D2D LTE and IoT

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Indo/French Workshop on D2D fo 5G/IoT
21 June 2016, Paris

Context & Outline

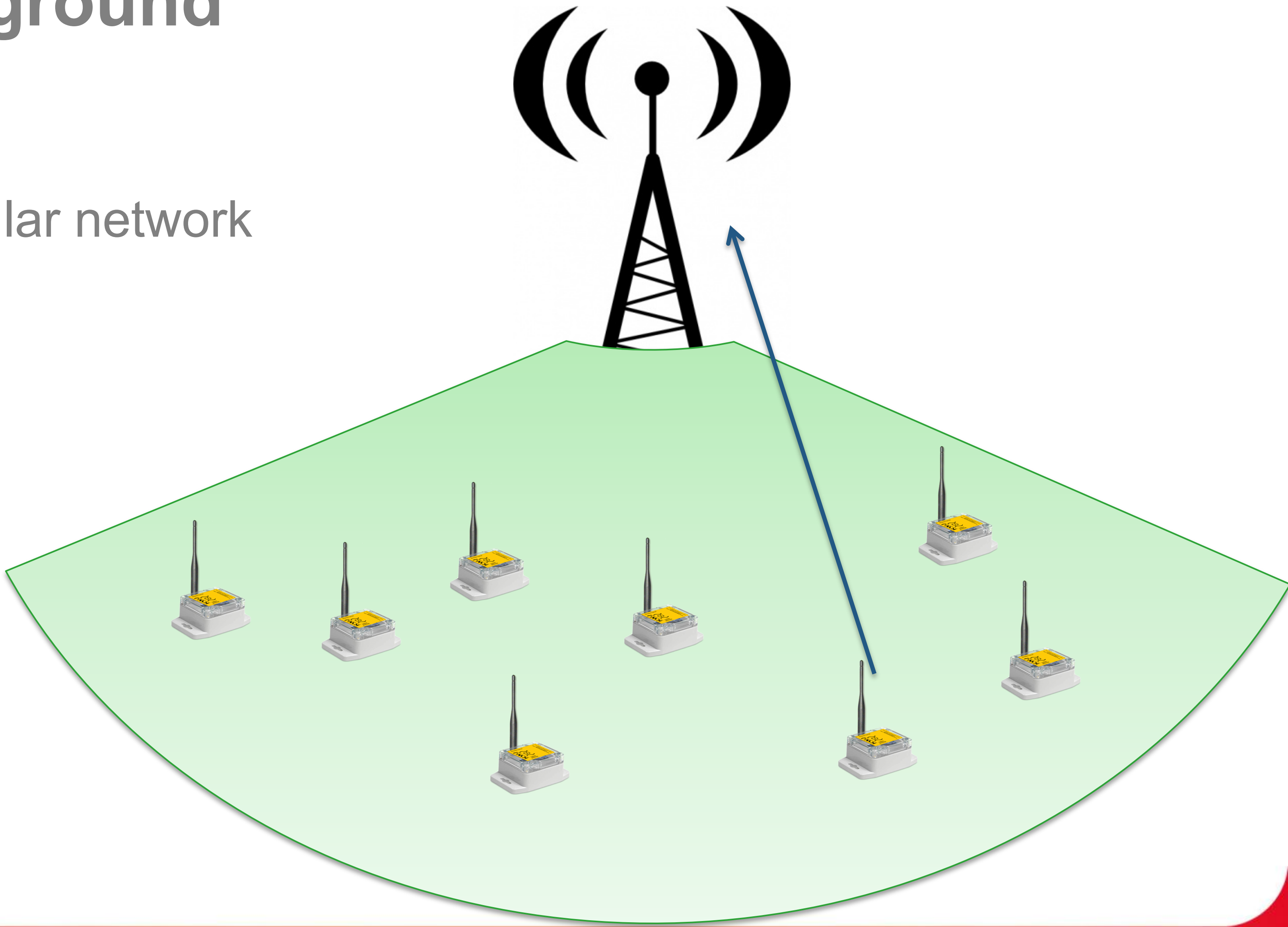
- Inria in CEFIPRA “D2D” project: protocols, multihop wireless networks (MAC, Routing, …), Internet of Things (IoT)
- Objective: identify techniques/algorithms/protocols/… that could be used for D2D-LTE/5G+

Outline: state of the art of some protocols/methods

1. Background: IoT in cellular context
2. Random Access (Media Access Control, MAC)
3. Routing, Neighbor/Link Discovery

Background

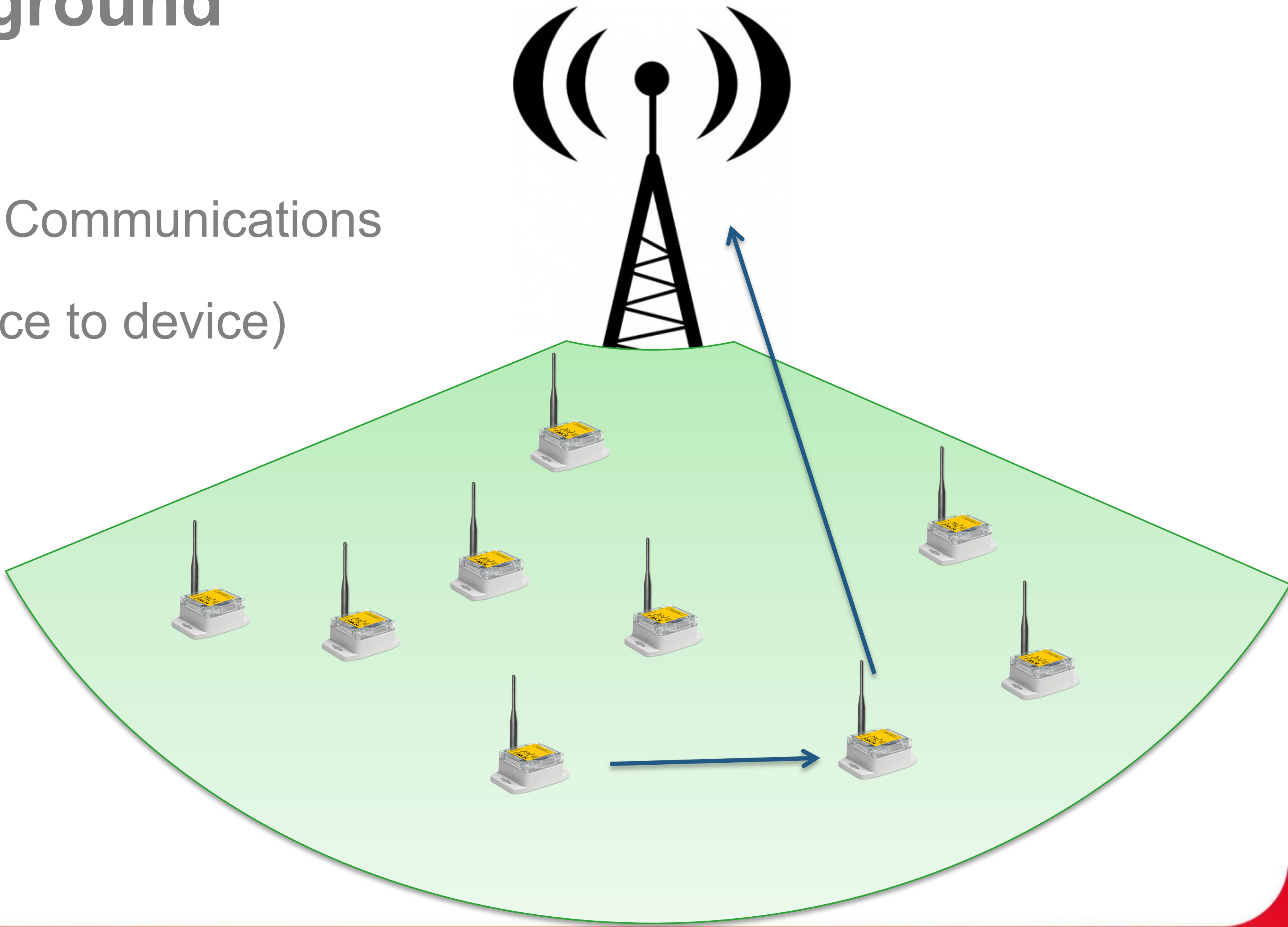
- Cellular network



Background

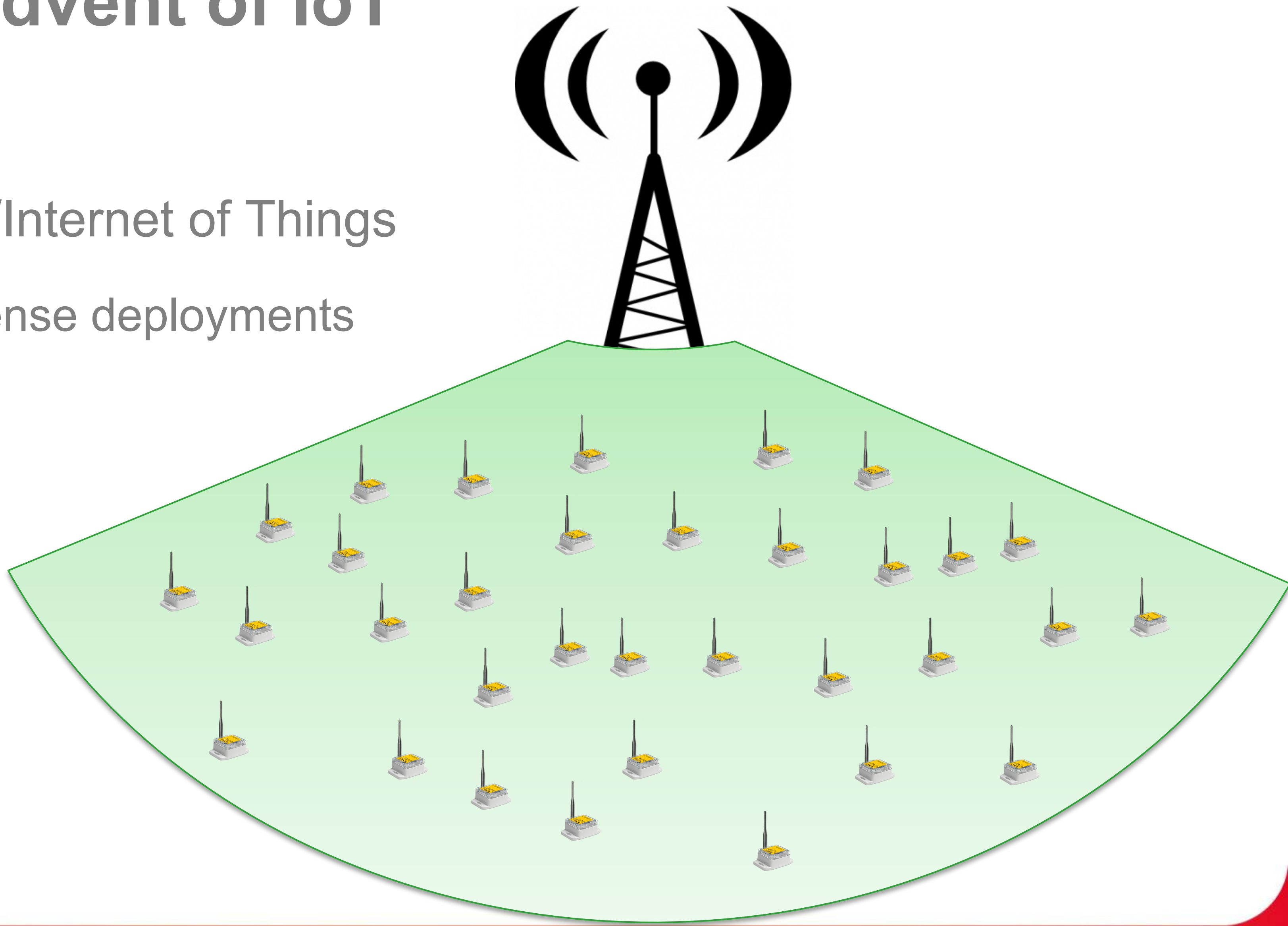
- D2D Communications

  (device to device)



