast mode and muting
- Pure Aloha with fast mode and slow down

Slotted Aloha

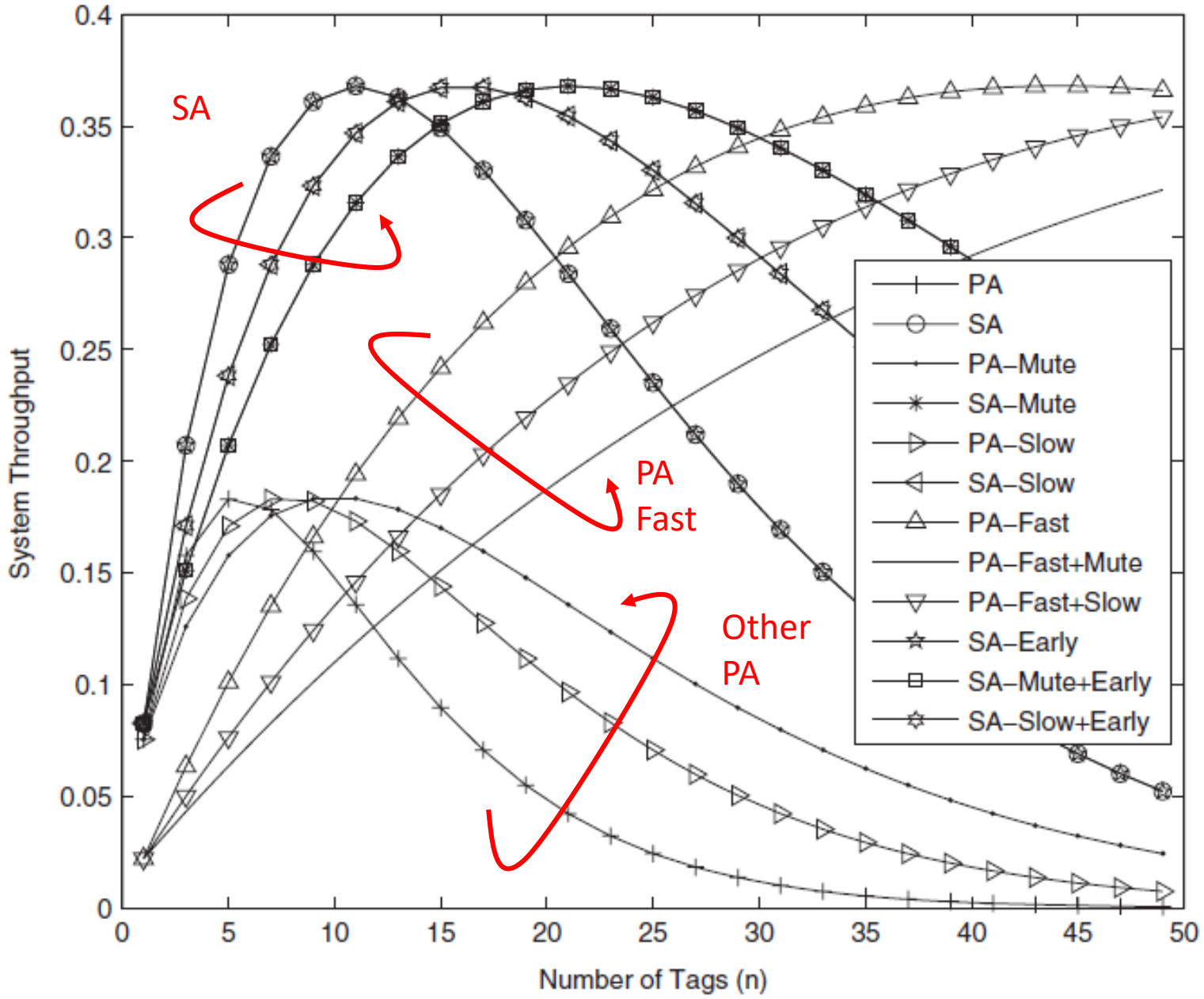


- Pure Aloha has a high probability of partial collision
- Slotted Aloha synchronize tags: tags are only allowed to respond at the beginning of each slot.
- Slot can have an “Early End” (to shorten an idle slot) by adding START_SLOT and END_SLOT commands.

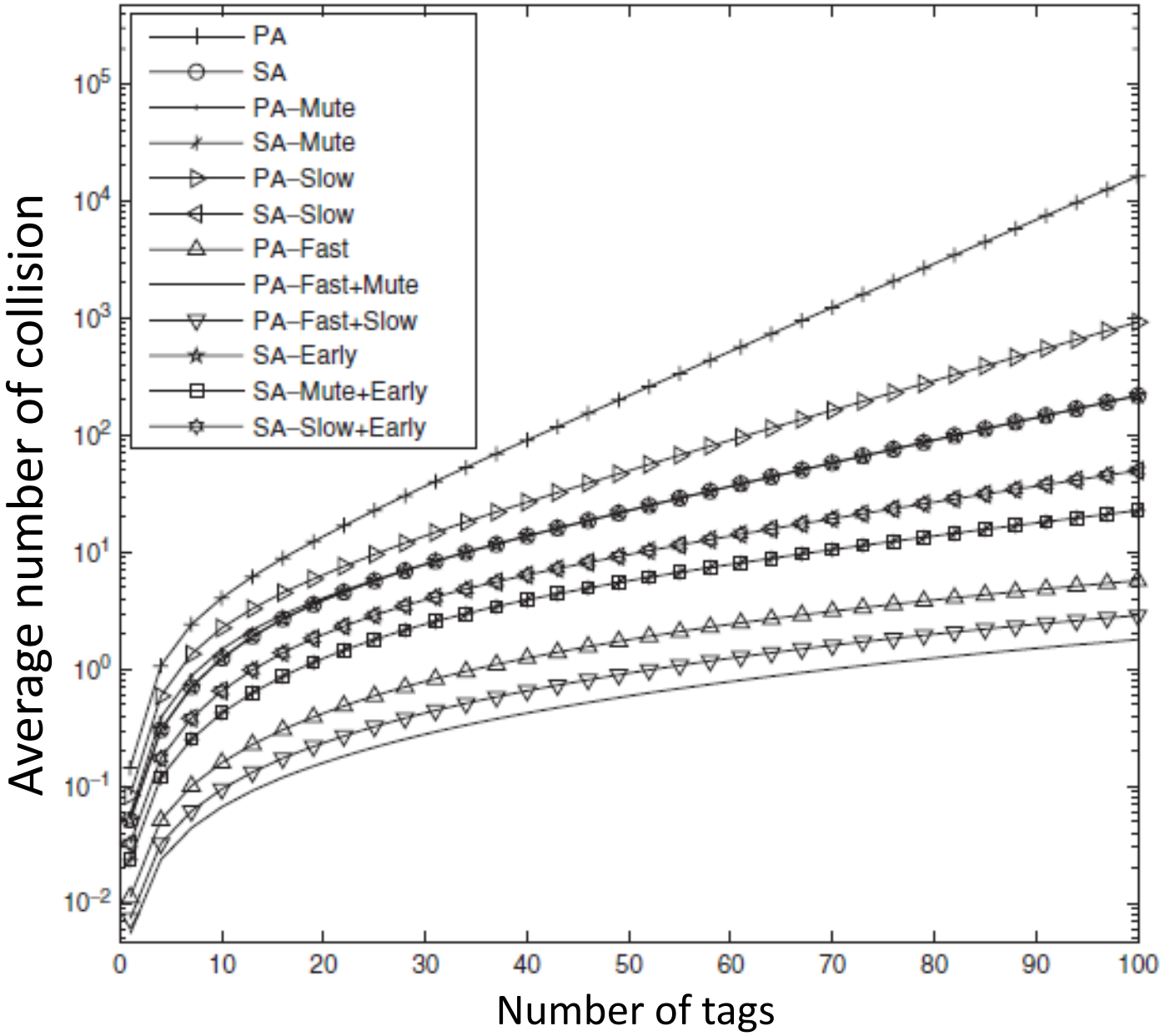
Hybrid Slotted Aloha

- Slotted Aloha with muting or slow down
- Slotted Aloha with early end
- Slotted Aloha with early end and muting
- Slotted Aloha with early end and slow down

System Performance of Aloha Variants



Average Number of Collision



Framed Slotted Aloha

- Tags in Pure and Slotted Aloha can reply more than once in a reading cycle.
- Define a “frame”:
  - A tag can ONLY reply once in one frame
  - Tags can be divided into groups to respond in different frames
  - During the collision detection, the number of tags can be “estimated”.
  - Frame size can then be dynamically adjusted to minimize collisions and idle slots.
- Basic Framed Slotted Aloha has fixed frame size: not very interesting. Frame size large: many idle slots with small number of tags; frame size small: many collisions with large number of tags.