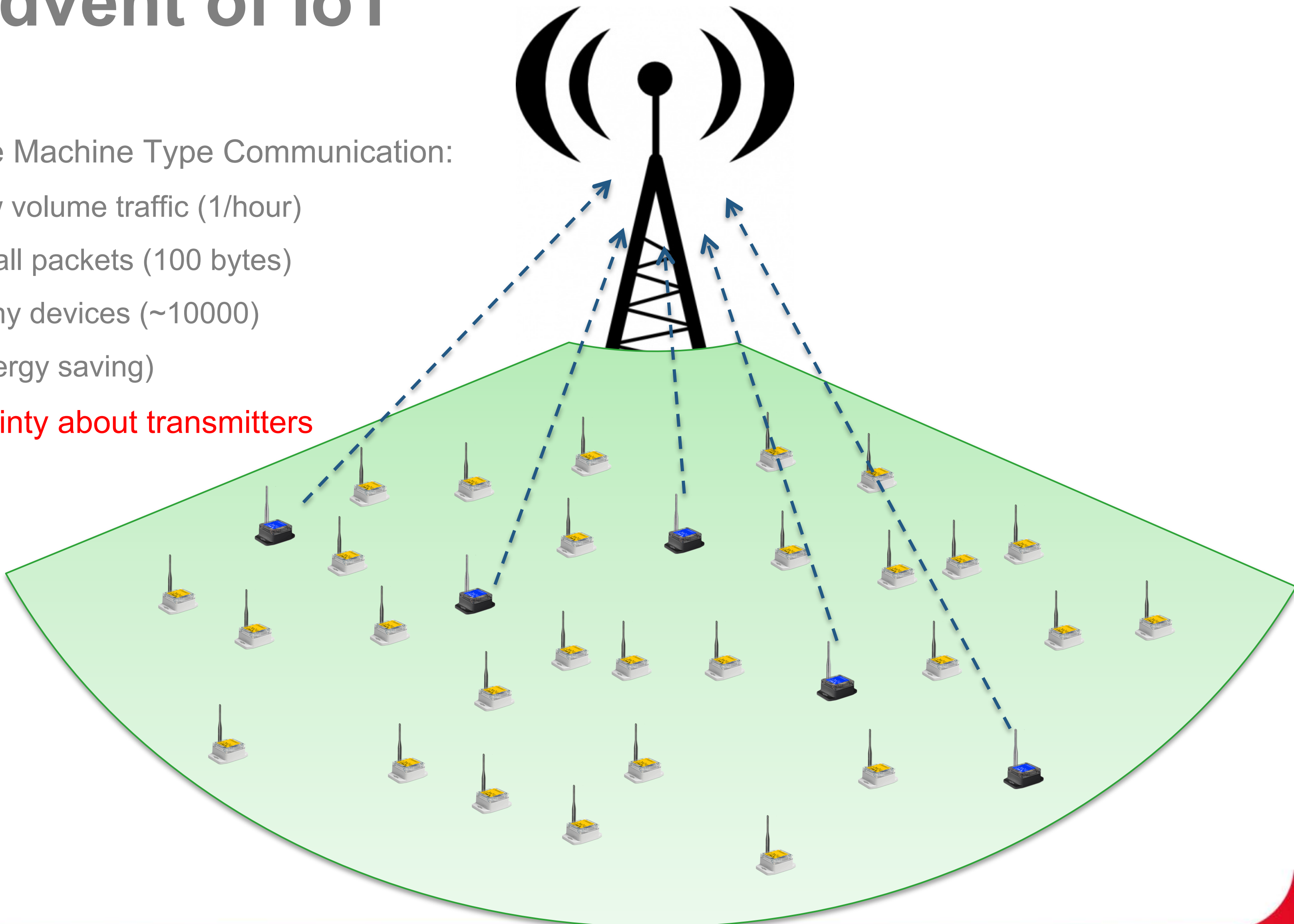
The advent of IoT

- 5G+/Internet of Things
  - dense deployments



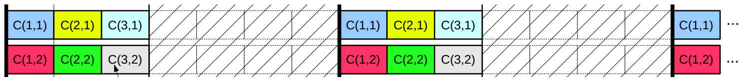
The advent of IoT

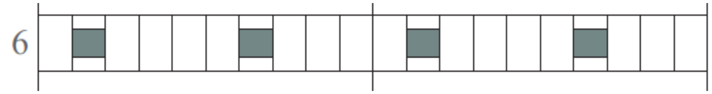
- Massive Machine Type Communication:
  - Low volume traffic (1/hour)
  - Small packets (100 bytes)
  - Many devices (~10000)
  - (energy saving)
- Uncertainty about transmitters



Issue: Massive Access

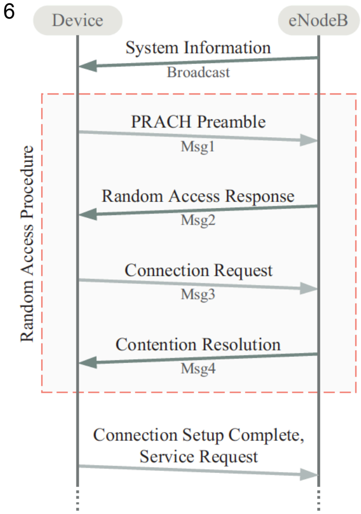
- Ineffcent to allocate ressource blocks (slots in a TDMA schedule)
- Inefficient to trigger the access procedure to the base station (eNodeB) for every small packet
  - Random Access Channel (RACH)
- How about using random access directly?
- Addressed by 4.5G/5G proposals
- See also [1]:





Ex: Rach Configuration Index 6

Contention-based random access procedure (from [1])



[1] Laya, A., Alonso, L., & Alonso-Zarate, J. (2014). “Is the random access channel of LTE and LTE-A suitable for M2M communications? A survey of alternatives.” IEEE Communications Surveys & Tutorials, 16(1), 4-16.

2

Random Access Protocols

Fundamentals: Multiple Access Protocols

- Multiple access on shared transmission medium
  - Fixed assignment
  - Polling
  - Reservation and scheduling
  - Random access
- Random Multiple Access (1970+; see [1])
  - Access the channel and send the packet: success / collision / idle
  - Channel Access Algorithms (CAA):
    - when to access the channel
  - Conflict Resolution Algorithms (CRA): (see overview in [2])
    - when several nodes collides, how to solve collision

[1] IEEE Transactions on Information Theory, Issue 2 - March 1985, Special Issue on “Random Access Protocols”

[2] Molle & Polyzos, “Conflict Resolution Algorithms and their Performance Analysis”, Research Report, 1993

Fundamentals: Aloha, Binary Exponential Backoff

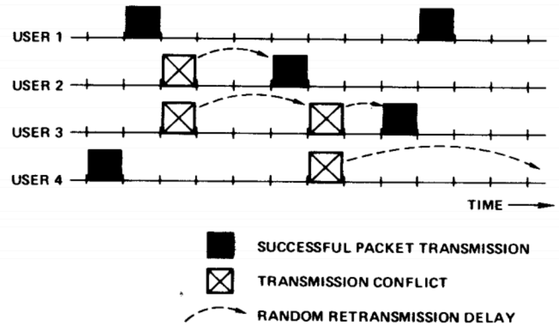


Figure 1—Slotted ALOHA random access

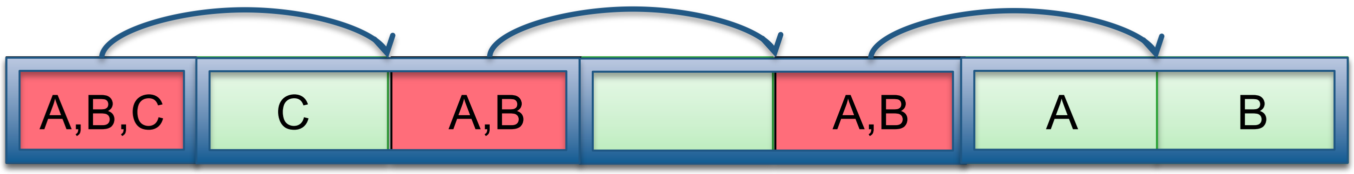
From: Lam & Kleinrock 1975 [2]

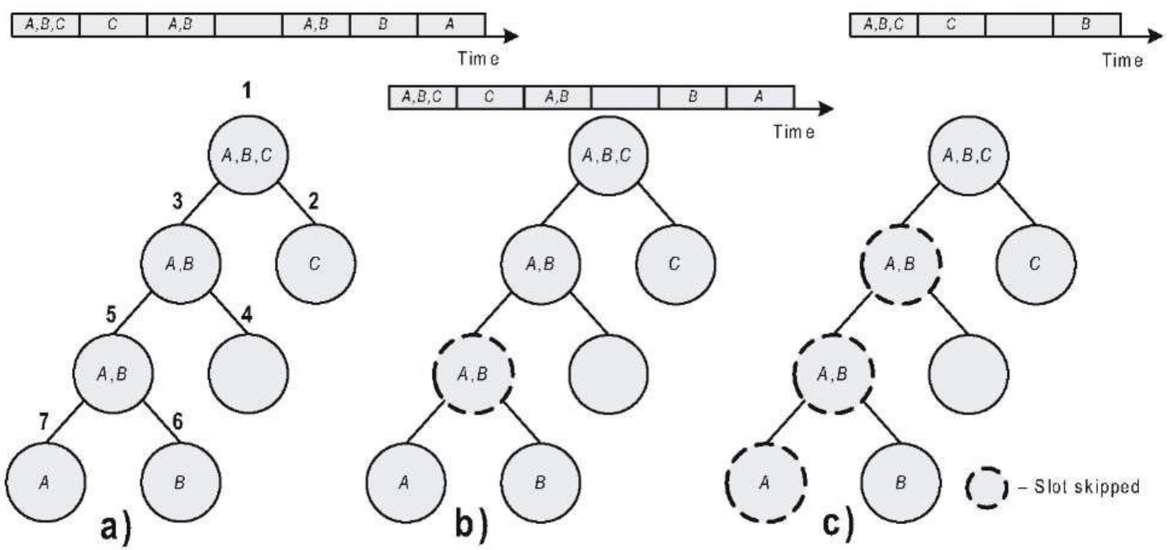
- Random access: ALOHA System [1]
  - 1/(2e) ~ 0.184% at most
- Slotted Aloha:
  - Maximum throughput: $e^{-1} = 0.3679$
- Stabilizing Aloha: consider events on the channel
  - Maintain a learning variable S_k where each node transmits with probability $1/S_k$
  - The k^{th} slot is either: idle, successful transmission, collision
  - Update S_k as S_{k+1} based on the outcome (for instance add a constant depending on the outcome)
- Adaptive backoff algorithms (Binary Exponential Backoff)
  - E.g.[2]: After the m^{th} collision, defer by time in window K_m ; example: $K_m = 2^m$

[1] N. Abramson (1970). "The ALOHA System - Another Alternative for Computer Communications" Proc. 1970 Fall Joint Computer Conference. AFIPS Press.

[2] Simon S. Lam and L. Kleinrock, "Dynamic Control Schemes for a Packet Switched Multi-Access Broadcast Channel", NCC, Anaheim, May 1975, AFIPS, Vol. 44, AFIPS Press

Fundamentals: Tree Protocol (CRA)





- Standard Tree Protocol (Capetanakis-Tsybakov-Mikhailov tree algorithms, 1978+),
- Modified Tree Protocol (Massey 1981, known collisions are avoided) , 0.375 - 0.381 (with bias)

Fundamentals: CRA Performance

- (See textbooks [1], [2], or overview [3])
- First-Come First-Serve - FCFS 0.487(1)
  - Independently discovered by Gallager [Galla78], Tsybakov and Mikhailov [Tsyba80], and others (G. Ruget and/or J. Pellaumail [Ruget81])
  - Deliver packets in First-Come First-Serve Order (good delay)
  - Variant: 0.487760, Mosely and Humblet 1985
- Protocol bounds:
  - $C \leq 0.5$ for in-order (FCFS) type of access [Panwar, Towsley and Wolf, 1985]
  - $C \leq 0.505$ for any free access algorithm [Mikhailov and Tsybakov, 1985]
  - $C_f \leq 0.568$, [Tsybakov and Likhanov, 1987]

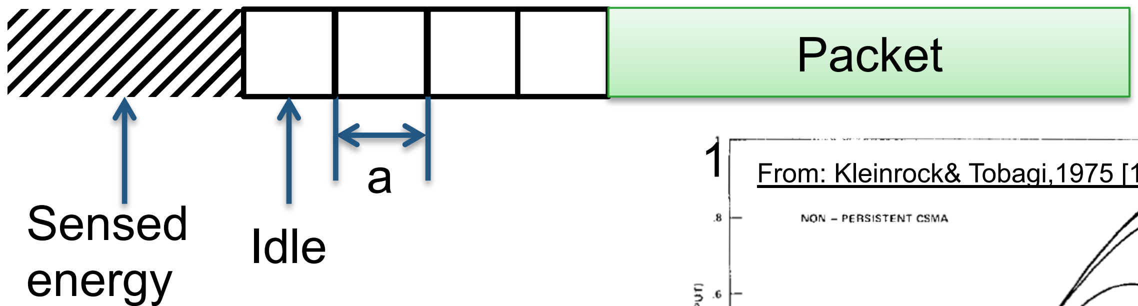
[1] Bertsekas, D. P., Gallager, R. G., & Humblet, P. (1992). “Data networks” New Jersey: Prentice-Hall International.

[2] Kumar A, Manjunath D, Kuri J. “Wireless Networking”. Morgan Kaufmann; 2008

[3] Molle & Polyzos, “Conflict Resolution Algorithms and their Performance Analysis”, Research Report, 1993

Fundamentals: Carrier Sense Multiple Access

- Carrier Sense Multiple Access (CSMA)/Listen Before Talk (LBT)



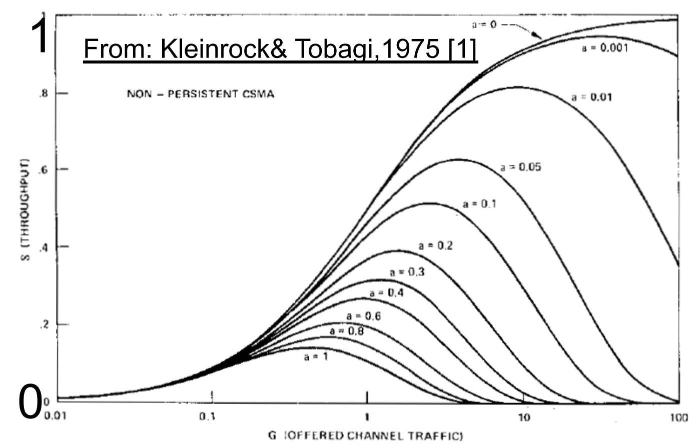


Fig. 3. Throughput in nonpersistent CSMA.