The Pigeonhole Principle

- If *n* discrete objects are to be allocated to *m* containers, then at least one container must hold no fewer than $\lceil n/m \rceil$ objects, where $\lceil\ \rceil$ is the ceiling function: the smallest integer $\geq x$.
- Similarly, at least one container must hold no more than $\lfloor n/m \rfloor$ objects, where $\lfloor\ \rfloor$ is the floor function: (the largest integer $\leq x$.
- For random and uniform probability, then the probability of at least one hole will hold more than one pigeon is: $1 - \frac{m(m-1)\cdots(m-n+1)}{m^n}$

The Q Algorithm

- The reader broadcasts a Q number (from history or preset) and sets the frame size to 2^Q ($0 \leq Q \leq 8$).
- Each tag, after receiving Q, chooses to reply in a random slot from 0 to $2^Q - 1$.
- The reader monitors each slot:
  - Idle slot, decrease Q by c_i.
  - Slot with collision, increase Q by c_c.
  - One tag in slot, do nothing
- Q is rounded and a new Q is sent in the QUERY_ADJUST.
- Do this again or start the next phase of handshake.
- Often $0.1 \leq c_i \leq c_c \leq 0.5$. Prior knowledge can have further optimization.

Optimal Frame Sizes

Q	Frame Size	Tag Number
3	8	1 – 11
4	16	12 – 19
5	32	20 – 40
6	64	41 – 81
7	128	82 – 176
8	256	177 - 354
8 with sub groups	256	> 355

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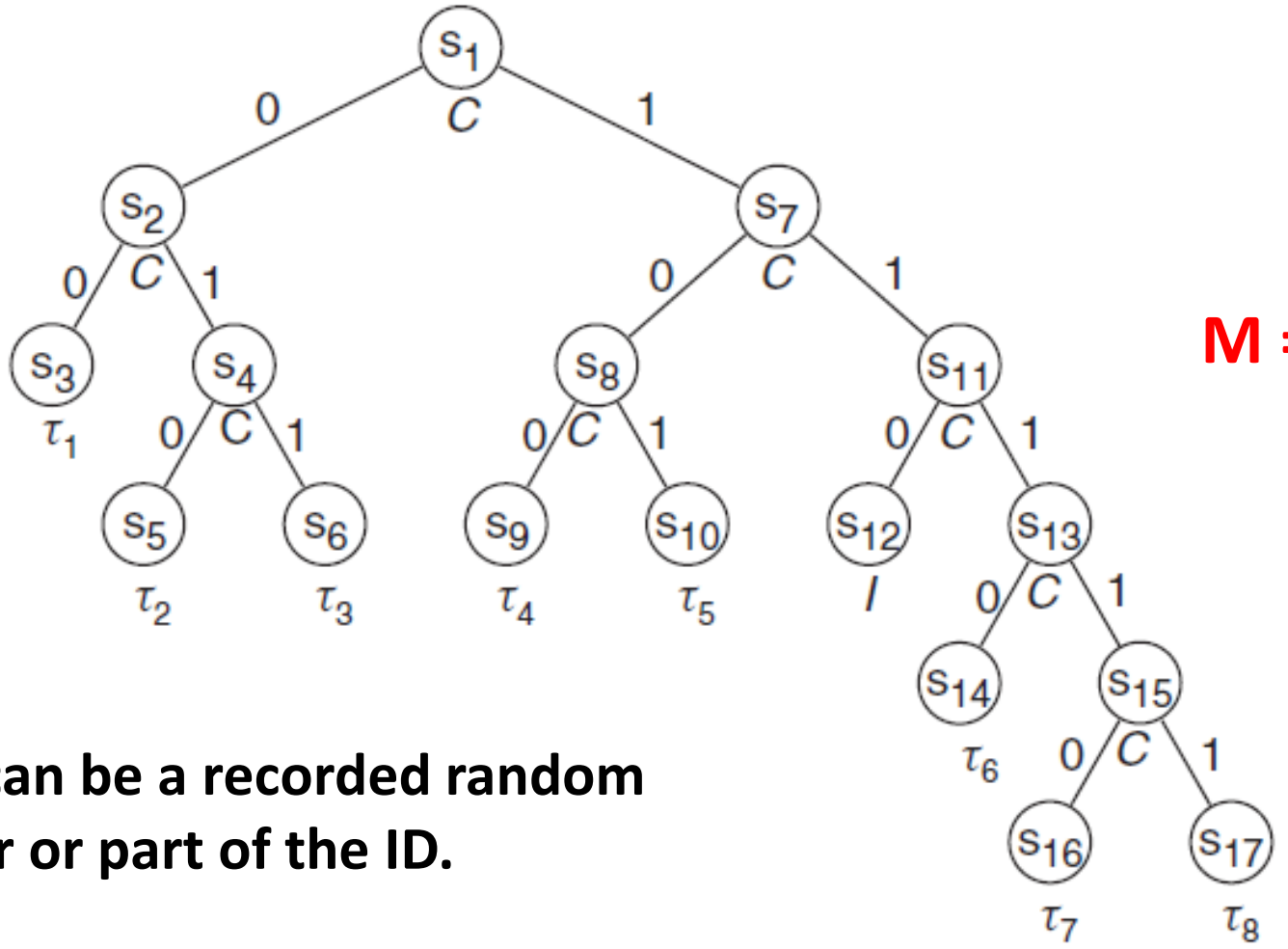
Tree Protocols

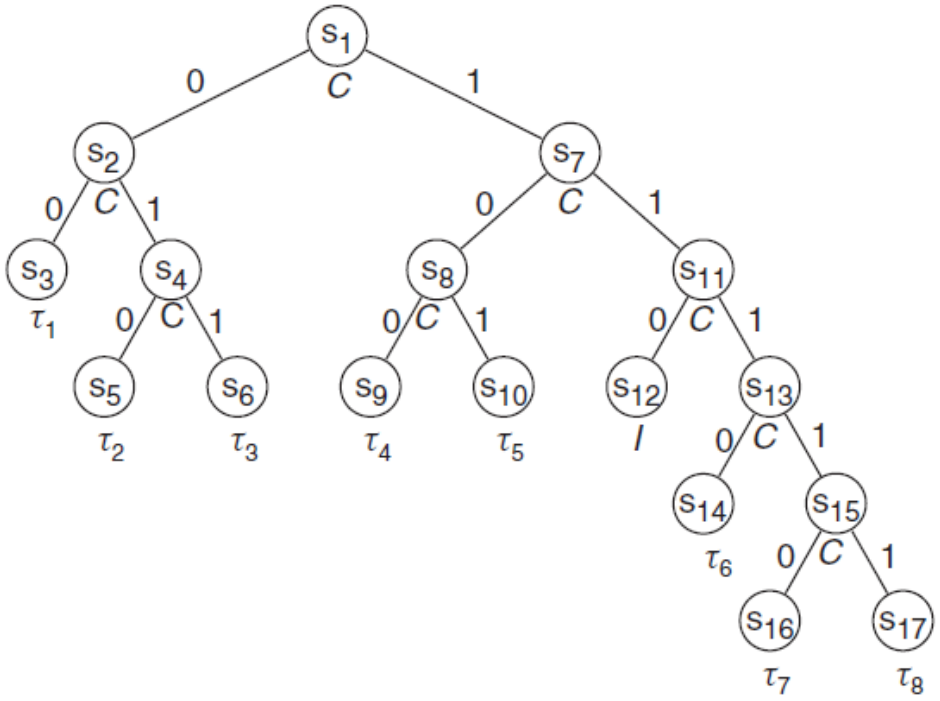
- Tree grows with a token to differentiate M branches
- Repeat until no more collision; token HISTORY is recorded



M = 2

Token can be a recorded random number or part of the ID.

Probe Timing of Tree Protocols



Slot 1	Probe	Slot 2	Probe	Slot 3	Probe	Slot 4	Probe	Slot 5	Probe
Coll.	0	Coll.	00	Single	01	Coll.	010	Single	011
$\tau_1 - \tau_8$		$\tau_1 - \tau_3$		τ_1		$\tau_2 - \tau_3$		τ_2	

Slot 6	Probe	Slot 7	Probe	Slot 8	Probe	Slot 9	Probe	Slot 5	Probe
Single	1	Coll.	10	Coll.	100	Single	101	Single	11
τ_3		$\tau_4 - \tau_8$		$\tau_4 - \tau_5$		τ_4		τ_5	

Characteristics of Tree Protocols

- The tag has to REMBMEBER all of its tokens in the entire time of the FRAME when the group of tags are identified.
- EPC Class 0: Tokens are selected bits in tag ID (not reconfigurable, and can take a long time in the worse case)
- EPC Class 1: Tokens are generated by random numbers
- Small M: possible large depth of the tree
- Large M: possible many idle slots

Aloha vs. Tree

- Tag requirements: memory for header or token.
- Tree remembers the history: deterministic
- Aloha is opportunistic: once matched, eliminate from batch. Eventually all tags can be read in infinite time.

- The fundamental tradeoffs between: opportunity and accumulated expertise!!!

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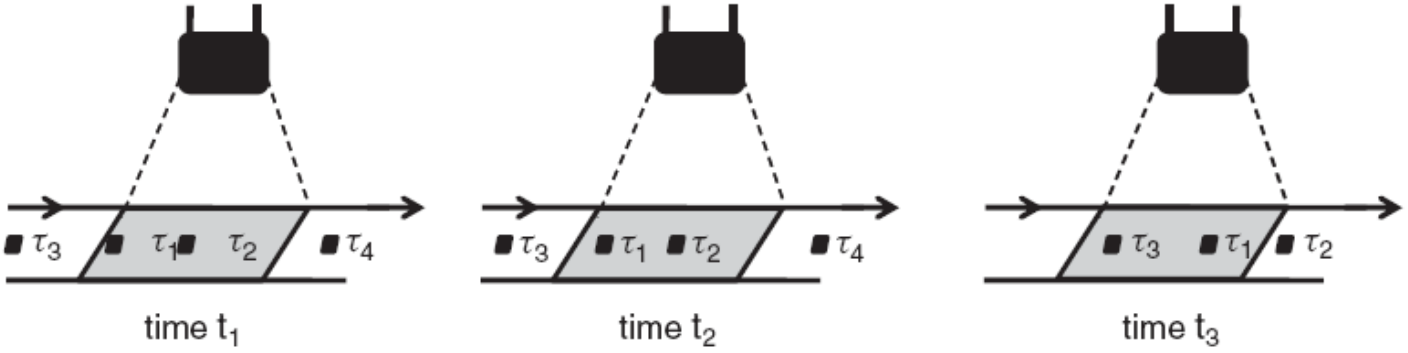
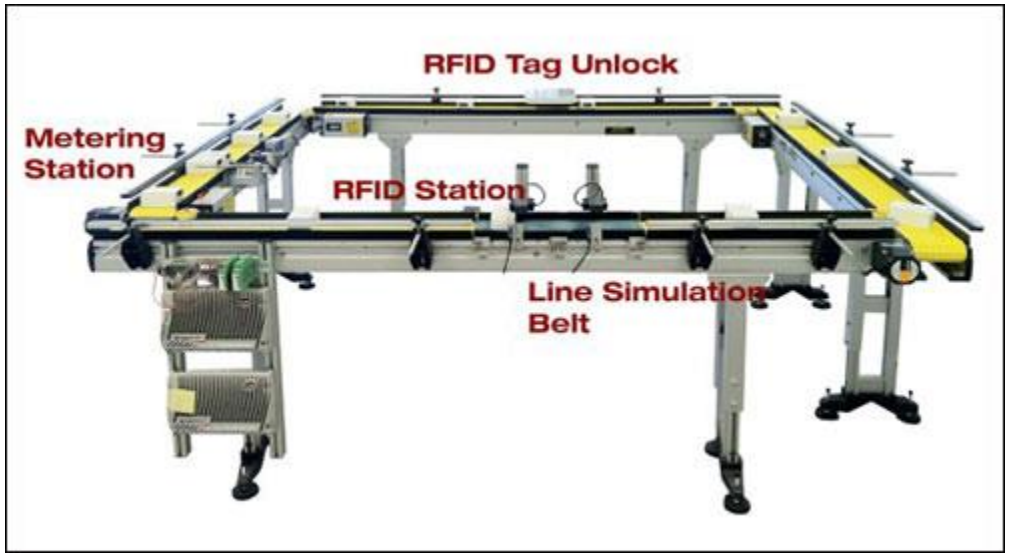
Moving Tags in Conveyor Belts

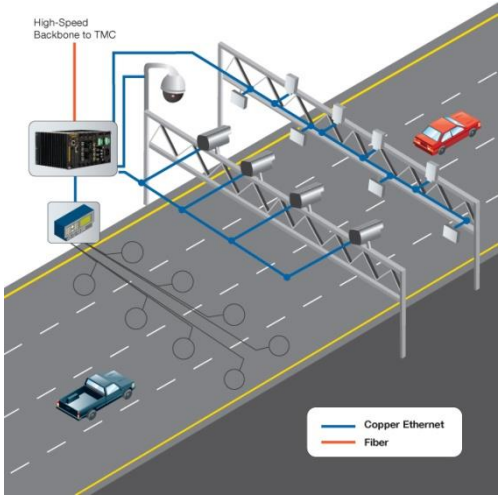
- Tag velocity from 0.1m/s to – 60m/s (about 200km/hour).
- If a frame takes 100ms to finish, the tag can move 0.01 m to 6m (may be larger than the reader range)

Conveyor belt logistics



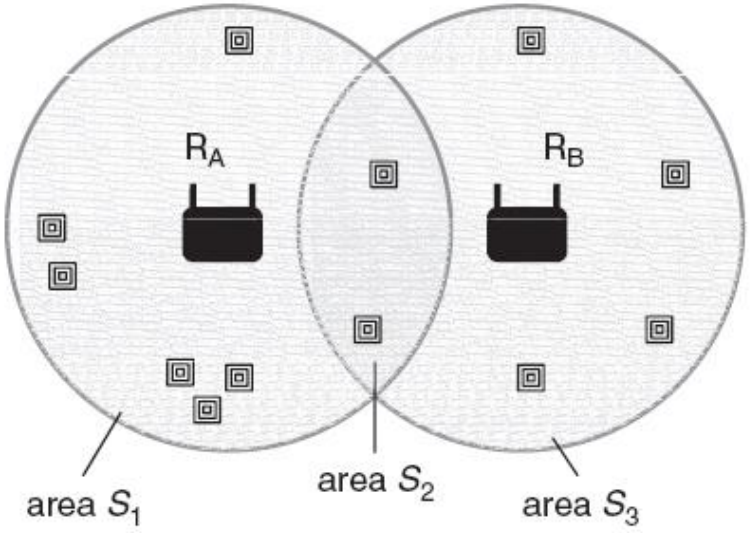


Fast Moving Tags For Traffic Control



Multi-Reader: Reader-Tag Collision

- If the tags are in the reading zone of two readers, then it will have signal collision that makes the reader commands ambiguous to the tag.
- In the SELECT and QUERY modes, tags are slaves and cannot change the transaction.
- Time division (TDMA) has to be set up by readers with tags in the overlapping reading zone.



Tag Classification

- Class 1: Identity tags
  - An electronic production code (EPC) identifier
  - A “kill” function permanently disable the tag
  - Optional password protected access
  - Optional tag memory
- Class 2: Higher functionality tags
  - An extended tag ID (128 – 1,024 bits)
  - Extended user memory
  - Authenticated access control
  - Extendable features (such as locating)
- Class 3: Semi-passive tags
  - An integral battery or stable power source
  - Sensor integration interface
- Class 4: Active tags
  - Protocols for tag-to-tag communications
  - Active communications in channel selection
  - Protocols to support advanced Ad hoc network

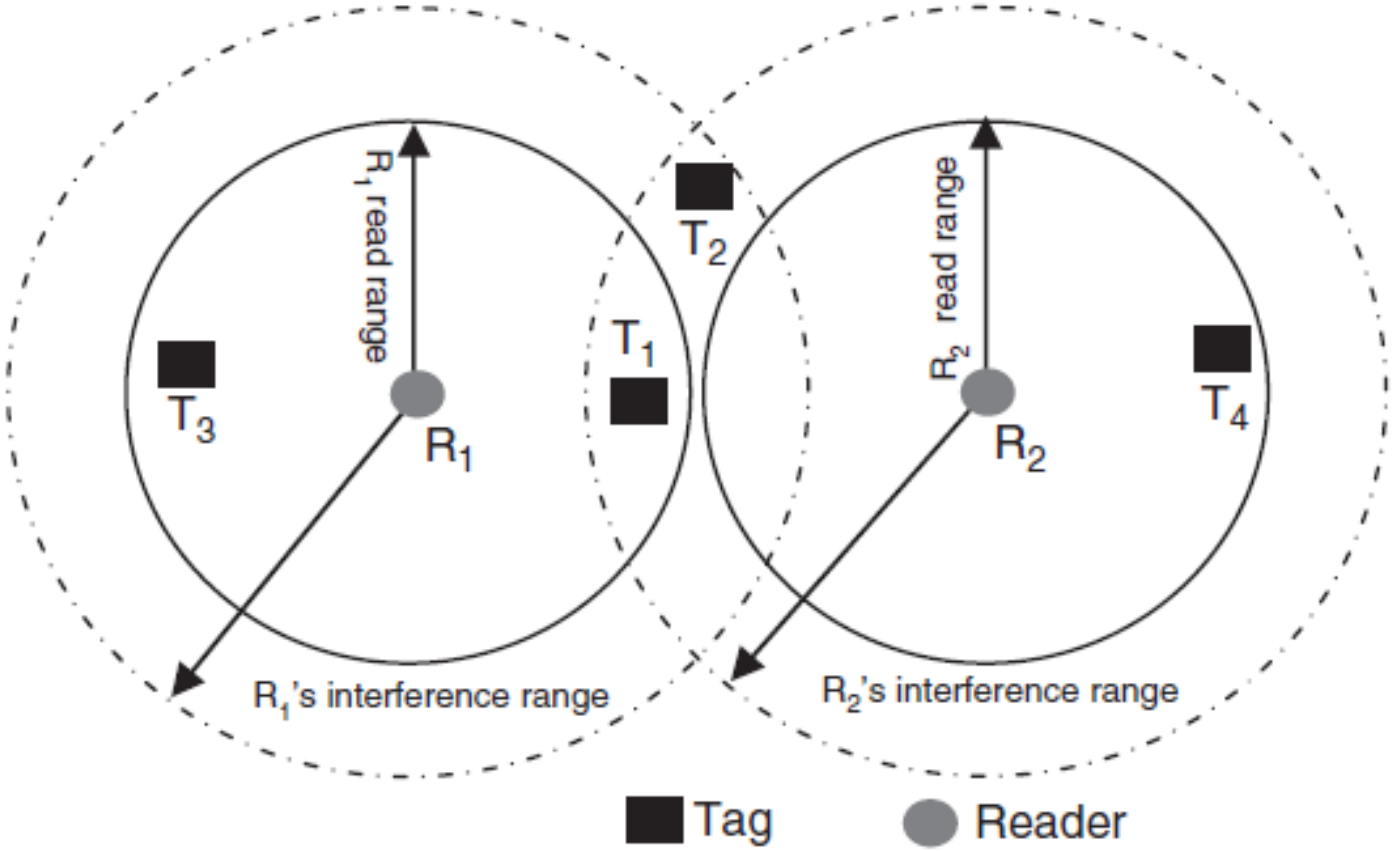
Each higher-class tag has backward compatible features