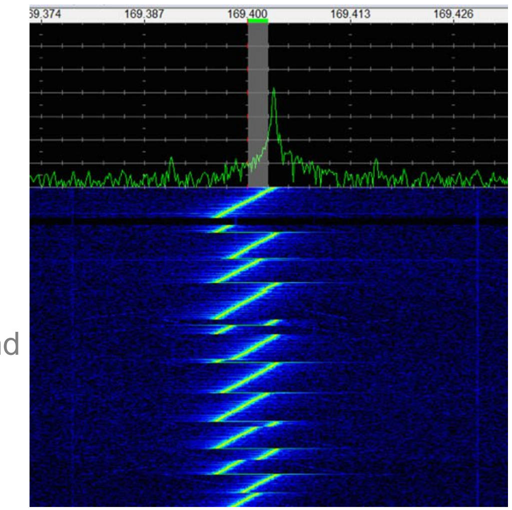
  - Persistent/non-persistent
  - CSMA/CD (collision detection)
  - CSMA/CA (collision avoidance),
  - Performance [1]: $S = \frac{aGe^{-aG}}{(1 - e^{-aG}) + a}$ ➔1 when a➔0 (with high G)

[1] Kleinrock, L., & Tobagi, F. A. ”Packet switching in radio channels: Part I--carrier sense multiple-access modes and their throughput-delay characteristics”. IEEE Transactions on Communications, 23(12), 1400-1416., 1975

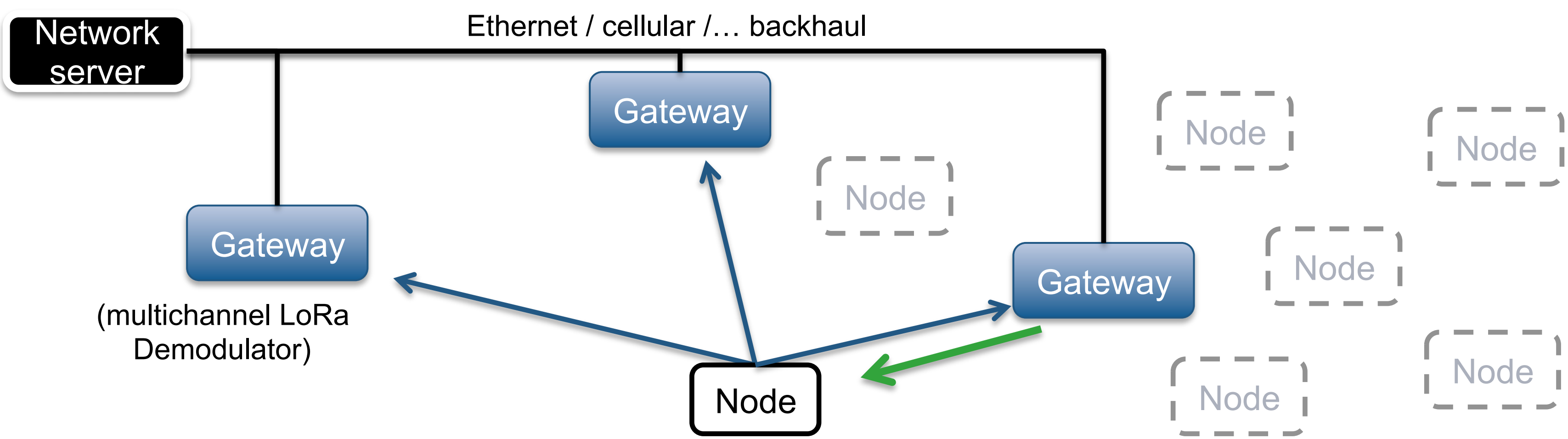
[2] “Delay distributions of slotted ALOHA and CSMA”, Y Yang, TSP Yum - IEEE Transactions on Communications 2003

Actual Protocols: LoRaWAN

- LoRa (Cycleo/Semtech) / LoRaWAN: Sub-Ghz, Low-Power Wide-Area Network (LPWAN)
  - LoRa Alliance (MAC Features), unlicensed band
  - Mostly uplink only
  - Efficient physical layer (up to -137 dBm sensitivity /155 budget) - regional ISM band (EU 868 MHz, 125/250 kHz of channel bandwidth, 250 bps to 50 kbps, 10 channels)
  - Variant of chirp-spread spectrum (CSS)
  - Different spreading factors (SF=7 to 12), and coding rates



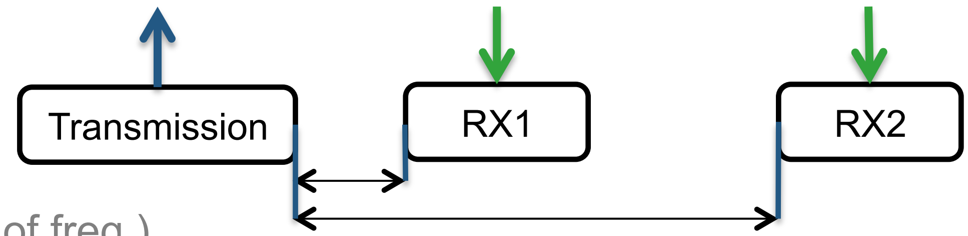
http://www.link-labs.com/what-is-lora/



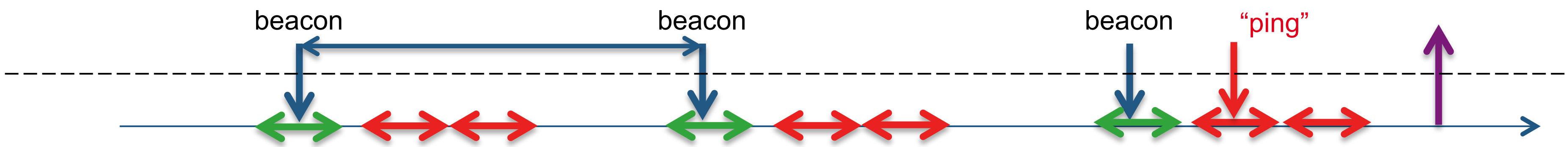
[1] Claire Goursaud, Jean-Marie Gorce. “Dedicated networks for IoT : PHY / MAC state of the art and challenges.” EAI endorsed transactions on Internet of Things, 2015,

Actual Protocols: LoRaWAN – MAC Layer

- Class A (All):
  - One transmission, RX DL opp.
    (Aloha type protocol, free choice of freq.)



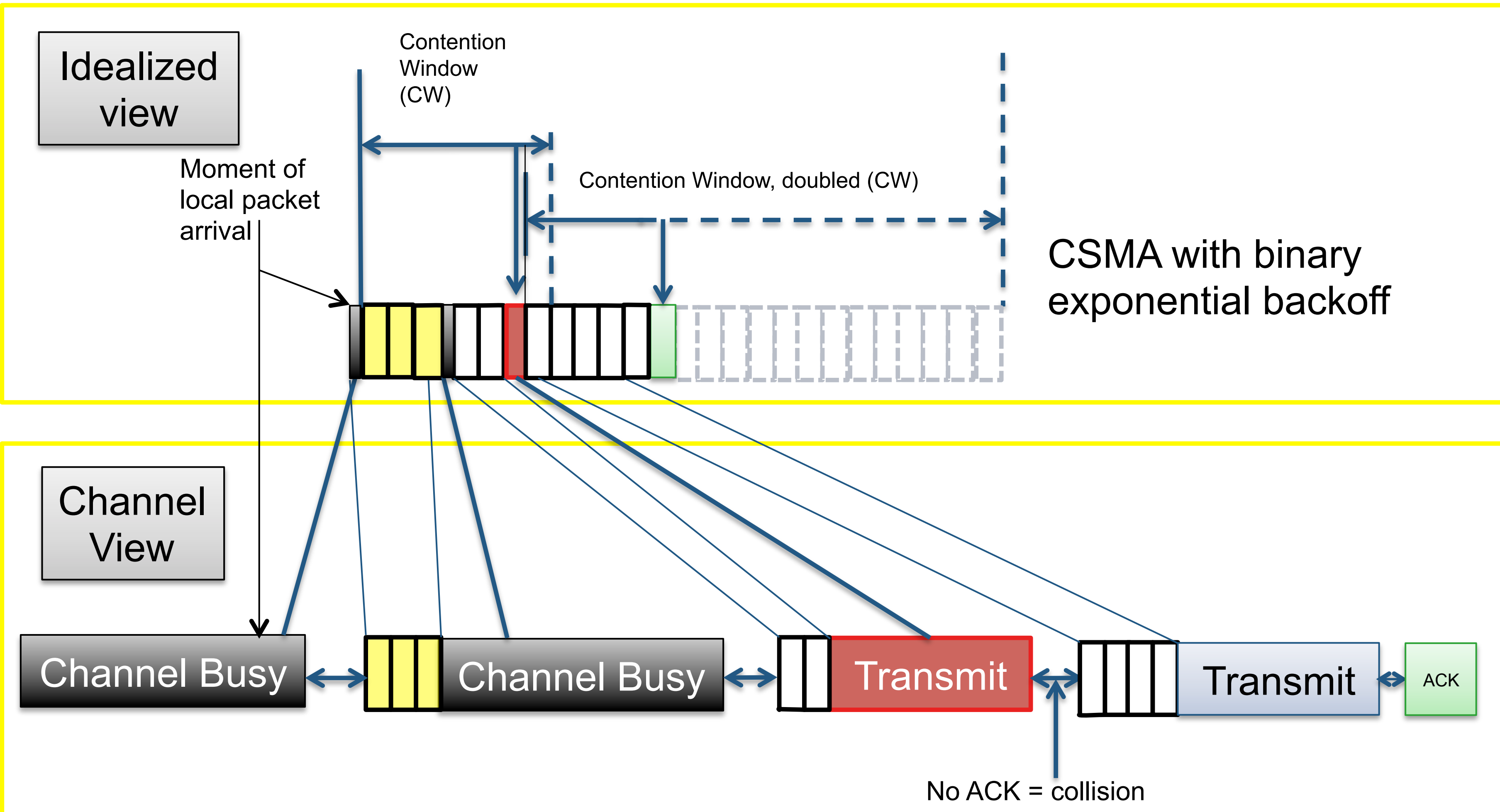
  - EU 868: Aloha + <1% duty-cycle limit (alternate: ETSI - LBT AFA) ; EU 433: same
- Class B (Beacon): "synchronous network initiated"
  - Beaconing from the gateways: devices listen for "beacon slot" and "ping slot"



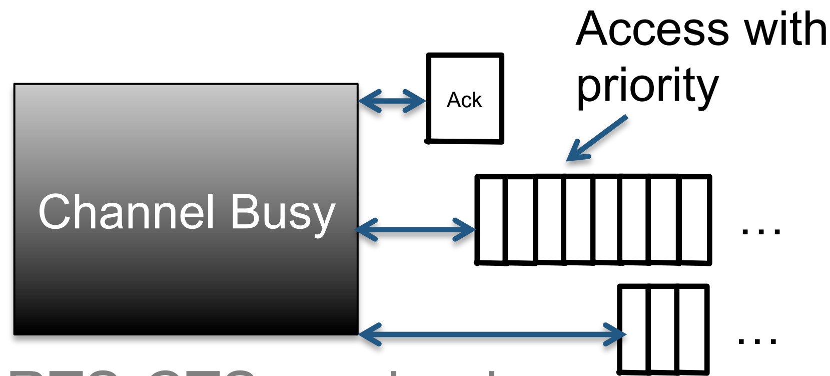
- Class C (Continuous): always on
- Possible control by the network server:
  - Duty-cycle, rate, tx-power, repetition rate, channel

+ randomization of slot indexes (offset)

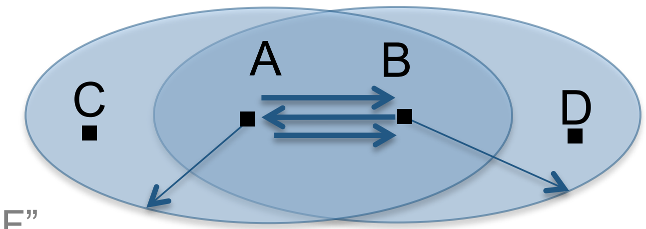
Actual Protocols: Wi-Fi - 802.11- Distributed Coordination Function (DCF)

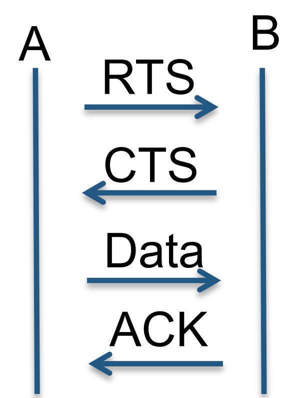


Actual Protocols: Wi-Fi - 802.11



- Priority, different IFS
  - 802.11e (2005): EDCA
  - Enhanced Distributed Channel Access
- NAV (virtual carrier sensing) and RTS-CTS mechanism,
  - For “multi-hop reservation” (MACAW)

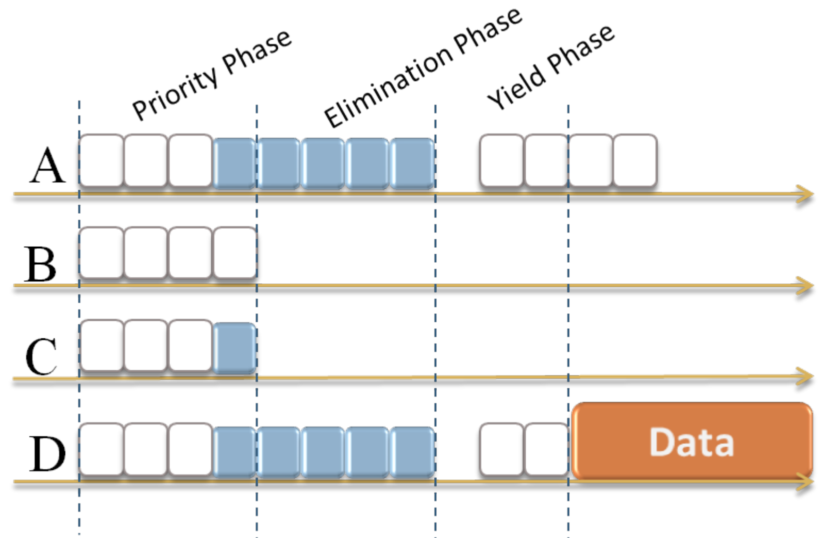


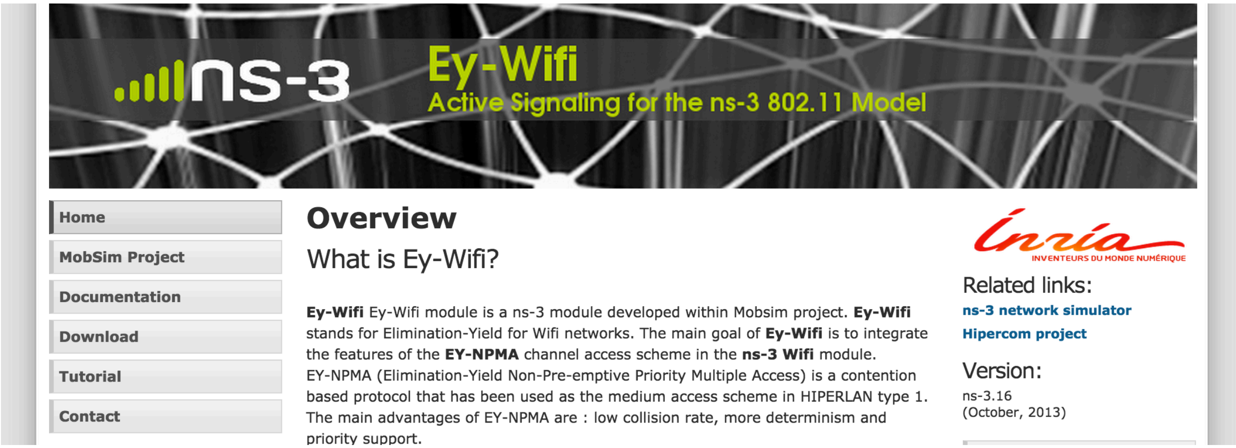


- Several variants:
  - 802.11 Point Coordination Function “PCF”
    - Polling (but not part of Wi-Fi Alliance interoperability)
  - 802.11e: HCCA = HCF [Hybrid Coord. Func.] Controlled Channel Access
  - 802.11s (mesh): MCCA = MCF [Mesh Coord. Func.] Controlled Channel Access
  - 802.11ah (Wi-Fi HaLow), sub-Ghz (802.11ac down-clocked by 10): PV1, RAW (Restricted Access Window), TWT (Target Wake Time) [ex: Newracom NRC7191], sectorisation, NDP,...
  - 802.11ax (~2018+): “color” DCF, increase CCA & ignore packets from other access points.