Reader, Tag and Interference

- Read range: distance that a reader can read tags CORRECTLY.
- Reader-reader communication distance: reader can read other readers (signal, beacon, synchronization) correctly
- Tag-to-tag interference distance: tags that make other tags cannot be read.
- Reader-to-tag interference: reader that interferes tag signal so it cannot be read by reader within its read range.
- Reader-to-reader interference: reader that interferes reader channel so it cannot read its tags or OTHER readers.

Multi-Reader: Reader-Tag Interference

Read Zone and Interference Zone

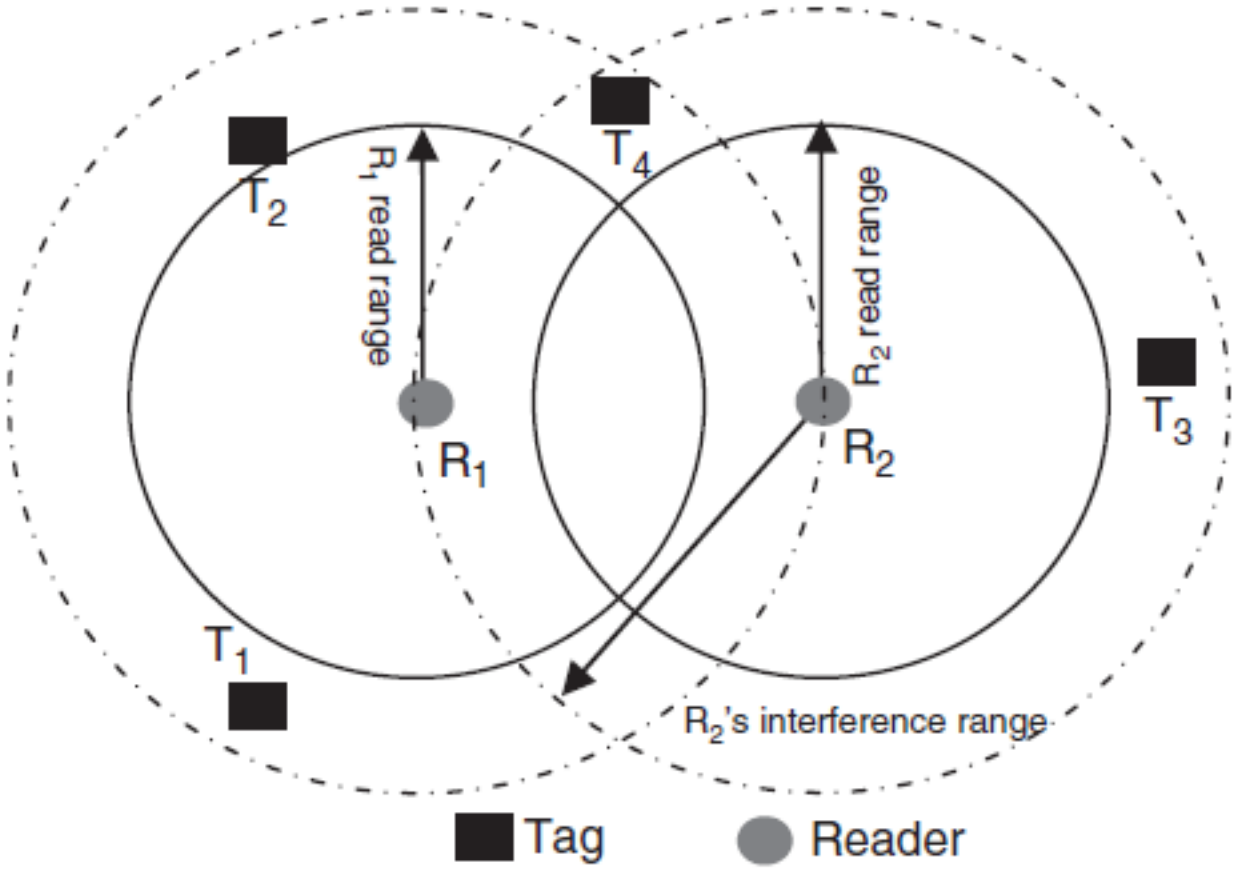


For tags : R_2 interference range is not much larger than its read zone.

For R_1: R_2 interference range is much larger than its read zone.

Multi-Reader: Reader-Reader Interference

Read Zone and Interference Zone



R_1 is directly interfered by R_2 : cannot use the same channel

Modes of Reader-Reader Interference

- Single interrogator mode:
  - No other reader works nearby, no additional requirement on The tag uses Miller modulated subcarrier to spread the spectrum and reduces transmitter jamming
- Multiple interrogator mode:
  - No. of available channel larger than no. of readers.
  - FCC has 50 + 2 1MHz channels available
  - Each interrogator works in one of the 50 channels (FDMA)
  - Channel assignment and hopping is agreed upon by handshake communication in the remaining 2 channels
- Dense interrogator mode:
  - Readers more than channels: TDMA on top of FDMA

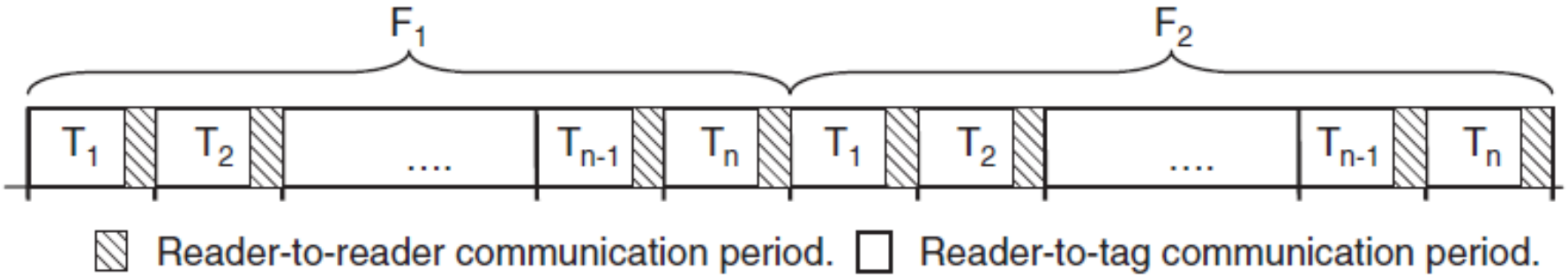
Anti-Collision Techniques

- Singulation by handshaking
- FDMA (frequency-division multiple access): not on tags
- TDMA (time-division multiple access): cooperative reader synchronization: cannot apply to reader-tag interference
- CDMA (code-division multiple access): spread spectrum by injecting pseudo-random code: too complex for tags
- CSMA (carrier-sense multiple access): detect the channel before transmit: LBT (listen before talk) for EU
- FHSS (frequency hopping spread spectrum): FCC
  - 5ms + n×0.5ms (n = 0..10) listening
  - A channel is free: allow to occupy up to 4s
  - Must release the channel for at least 100ms, repeat listening

Reader Anti-Collision Algorithms

- Schedule-based:
  - TDMA
    - DCS (Distributed color selection)
    - Colorwave
    - AC-MRFID
  - HiQ learning
- Control-based:
  - Pulse
  - DiCa
  - McMAC
- Central Cooperator-based
- Coverage-based
  - Clustering
  - Transmission power control
- Hybrids
  - Adaptive channel hopping algorithm (ACHA)

TDMA: Framed Slotted Aloha



- Framed slotted Aloha with reader-to-reader time reserved after each tag slot.

- TDMA and its variations (DCS, Colorwave and AC-MRFID) use various algorithms to select “time slots” (or colors, as long as the algorithm goes) for each reader: synchronized distributed network: time and energy consuming.

TDMA: DCS

- Distributed color selection (DCS): color: time slot
- A reader with a queued request transmits only in its "color".

- Collision detected, current color $\Leftarrow$ random(maxcolor)
  - Broadcast kick with new color
- Receive kick from others with current color, current color $\Leftarrow$ random(maxcolor)

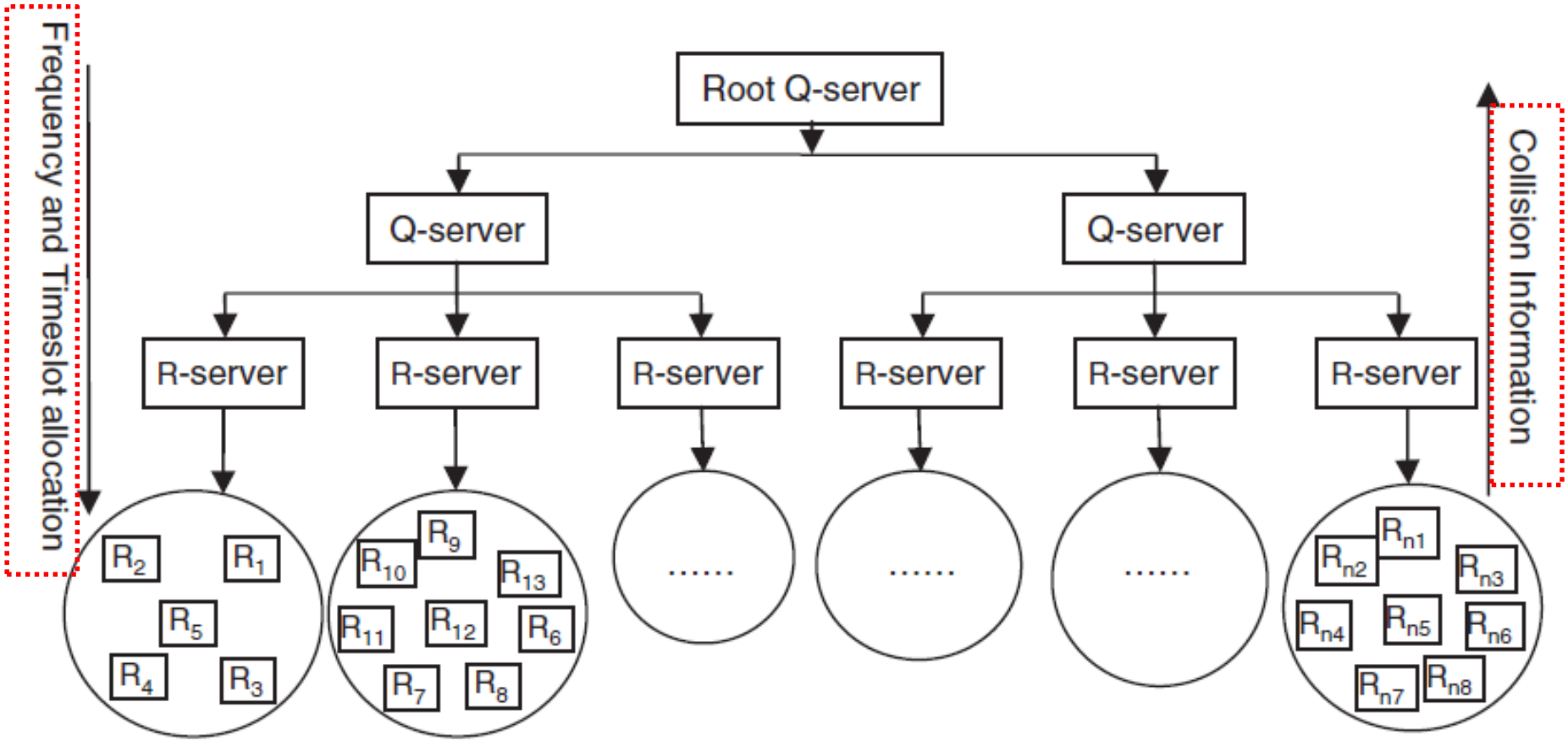
- Kick: switch and reservation
- Maximum number of colors is fixed
- Each reader keeps track of what colors are potentially available

Variation of DCS

- Colorwave: Variable maximum distributed color selection (VDCS)
- When too many kicks are received for the local reader, maxcolor is increased.
- Small maxcolor: more small groups of readers that will not interfere with others.
- Large maxcolor: more choices in dense reader zone.

Hi-Q Learning

- Resource (time slots and frequency) management through a hierarchical network.
- Readers report their collision situation to *Q*.



Controlled Mechanism-Based

- Each readers sends notification control signal (beacon) constantly.
- After hearing beacons from other readers, choose time slots or frequency accordingly.
- Assume read range (reader-tag collision) is much smaller than the range that beacon can be heard.

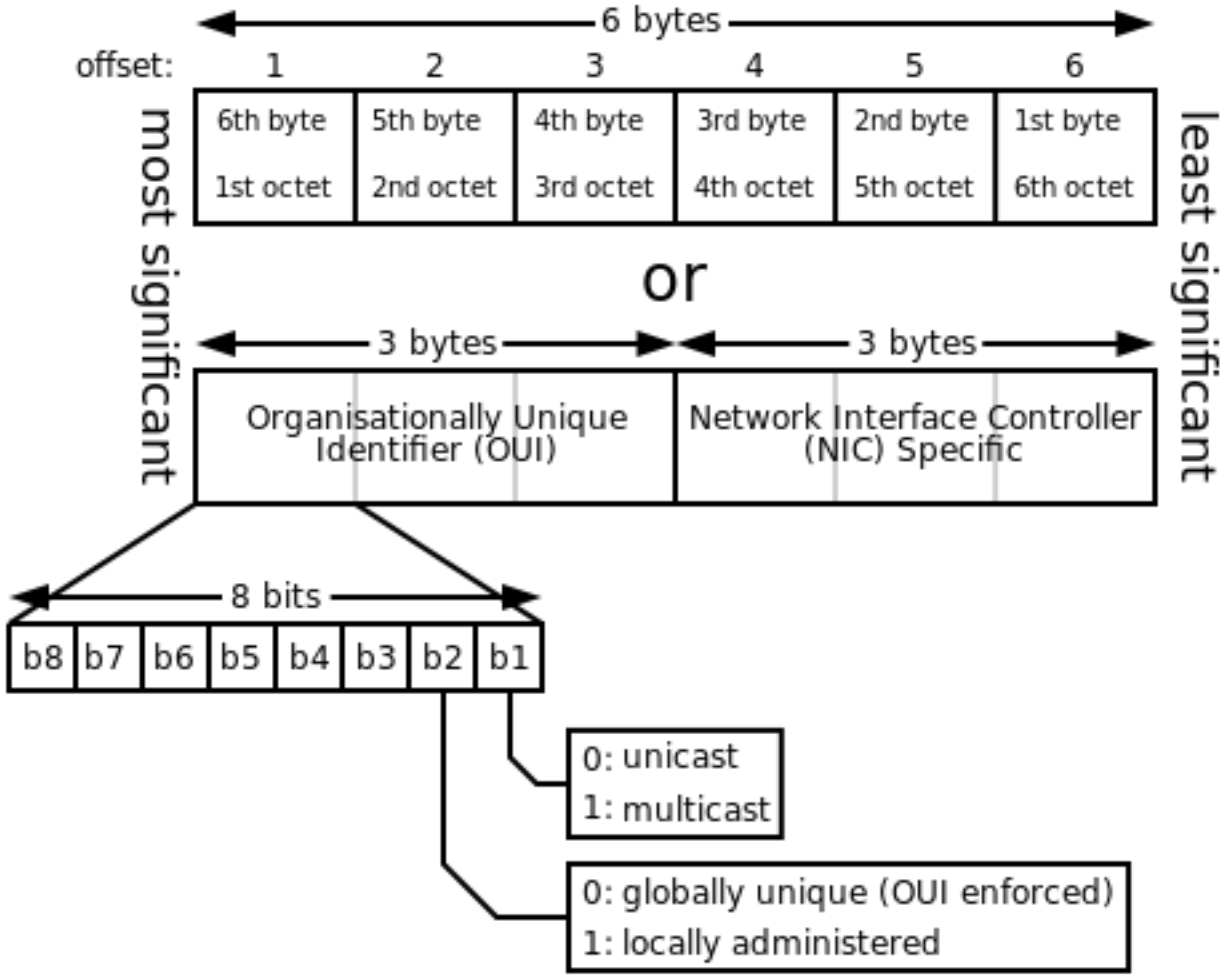
- Pulse protocol: at least two channels
  - Reader-to-tag in a data channel
  - Reader-to-reader in a control channel including beacon

Controlled Mechanism: DiCa

- DiCa (Distributed tag access with collision avoidance): more complex beacon
  - BRD_WHO: Pooling to see any reader is reading tags
  - BUSY: The present tag is now reading tags
  - BRD_END: Data channel is available after the tag reading is done.