Actual Protocols: Hiperlan/1 - “Black burst”

- Idea: EY-NPMA
  - Add pilot sequence
  in the access competition
  - Triple elimination: $p_1 p_2 p_3$
- In Hiperlan (ETSI 1993 [1]).
  - Revisited,
    Ey-Wifi [2]





[1] “HIgh PErformance Radio Local Area Network (HIPERLAN) Type 1; Functional specification” ETS 300 652, ETSI, June 1996

[2] Hana Baccouch, Cédric Adjih, Paul Muhlethaler. Active Signaling for 802.11 Networks in the ns-3 Simulator, PEMWN 2012

Ideas: Beyond Classical Random Access

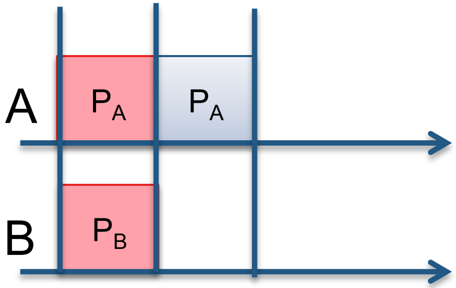
- Without carrier sense: bounds 0.5 & 0.568
- Possible to improve performance with physical layer
  - Capture, Multiple Packet Reception (MPR), Successive Interference Cancellation (SIC)
- Some Examples:
  - In [1], B. Tsybakov, 2004 .
    - Multipoint to point wireless channel with and without capture and Multiple Packet Reception (MPR).
    - Max throughput: 0.6548 with capture + multi-packet reception
  - In [2], Gore and Abhay, 2010
    - Power controlled capture, FCFS
    - maximum stable throughput of 0.5518

[1] B. Tsybakov, “Packet Multiple Access for Channel with Binary Feedback, Capture and Multiple Reception,” IEEE Trans. Inf. Theory, vol. 50, no. 6, pp. 1073–1085, Jun. 2004

[2] Gore and Abhay, "Power-controlled FCFS splitting algorithm for wireless networks." Vehicular Technology, IEEE Transactions on 59.2 (2010)

Idea: Using Successive Interference Cancellation

- Motivating example from SICTA (Yu&Giannakis 2005 [1])
- Receive P_A
- Use successive interference cancellation on $P_A \odot P_B$
- Enriched feedback:
  - 0 / k (number of colliding nodes) / e
- Double the performance of the "Modified Tree Algorithm": 0.693



From Yu & Giannakis 2005 [1]

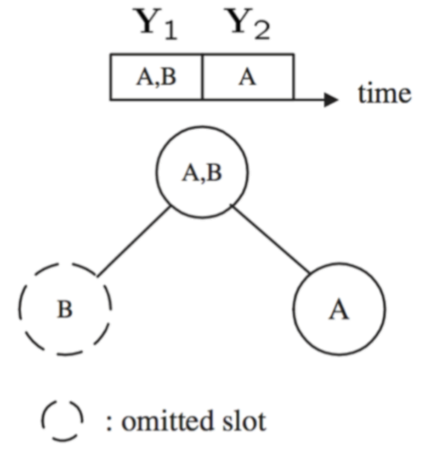


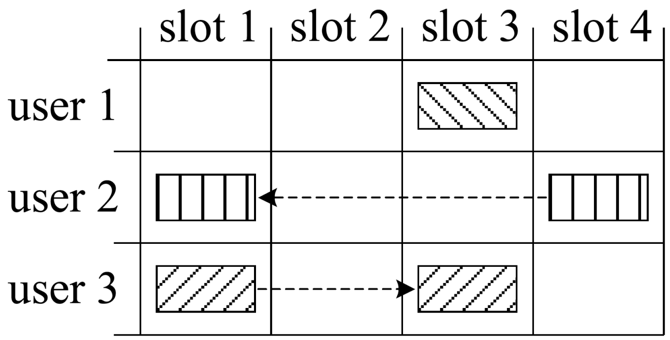
Fig. 1. A motivating SICTA example

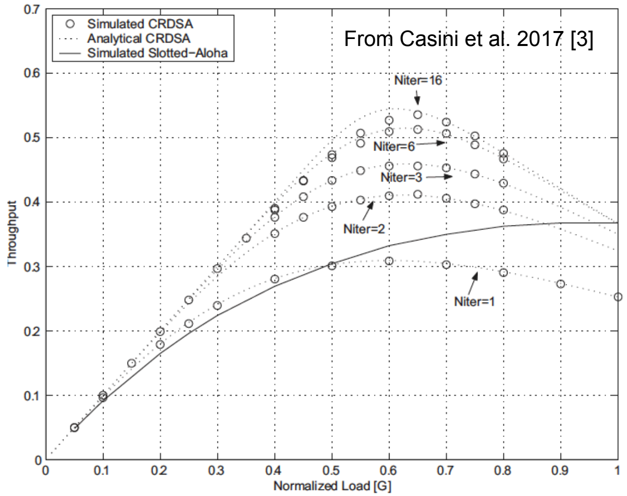
[1] Yu, Yingqun, and Georgios B. Giannakis. "SICTA: a 0.693 contention tree algorithm using successive interference cancellation." INFOCOM 2005.

Idea: Coded Random Access Protocols

- Paolini et al. 2014 [1]: Overview of "Coded Random Access"
  - Example:
    - 3 users, 3 packets (+repetitions)
    - ¾ vs ¼ packets
    - No feedback
- Decoding:
  - successive interference cancellation
  - In general, analogy with erasure-coding (Livia 2011 [2])
- Prior example (Casini et al. 2007 [3]):
  - Performance:
    - $T_{max} \approx 0.55$ with 2 replicas

From Paolini et al. 2014 [1]

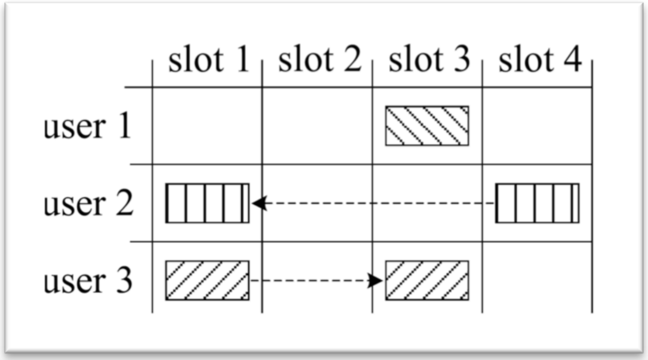


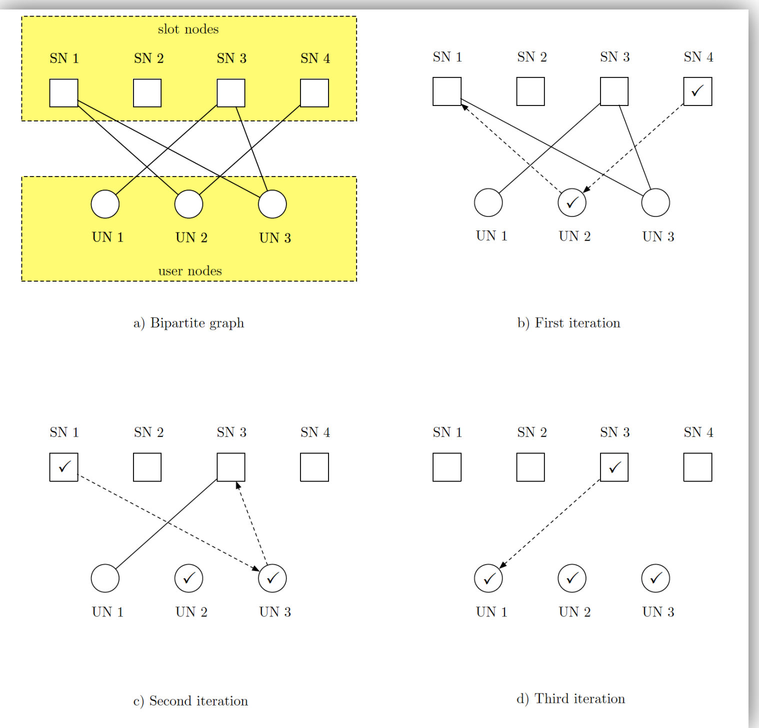


[1] Paolini, E., Stefanovic, C., Liva, G., & Popovski, P. (2014). "Coded random access: How coding theory helps to build random access protocols". arXiv.
[2] Liva "Graph-based analysis and optimization of contention resolution diversity slotted ALOHA." *IEEE Transactions on Communications* 59.2 (2011)
[3] Casini E, De Gaudenzi R, Herrero OD. "Contention resolution diversity slotted ALOHA (CRDSA): An enhanced random access scheme for satellite access packet networks". IEEE Transactions on Wireless Communications. 2007 Apr;6(4):1408-19

Coded Random Access

From Paolini et al. 2014 [1]





- From [1,2], analogy with erasure-coding codes (like LDPC):
  - Bipartite graph representation
  - Decoding
  - “Stopping sets”: cycles in the graph, block decoding
  - Proper distribution of degrees
- If N/M constant (and grows): limit G*:
  - Decoding “almost certainly” terminate of G < G*
  - Certainly will have undecoded packets of G > G*
- Liberty: distributions of degrees (nb packets)
  - With proper distribution, G* = 1 packet/slot

  “The way the rate distribution is optimized follows the footsteps of the degree distribution optimization algorithms used in the design of low-density parity-check (LDPC) codes” [1]
- Frameless version possible
- “Coded” version possible

[1] Paolini, E., Stefanovic, C., Liva, G., & Popovski, P. (2014). “Coded random access: How coding theory helps to build random access protocols”. arXiv.
[2] Liva "Graph-based analysis and optimization of contention resolution diversity slotted ALOHA." *IEEE Transactions on Communications* 59.2 (2011)

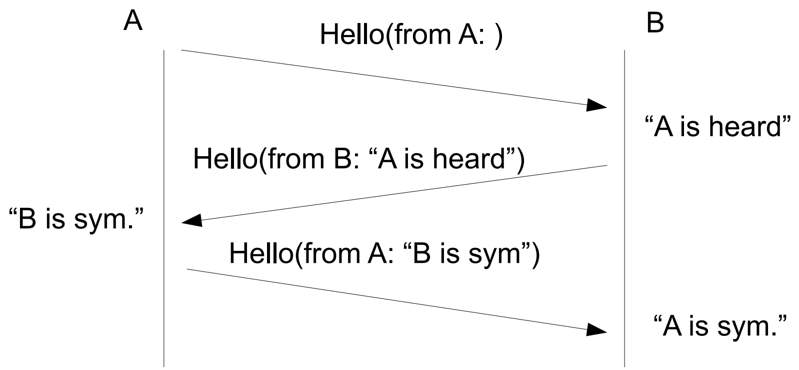
3

Routing/Link/Neighbor Discovery

Sous-titre facultatif

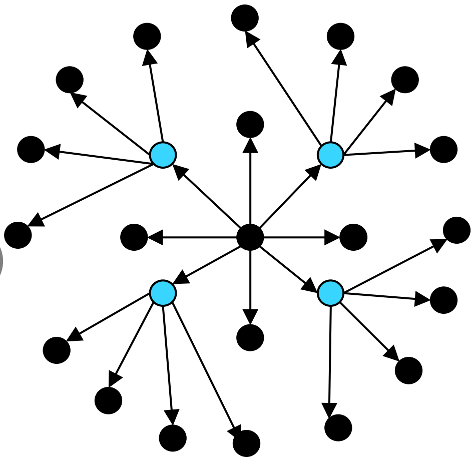
Wireless Multihop Routing – OLSR

- OLSR (Optimized Link State Routing) RFC 3626, OLSRv2 RFC 7181
- Link State protocol (based on Hiperlan)
  - Periodic messages
  - Neighbor sensing:
    - “HELLO” messages: list of neighbors
  - Topology discovery: what is the graph?
    - List of some neighbors (“TC” messages)
  - Sent to the whole network



Wireless Multihop Routing – OLSR

- Optimisation (MPR-flooding)
  - Based on MPR, "multi-point relays"
  - not all nodes retransmit in a flooding (of *TC messages*)
  - not all nodes send *TC messages*
  - not all neighbors are sent in *TC messages*
  - *Still shortest path*
- Physical Layer:
  - Assumption of "neighborcast" primitive
  - Fixed modulation
  - Link filtering (ETX, radio link estimates…)
- MAC Layer, tactical radios:
  - TDMA (spatial reuse?)
  - Broadcast/control sub-frame



Some IoT / Wireless Sensor Protocols on 802.15.4

2003

Lots of research

- IEEE 802.15.4 (Low Power Network)
  - 2.4 GHz: 16 channels, 250 kbps, DSSS, OQPSK, 127 bytes: ~30-100 meters, multi-hop wireless network
  - Also sub 1-GHz (868 MHz, 20 kbps / 915 MHz, 40 kbps)
- Later: IEEE 802.15.4g (Wi SUN Alliance)
  - Sub 1 GHz
  - Extensions to the physical layer (2012)

IEEE 802.15.4
Basic MAC

IEEE 802.15.4 Physical Layer (2.4 GHz, sub-1 GHz), 2003-

Some IoT / Wireless Sensor Protocols on 802.15.4

2003

Lots of research

Zigbee

Zigbee Application Framework

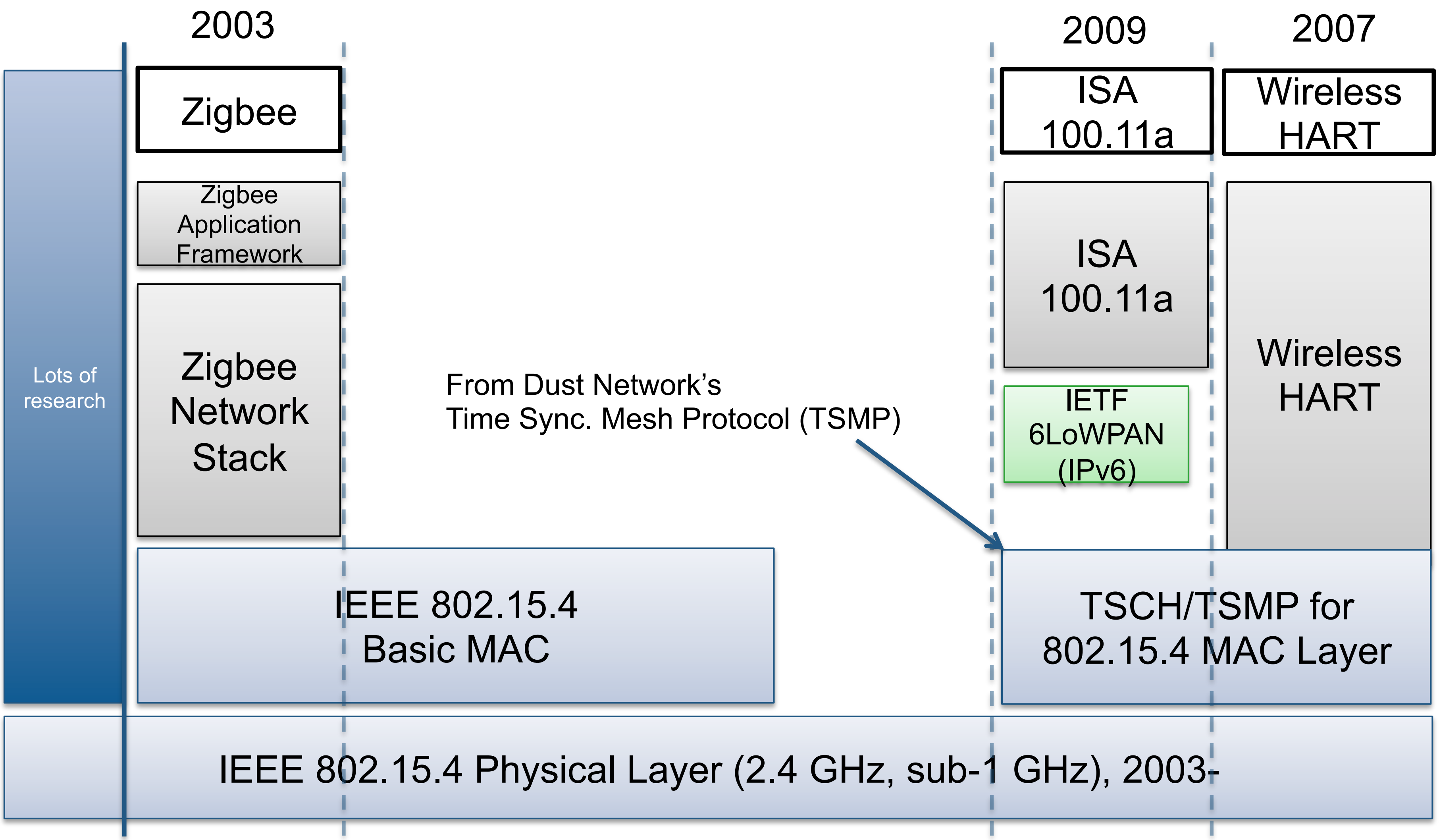
Zigbee Network Stack

IEEE 802.15.4 Basic MAC

IEEE 802.15.4 Physical Layer (2.4 GHz, sub-1 GHz), 2003-

- IEEE 802.15.4 (Low Power Network)
  - 2.4 GHz: 16 channels, 250 kbps, DSSS, OQPSK, 127 bytes: ~30-100 meters, multi-hop wireless network
  - Also sub 1-GHz (868 MHz, 20 kbps / 915 MHz, 40 kbps)
- Later: IEEE 802.15.4g (Wi SUN Alliance)
  - Sub 1 GHz
  - Extensions to the physical layer (2012)
- Zigbee Alliance, Dust Networks, …

Some IoT / Wireless Sensor Protocols on 802.15.4



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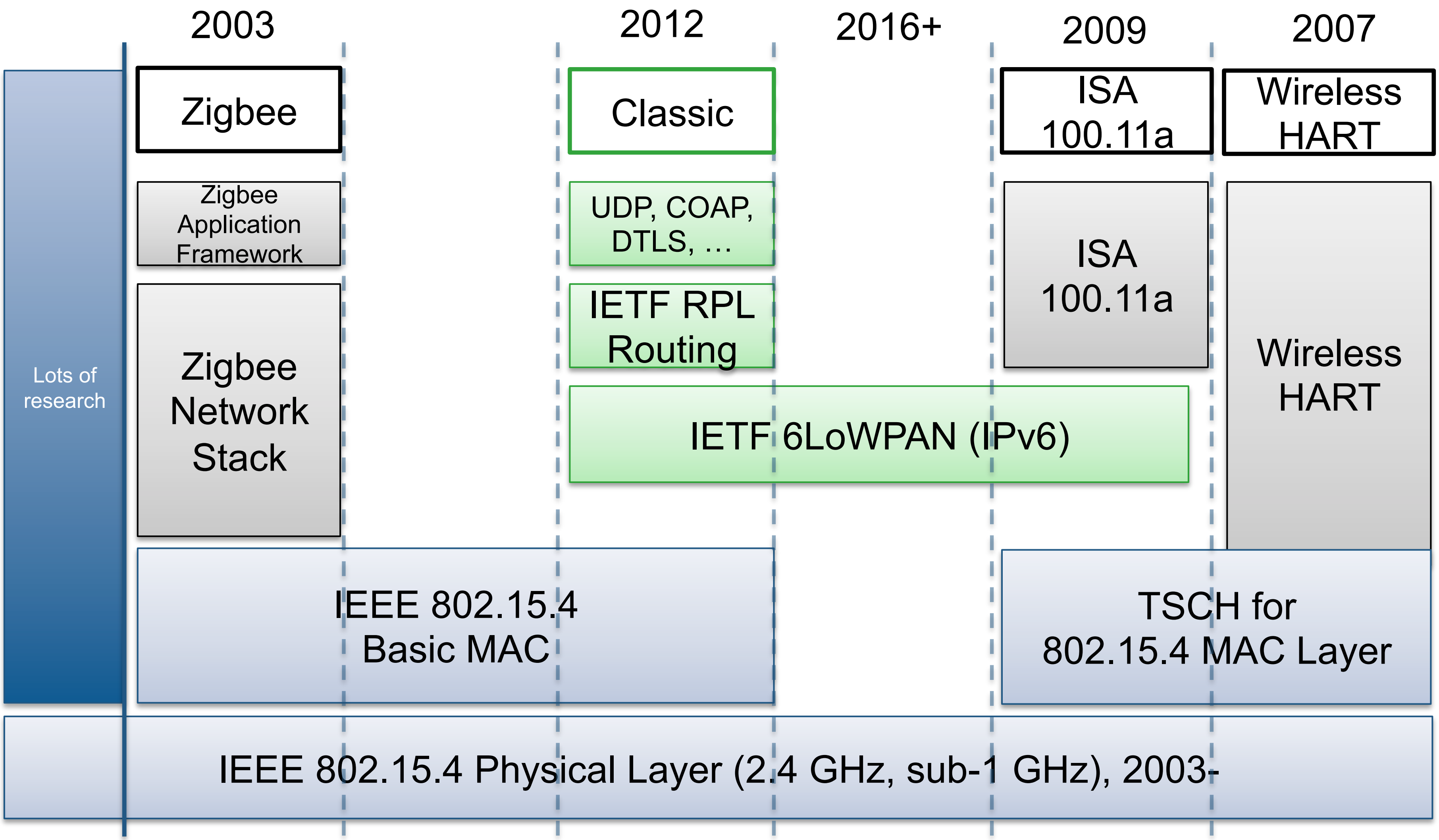
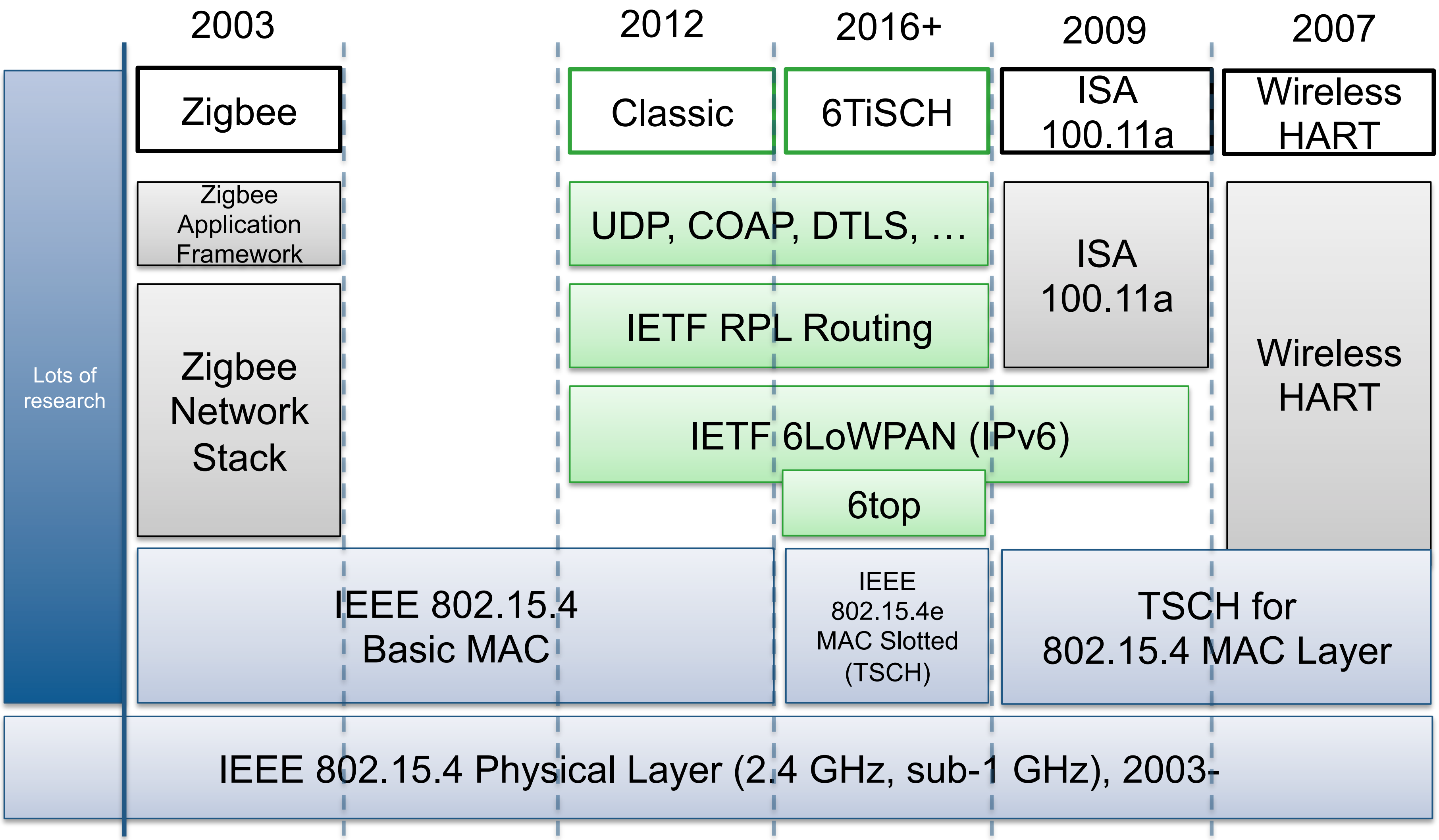
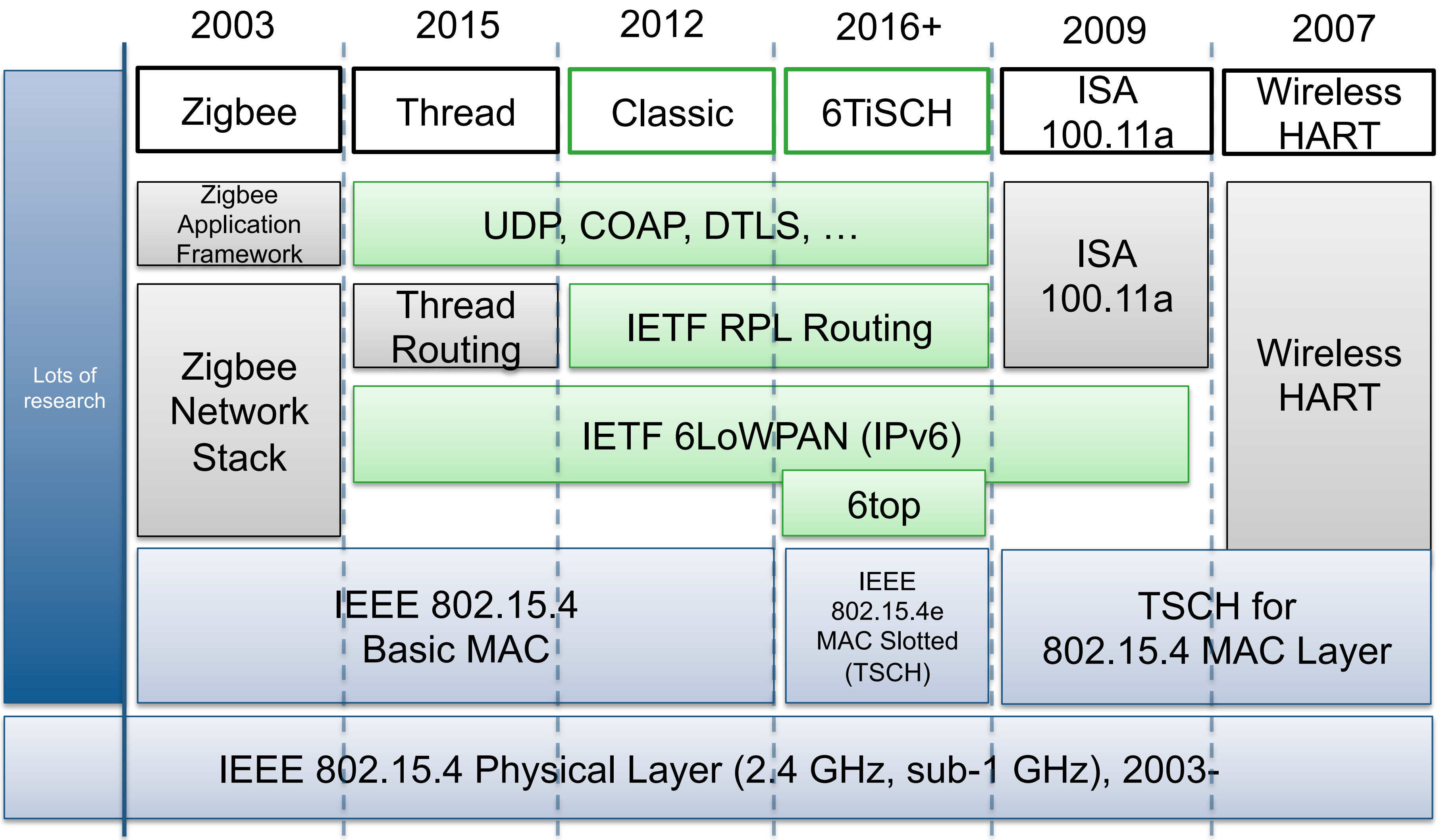