Controlled Mechanism: MCMAC

- MCMAC (multi-channel media access control)
- Similar to LBT, but uses MAC address for readers
- Multiple data channel and one control channel



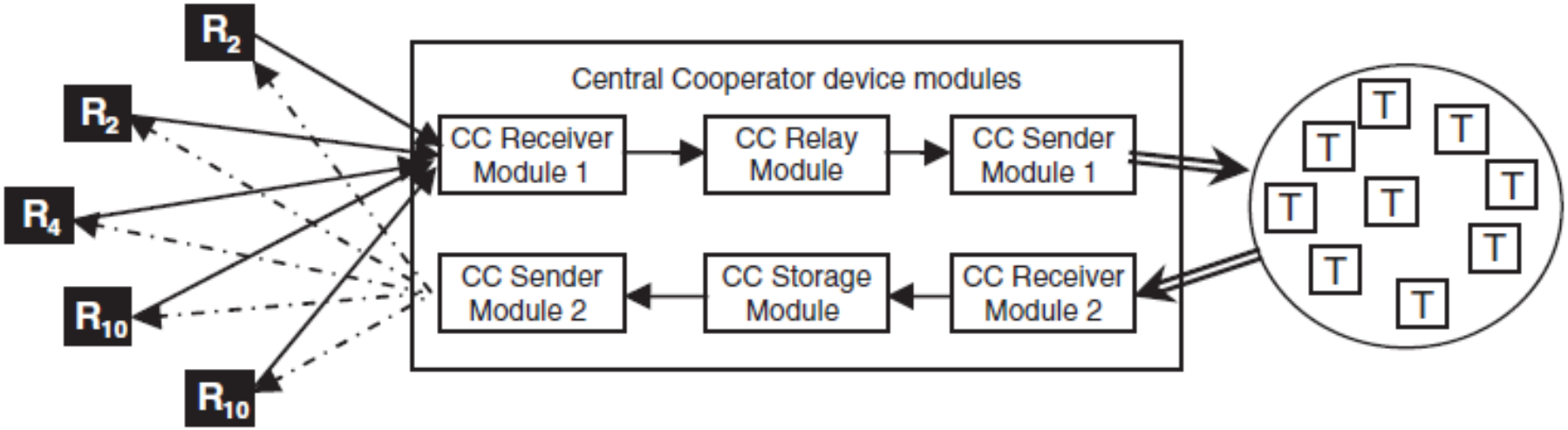
MAC address (inherited from Ethernet and IEEE 802)

Coverage Based

- Adaptive transmission range to form least overlapping clusters of readers.
- Clusters can be dynamically adjusted based on movement and traffic.
- Cluster head is elected to form an Ad Hoc Network with middleware.

Central Cooperator Based

- Central cooperator (CC) is the ONLY device to power and talk with the tags.
- Appropriate for smart shelves: CC is mounted on shelf, and can communicate with tags and mobile readers



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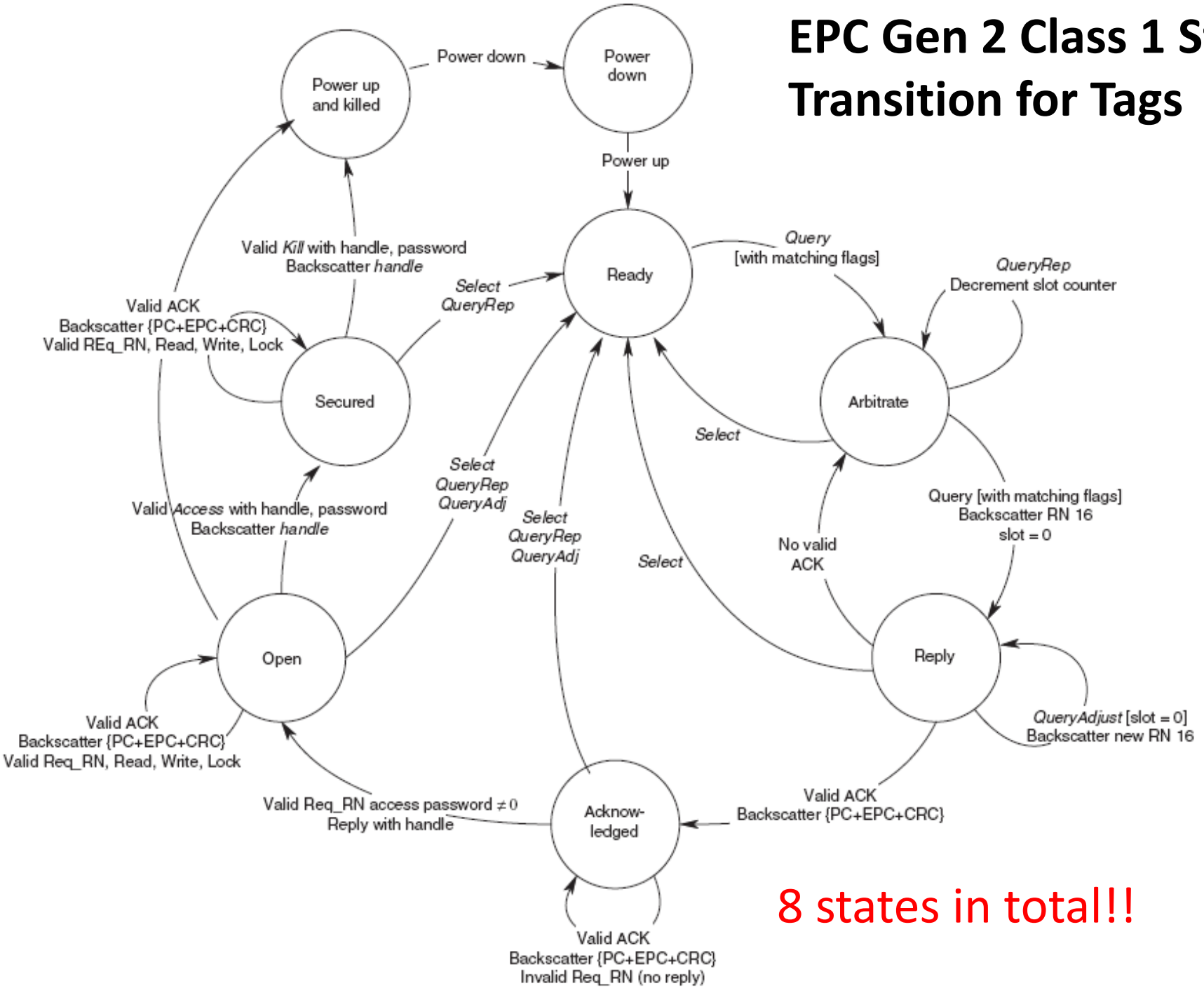
EPC Gen 2 Class 1

- Also called ISO (International Organization for Standardization) 18000-6C
- EPC was the creation of the MIT Auto-ID Labs (Prof. Sanjay Sarma) and a consortium of over 120 global corporations (Mainly Walmart and Proctor Gamble) and other university labs.
- EPC is adopted by most US RFID companies (Impinj, Alien, Intermec, etc.)
- EPC identifiers were designed to identify each item manufactured, as opposed to just the manufacturer and class of products, as bar codes do today.

EPC Gen 2 Class 1

- The EPC system is currently managed by EPCglobal, Inc., a subsidiary of GS1.
- GS1 originated from bar code as an international, no-profit organization, and now control all product codes
- **Reader-talk-first (RTF)** protocols supporting both Aloha and Tree protocols

EPC Gen 2 Class 1 State Transition for Tags



8 states in total!!