Some IoT / Wireless Sensor Protocols on 802.15.4

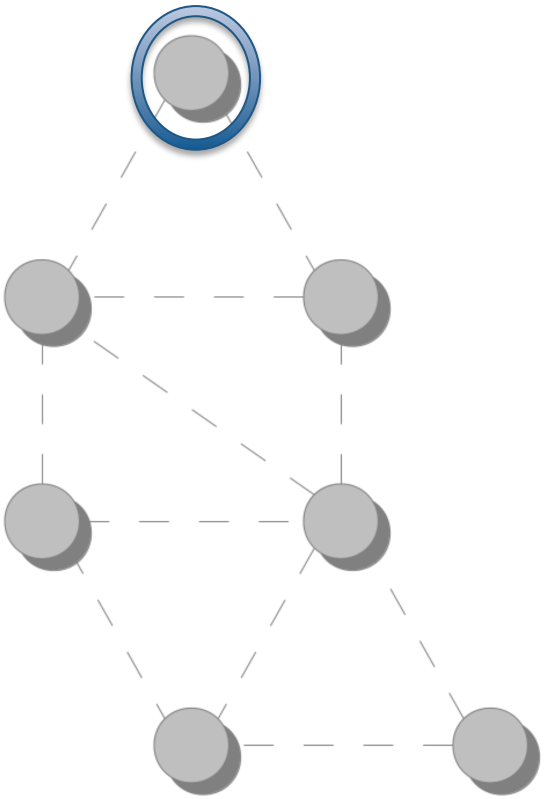


Some IoT / Wireless Sensor Protocols on 802.15.4



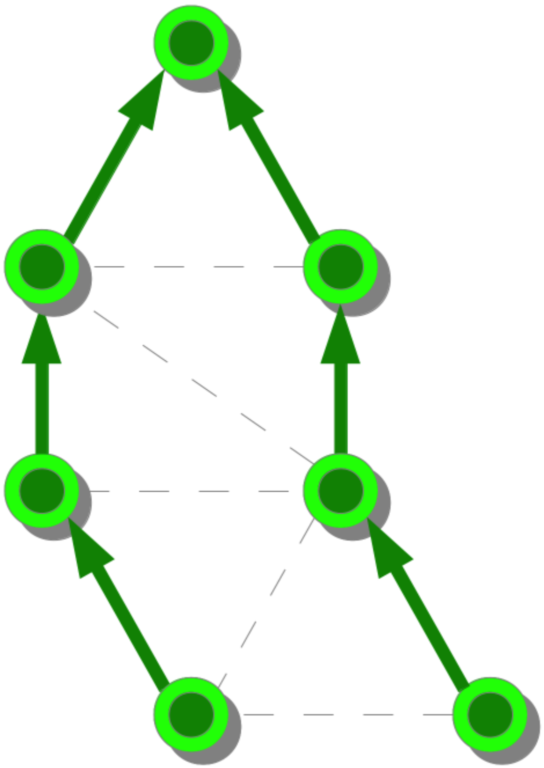
(IETF) Routing Protocol RPL: Principles

- IPv6 for constrained devices:
  6LoWPAN (RFC 4944+)
- Routing protocol for Low-Power and Lossy Networks (LLN), on top of
  6LoWPAN: RPL (RFC6550, …)
- Simplified routing:
  - Routing tree to a sink (root)



RPL Overview: Principles

- RPL (RFC6550):
  - Routing tree to a sink (root)



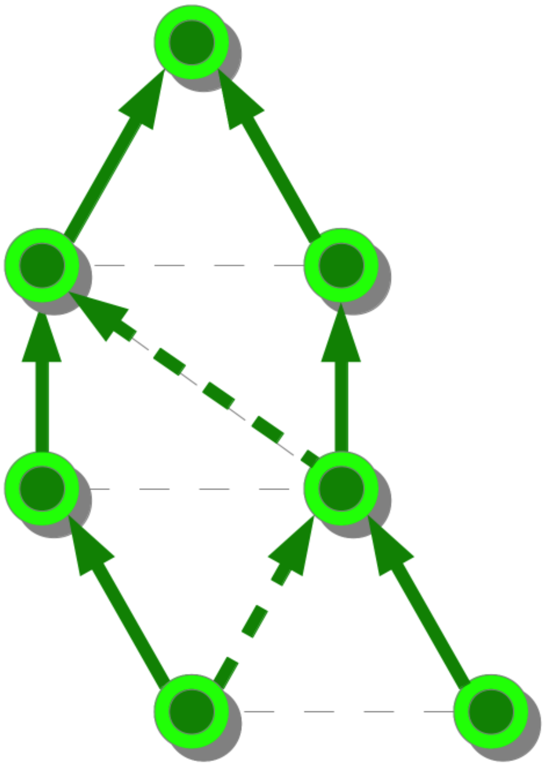
RPL Overview: Principles

- RPL (RFC6550):
  - Routing tree to a sink (root)
  - More: DODAG to sink,

    (Destination-oriented

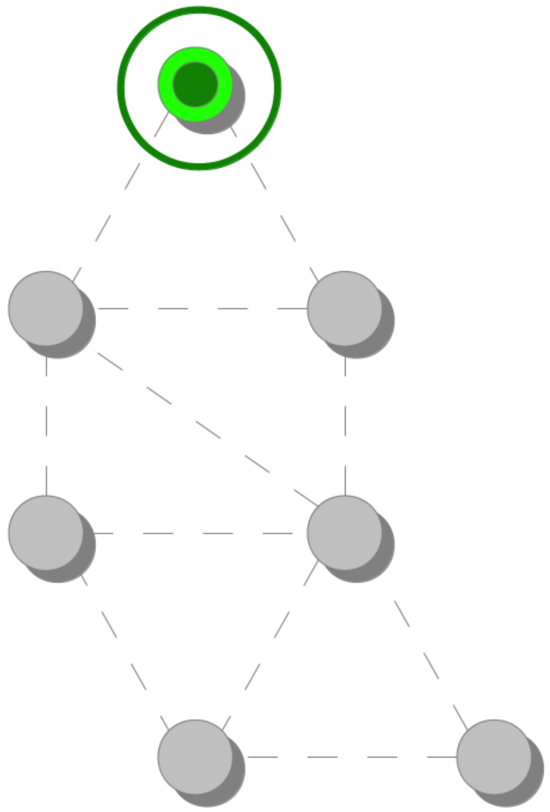
    Directed Acyclic Graph)
  - One preferred parent

    + other optional parents



RPL Overview: Messages

- RPL Protocol Message(s):
  - DODAG Information Object
    - (DIO)
    - Metric to reach the sink
    - Sent by every node



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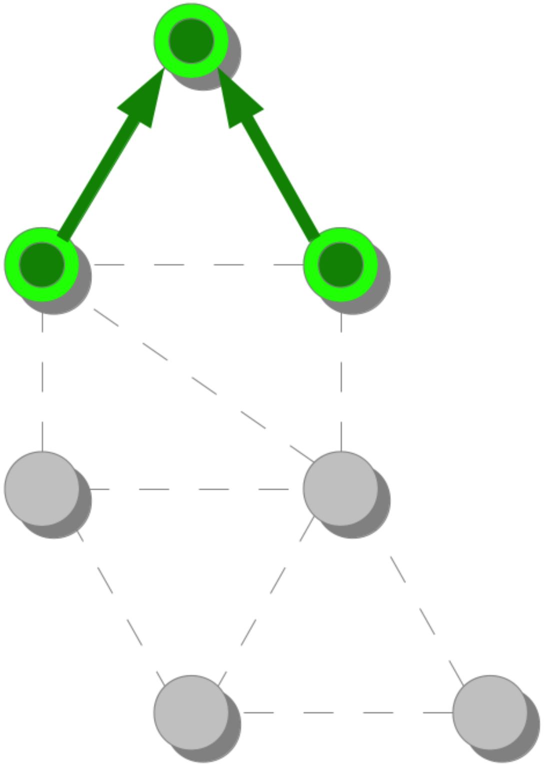

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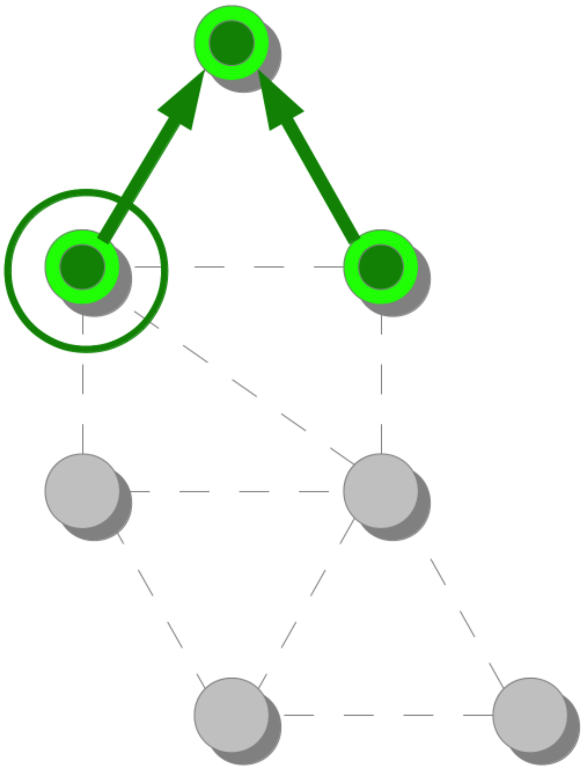

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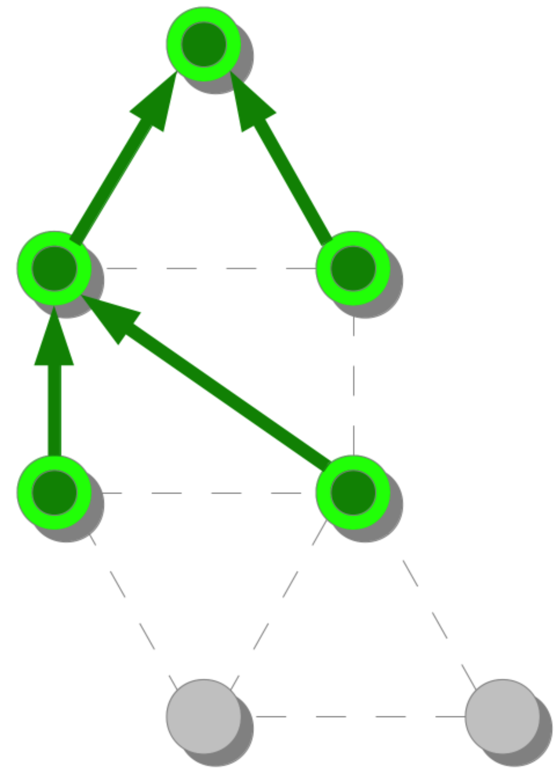

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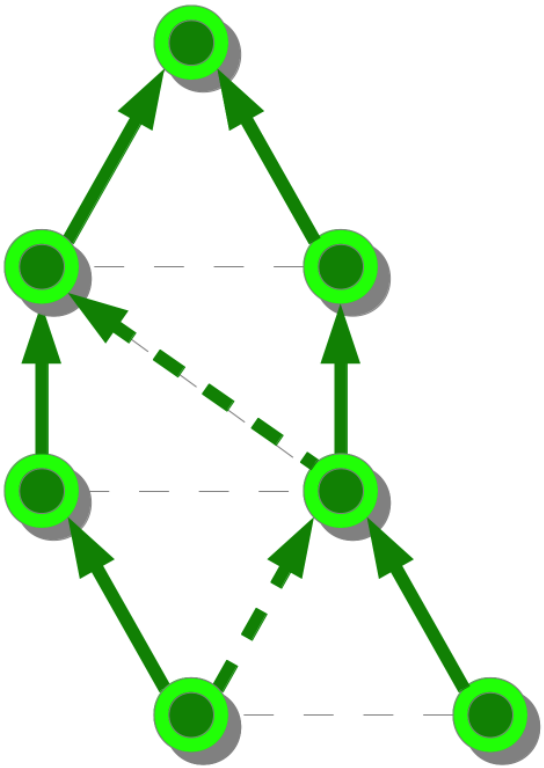
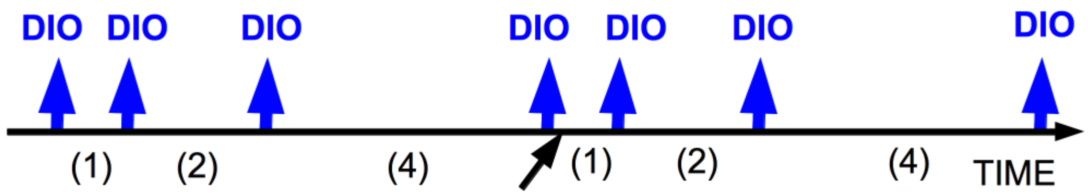
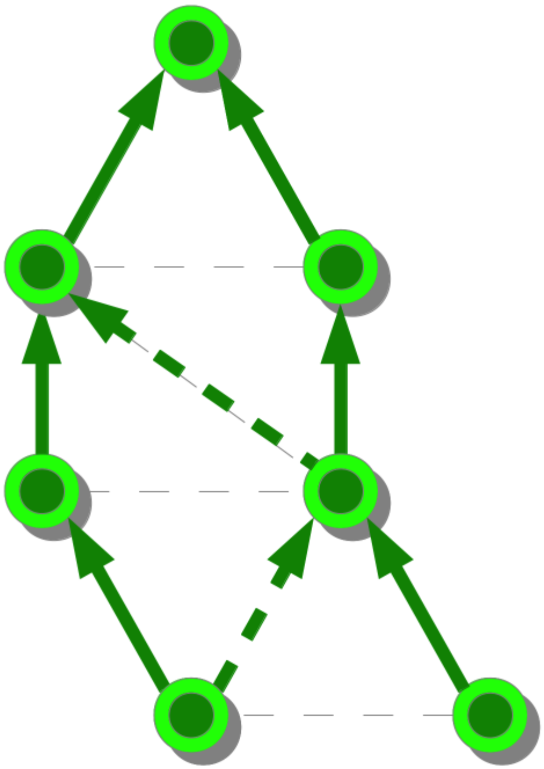


RPL Overview: Trickle

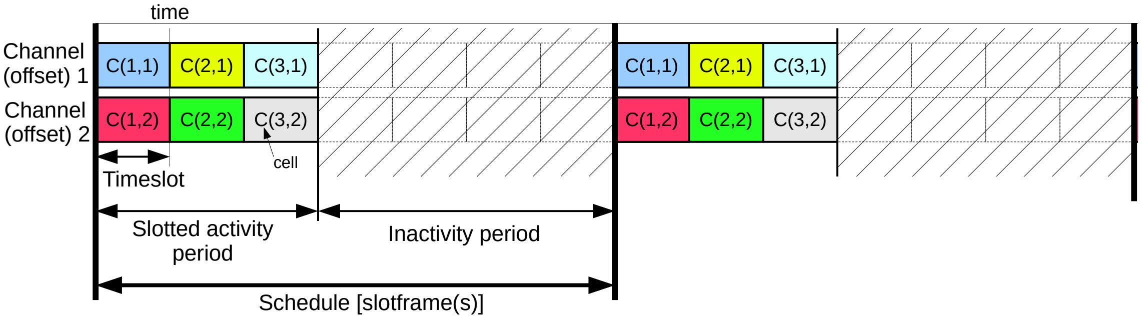
- Trickle (RFC 6206, [Levis et al. '04]):
  - Optimization
  - No topology change:
    - Exponential increase in the interval of RPL messages (DIO)
  - Change detected: Reset interval





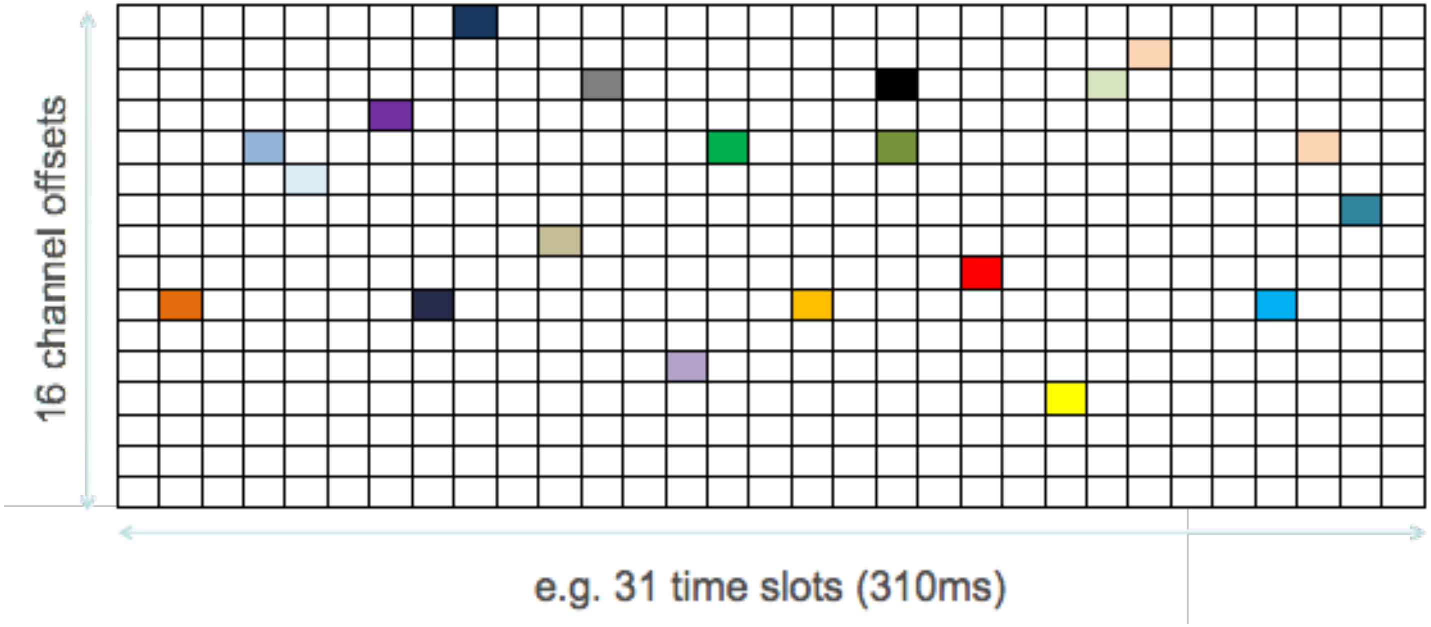
IETF 6TiSCH - IPv6 over the TSCH mode of IEEE 802.15.4e

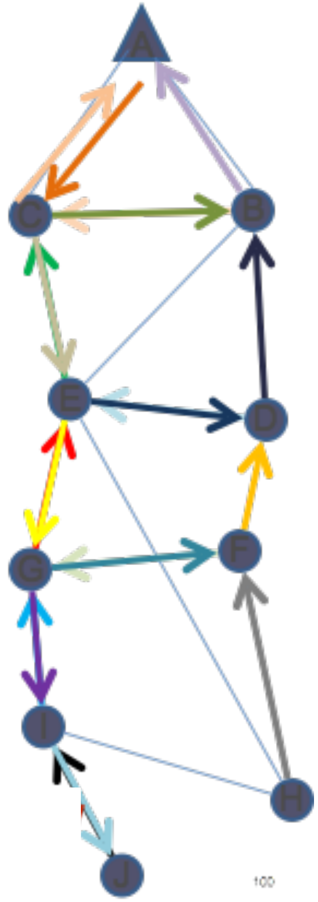
- Working Group at IETF, 6TiSCH
  - “IPv6 over the TSCH mode of IEEE 802.15.4e”
  - TSCH: “Time-Slotted Channel Hopping (TSCH)”
- Main ingredients:
  - Proposes TDMA for 802.15.4 networks
  - Routing protocol RPL, IPv6 with 6LoWPAN
  - Uses channel hopping



- Distributed Schedule:
  - RPL routing tree is used for time synchronization (with parent)
  - Nodes send periodic “Enhanced Beacons” (Aloha, in specific slots of the frame)
  - Default, centralized: all topology information is sent to a PCE (Path Computation Element)

IETF 6TiSCH - IPv6 over the TSCH mode of IEEE 802.15.4e

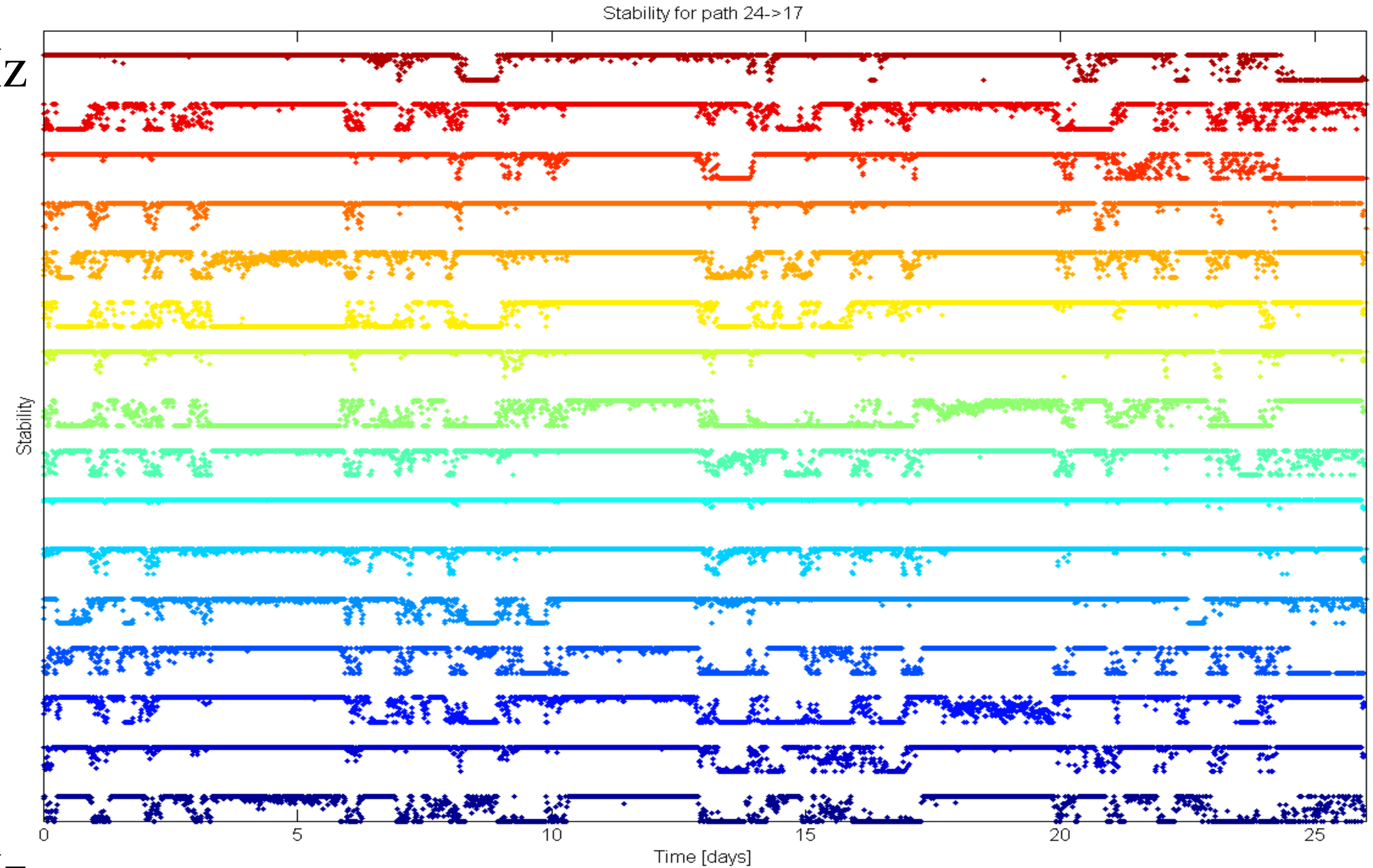




From: “Time Slotted, Channel Hopping Field Experience”,
Pister et al., presentation of contribution
IEEE 802.15-08-0583-02-004e