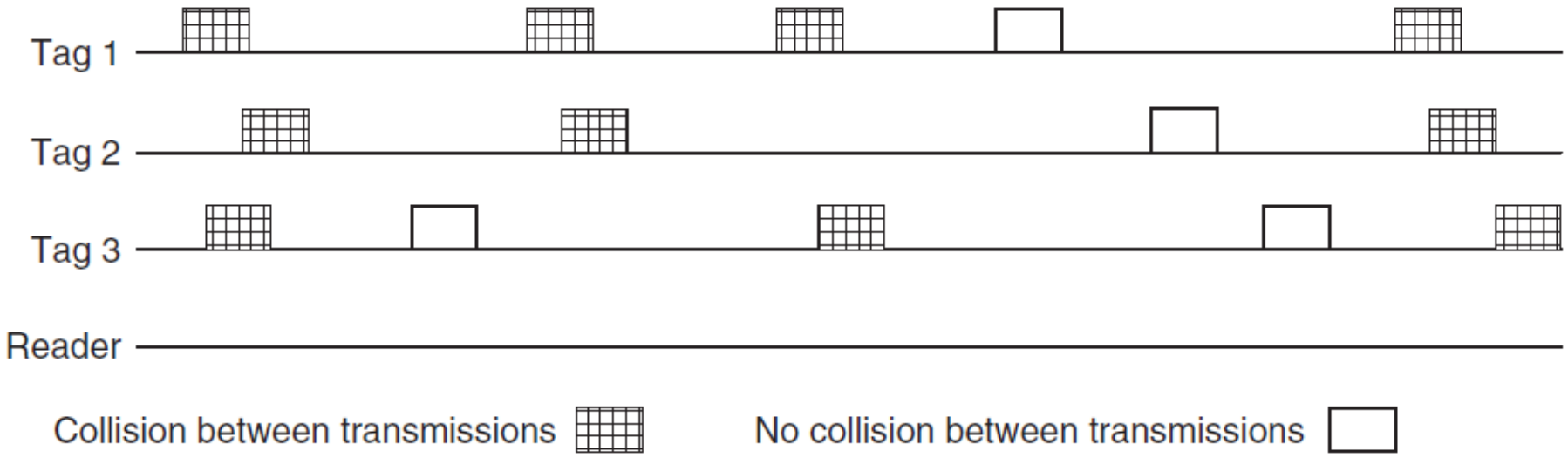
EPC Gen 2 Class 1 Commands

- POWERUP
- SELECT
- QUERY
- QUERYREP
- QUERYADJ
- ACK
- NAK
- REQ_RN
- SELECT
- READ
- WRITE
- KILL
- LOCK
- ACCESS
- BLOCKWRITE
- BLOCKERASE
- BLOCKPERMALOCK
- T2TIMEOUT
- INVALID

19 commands in total!!

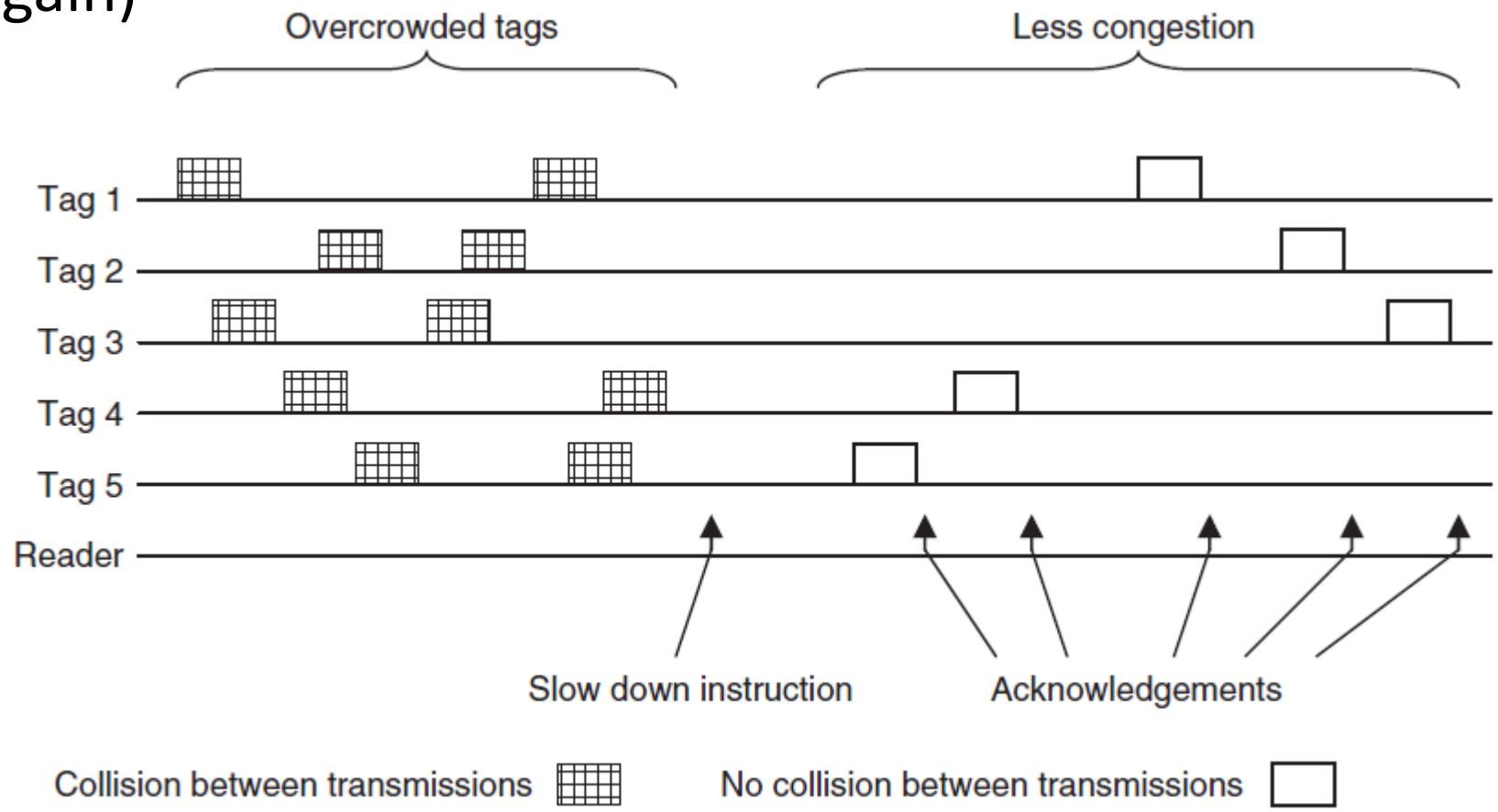
Supertag: TTO and TTF Protocols

- Unslotted Aloha (or pure Aloha) protocol
- Tag talk only (TTO) or Tag talk first (TTF)
- TTO: free-running Aloha; no reader intervention



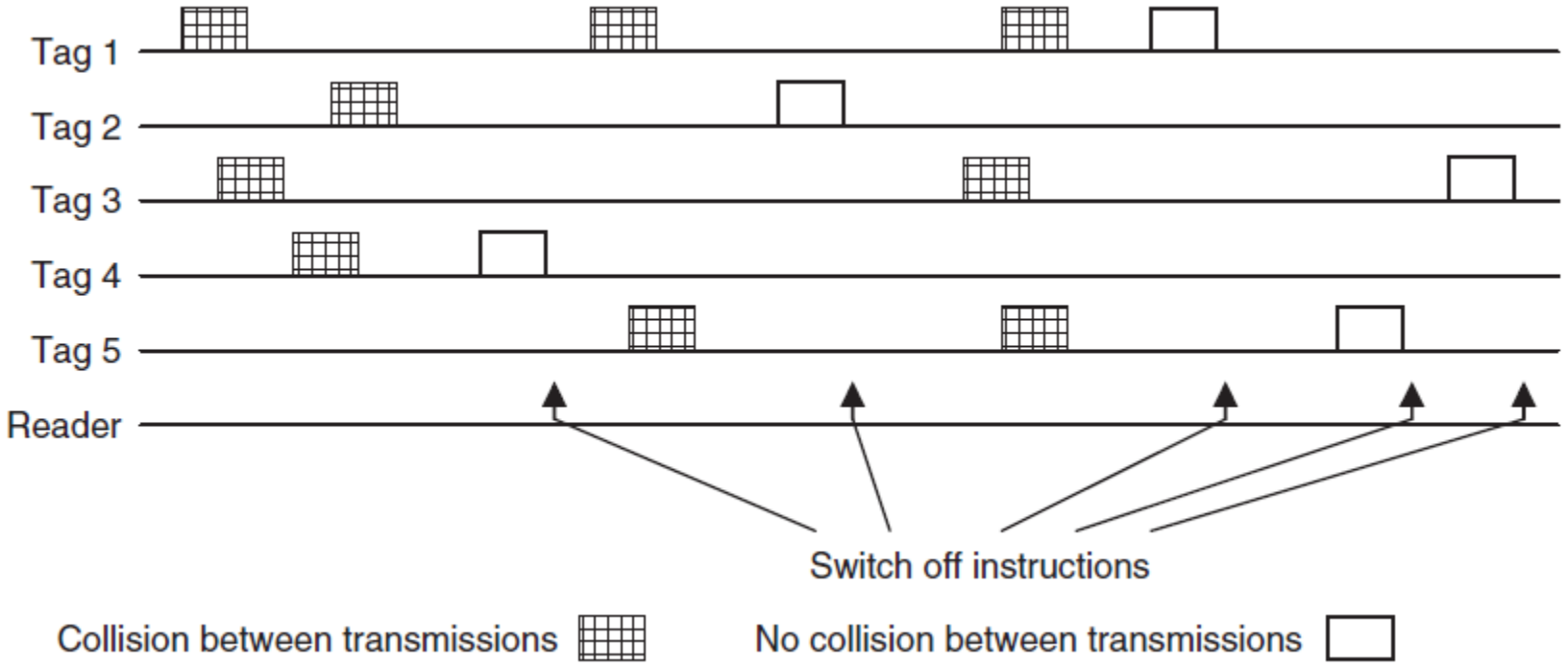
Supertag TTF Protocol (1)

- After reader detects collision from checking CPC of tag ID code, reader instructs tags to slow down (tags choose a longer period within which a random delay to report again)



Supertag TTF Protocol (2)

- Supertag has four layers of slow-down frame for optimization in most situations.
- Supertag also supports MUTE: An acknowledge tag will only report again after a fixed delay (back to TTF random choice within a frame).

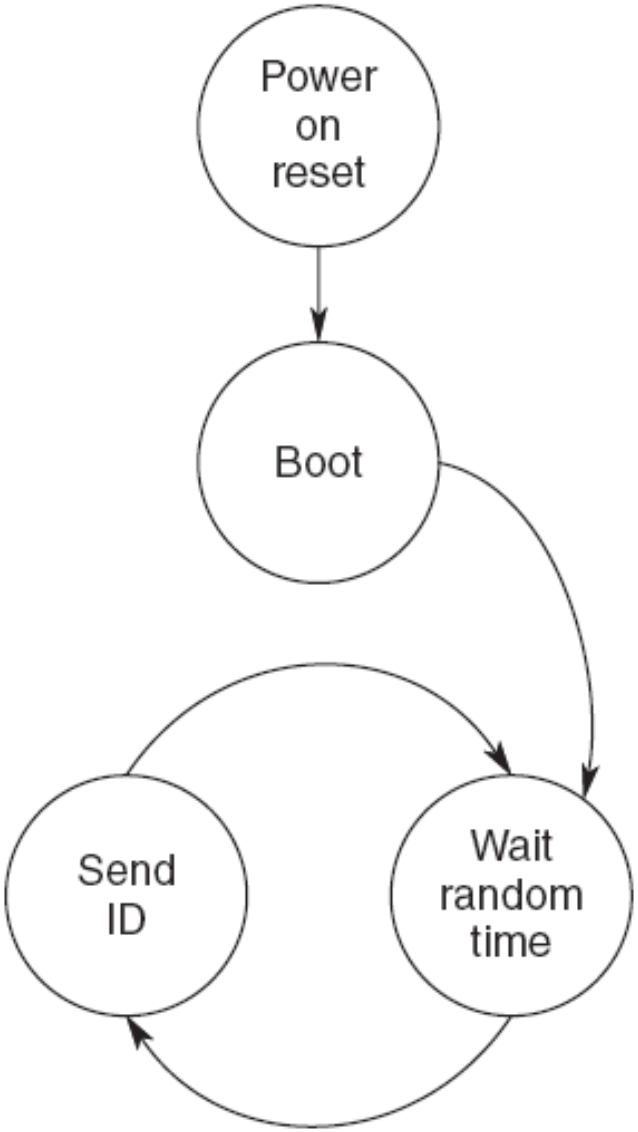


IP-X

- Also called ISO 18000-6D or ISO 18000-8
- Originated by iPico in 1990's (first in South Africa and then in Canada), which presently shrinks its RFID involvement. Now also by EM-Microelectronics
- Tag-talk-only (TTO) as a subset of Supertag: free-running unslotted Aloha protocol.
- TTO has NO reader commands. Tags report their ID once powered up by the reader with a random delay (Pure Aloha with partial collision)

IPICO
RFID REALISED

IP-X State Transition (TTO)



Pure Aloha with partial tag collision

4 states in total!!

Much cheaper tags and readers, but limited multiple tag handling.

IP-X Commands

Command	Op Code	CRC-5	Comments
READ	4	5 bits	Read 1 to 16 pages concatenated
WRITE	3	5 bits	Write one page of memory
LOCK	2	5 bits	Lock memory pages
TEST	1	-	Reserved (factory use only)
CONFIG	0	5 bits	Write configuration data
TTO PAGES	6	5 bits	Configures TTO pages (number of pages send in arbitration)
SUSPEND	5	5 bits	Suspend arbitration until RESUME or power-on reset
RESUME	7	5 bits	Resume arbitration

8 commands in total, 4 essentials (in TTO, no “read” needed)

Variation of IP-X: TOTAL

- TOTAL: tag only talks after listening
- TOTAL is meant to add TTF tags to be readable by RTF readers (even mixed with RTF tags)
- Once energized, TOTAL tags first listen for interrogations from RTF reader communication (with command modulation)
- If RTF communication detected, tags can respond in the RTF tag fashion (dual-protocol mode), OR
- Tags keep quiet for a prescribed period of time and then start listening again: when no reader communication detected, transmit as a TTF tag. (There must be an independent TTF reader, or time shared with RTF reader)

Outline

- Overview of anti-collision algorithms
- Aloha-based protocols to resolve tag collision
- Tree-based protocols to resolve tag collision
- Problems of moving tags and reader collision
- EPC and IP-X protocol and commands
- Comparison of RTF (EPC) and TTF (IP-X) protocols

When IP-X is Better than EPC (1)

- IP-X has much less modulation from reader to tag: smaller bandwidth, less self interface, less reader-reader interference, and reader-tag interference during TTO
- Royalty and IP: Basic IP-X is free (acceleration is not), while EPC has member fees and up-front payment.
- IP-X has the same protocol for 13.56MHz, 900MHz and 2.4GHz, while EPC has small difference for different frequency range (frequency/timing parameters from reader to tag)
- IP-X tags have smaller layout (IP-X, about 3,600 gates, while EPC > 10,000 gates)
- IP-X has fast and simple inter-tag anti-collision algorithms.

When IP-X is Better than EPC (2)

- IP-X can be applied to tag speeds > 200km/h, but EPC limits tag speed < 30 km/h
- IP-X can use entirely quiet reader in tag-talk only mode (TTO, no modulation), when there is **NO** read-to-reader or reader-to-tag interference (dense reader mode)
- IP-X has less bandwidth requirement for reader-to-tag: much easier to fit the regulation spectrum.
- IP-X can operate in no reader TDMA; EPC needs TDMA protocols with multi-readers with overlapping read zone.
- IP-X does not allow blank tags (part of code is required in fuse-based ROM): better for authentication

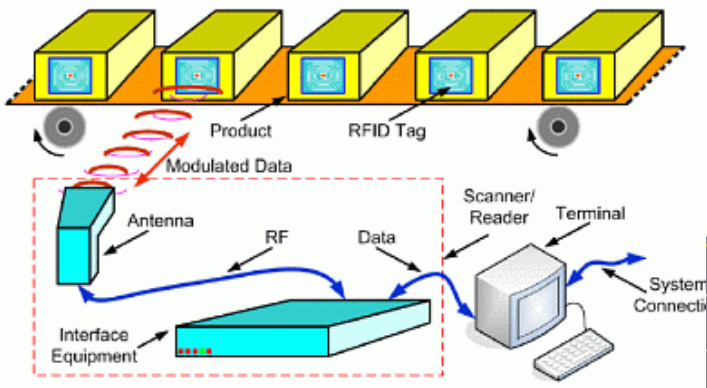
When EPC is Better Than IP-X

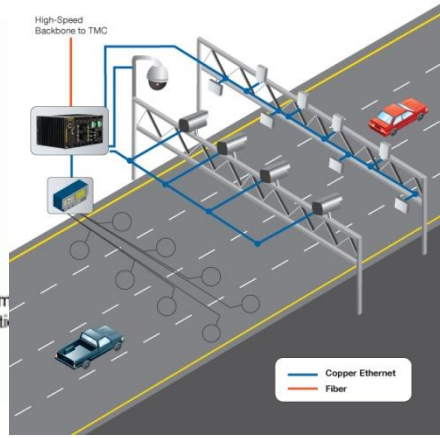
- EPC is more scalable with increasing number of tags
- EPC is has more configurable protocol to enhance readability
- By using a header/token for tag pooling, more security can be applied to the tag transmission
- EPC supports both stochastic and deterministic anti-collision protocols
- EPC supports Class 0 (no header/token) – Class 5 (basically an active radio) with the same command set
- EPC has better read-failure reports

EPC vs. IP-X

EPC

IP-X





Multi-Modes or One Universal Standard

- Purposes for air protocol standardization
  - Readers from company A can read tags from company A, B, C, D
  - Readers from company A can be used in multiple countries
  - Easier FCC approval
  - Security and privacy can be quantified
- Purposes for code standardization
  - Code has universal meaning or published conversion tables

Is There a Solution?

- Reader talk first (RTF, EPC) vs. Tag talk first (TTF, IP-X)

What I Learned, Not Learned

- “自主創新, 兼容並蓄” (Be innovative that you can always do what you want, but simultaneously what others do can always be included.)
- Paradigm shift vs. plug-and-play
- New features vs. backward compatibility

- We have only one free space in any wireless communication with scarce spectrum resources: You simply cannot have everything

What Do You Learn

- How to detect signal collision during multiplexing
- Aloha, slow-down, mute, slotted, framed
- Tree-based protocols
- Concerns for multi-readers and moving tags
- EPC vs. IP-X; TTO, TTF vs. RTF