26 Days: 24→17 Path

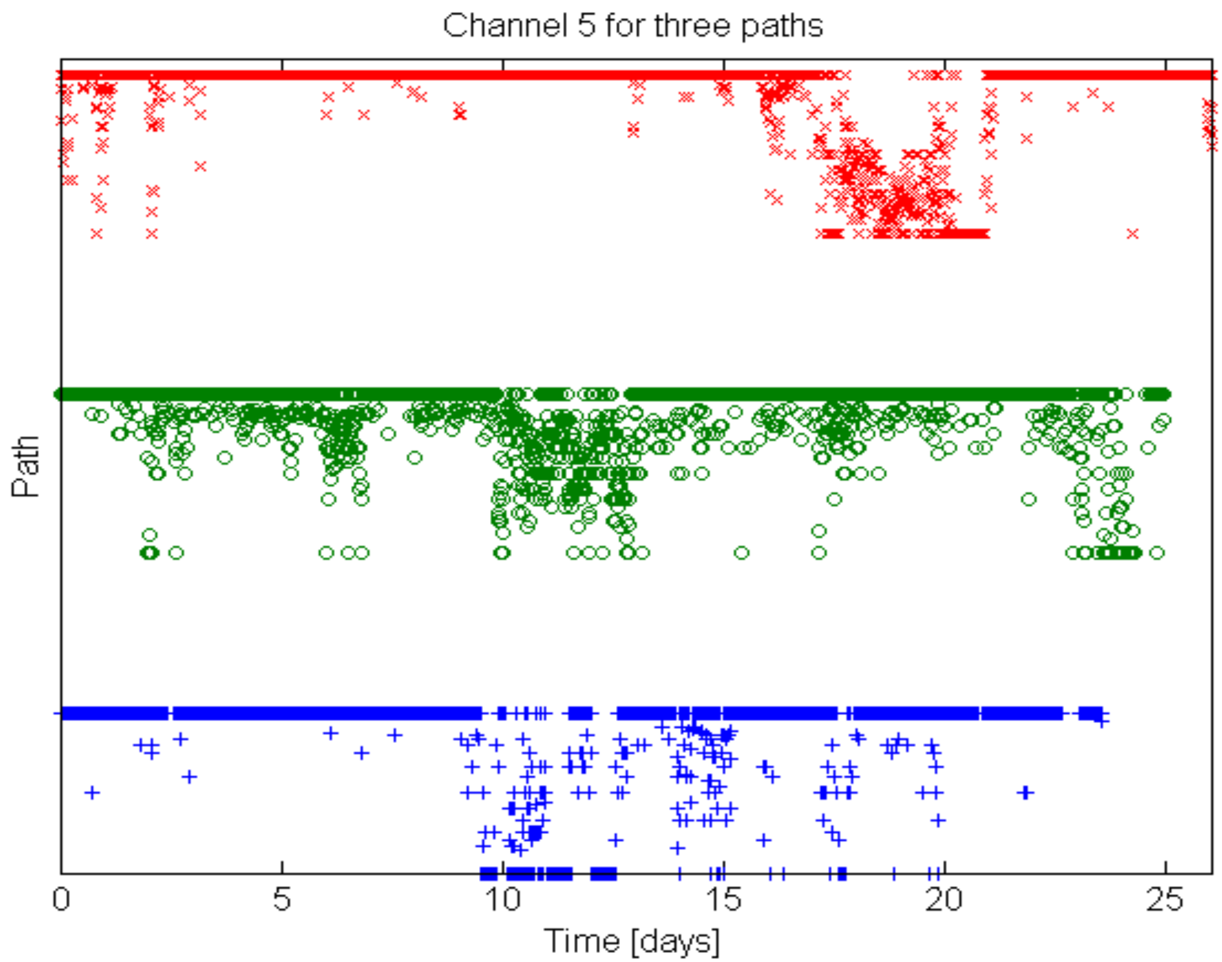
2.48GHz



2.40GHz

[1] "Time Slotted, Channel Hopping Field Experience", Pister et al., presentation of contribution IEEE 802.15-08-0583-02-004e

Three Paths - Channel 5 Over 26 Days



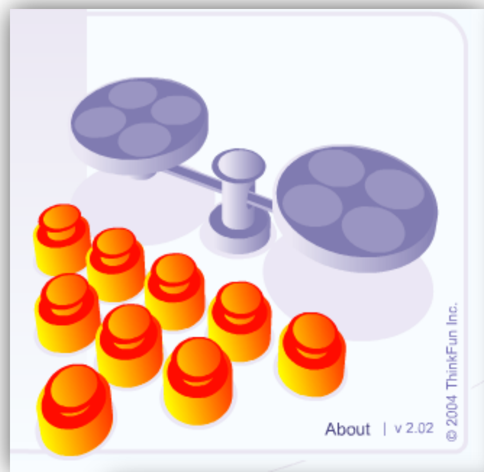
[1] "Time Slotted, Channel Hopping Field Experience", Pister et al., presentation of contribution IEEE 802.15-08-0583-02-004e

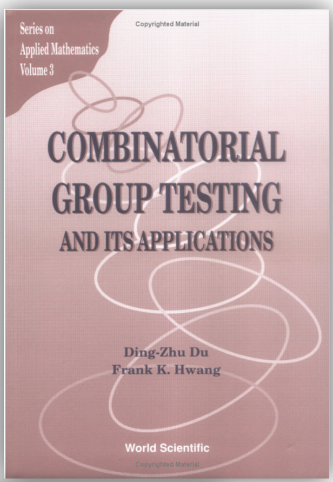
Group Testing

- Group Testing
- http://www.puzzles.com/PuzzlePlayground/HeavyWeight/HeavyWeight.htm
- Combinatorial mathematics
- Group Testing for Random Access:
  - Hayes 1978 [1], applied to polling: “Probing”
  - Also, Wolf 1985 [2]

Example test plan

4 nodes, x_i: “has packet”

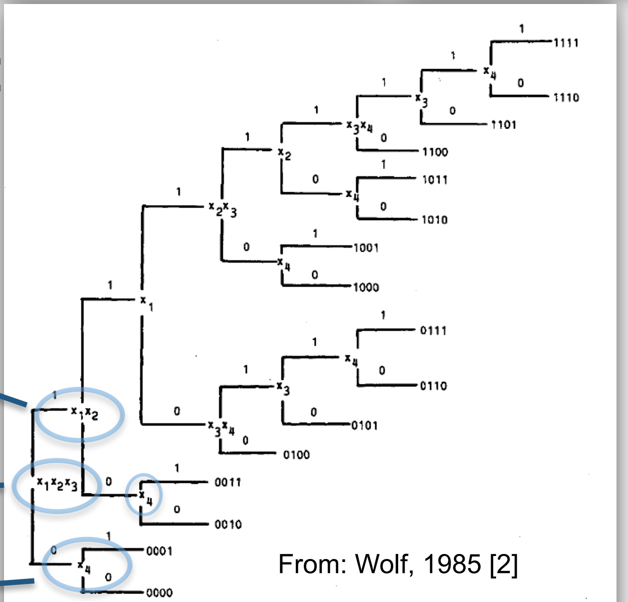




x_1 & x_2

x_1 & x_2 & x_3

x_4

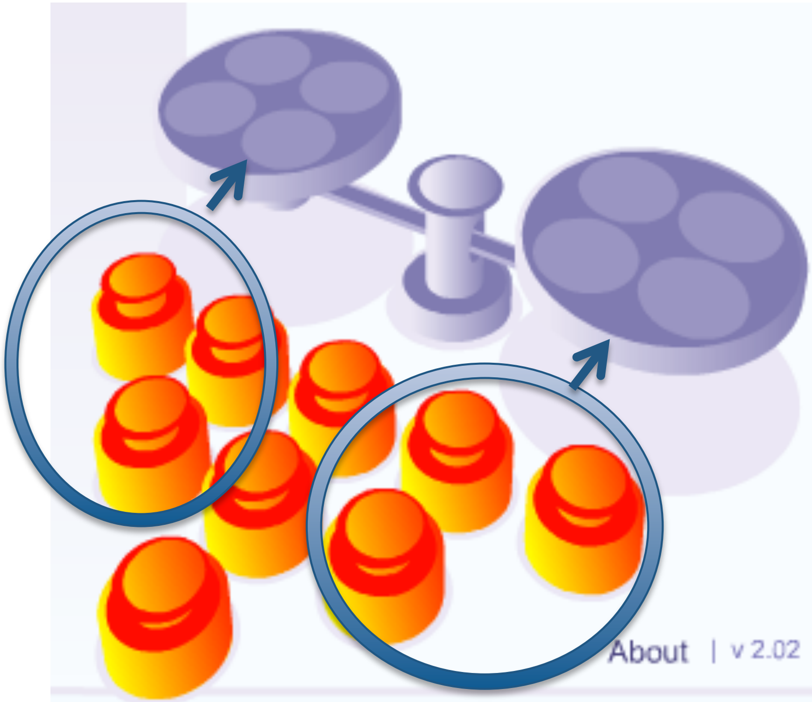


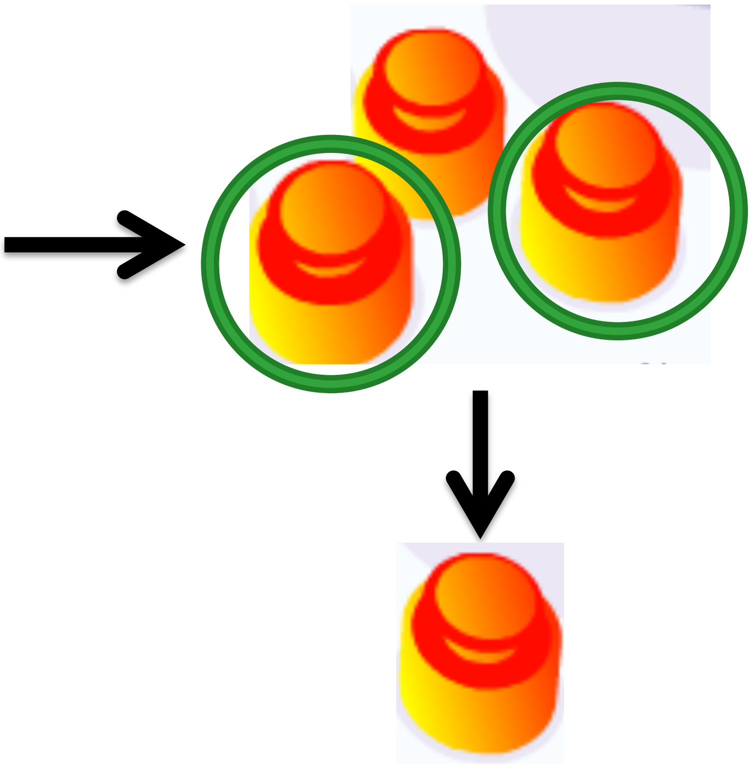
From: Wolf, 1985 [2]

Fig. 1. A specific test plan.

[1] Hayes, J. F. "An adaptive technique for local distribution." IEEE Transactions on Communications 26.8 (1978): 1178-1186.
[2] Wolf, Jack. "Born again group testing: Multiaccess communications." IEEE Transactions on Information Theory 31, no. 2 (1985): 185-191.

Group Testing



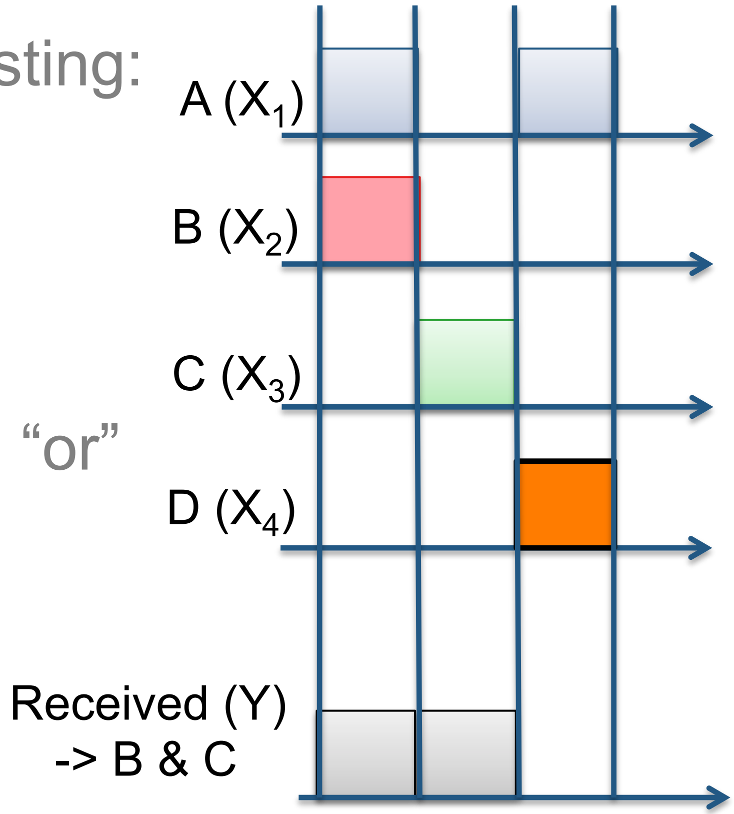


Neighbor Discovery with Group Testing

- Test neighborhood with group testing:
  Luo & Guo 2008 [1]

$$\boldsymbol{Y} = \underline{\boldsymbol{S}}\,\boldsymbol{X}$$

- where X is sparse and addition = “or”
- Error vs transmission cost
  - Number of nodes: *K*
  - Error: $O(K^{-1})$
  - Message size: $L = 4(\log K)^2 \log\log K$



[1] Luo J, Guo D. “Neighbor discovery in wireless ad hoc networks based on group testing”. In IEEE Communication, Control, and Computing, 2008 46th Annual Allerton Conference on 2008 Sep 23 (pp. 791-797).

Neighbor Discovery with Compressive Sensing

- Specific sequences, in Guo&Zang, 2011 [1,2]
  - Second-order Reed-Muller code (good for sparse recovery)
  - Decoding with a chirp reconstruction algorithm
  - More realistic channel model: $\boldsymbol{Y} = \sqrt{\gamma}\,\underline{\boldsymbol{S}}\boldsymbol{X} + \boldsymbol{W}$
  - Example: 1,000,000 nodes, 30 neighbors, <u>sequence of 4096 symbols</u>

    99.9% accuracy (at 16 dB SINR)
- FlashLinQ technology [3]
  - Based on OFDM,
  - Neighbor discovery over a large number of orthogonal time-frequency slots
- Linked with multi-user detection

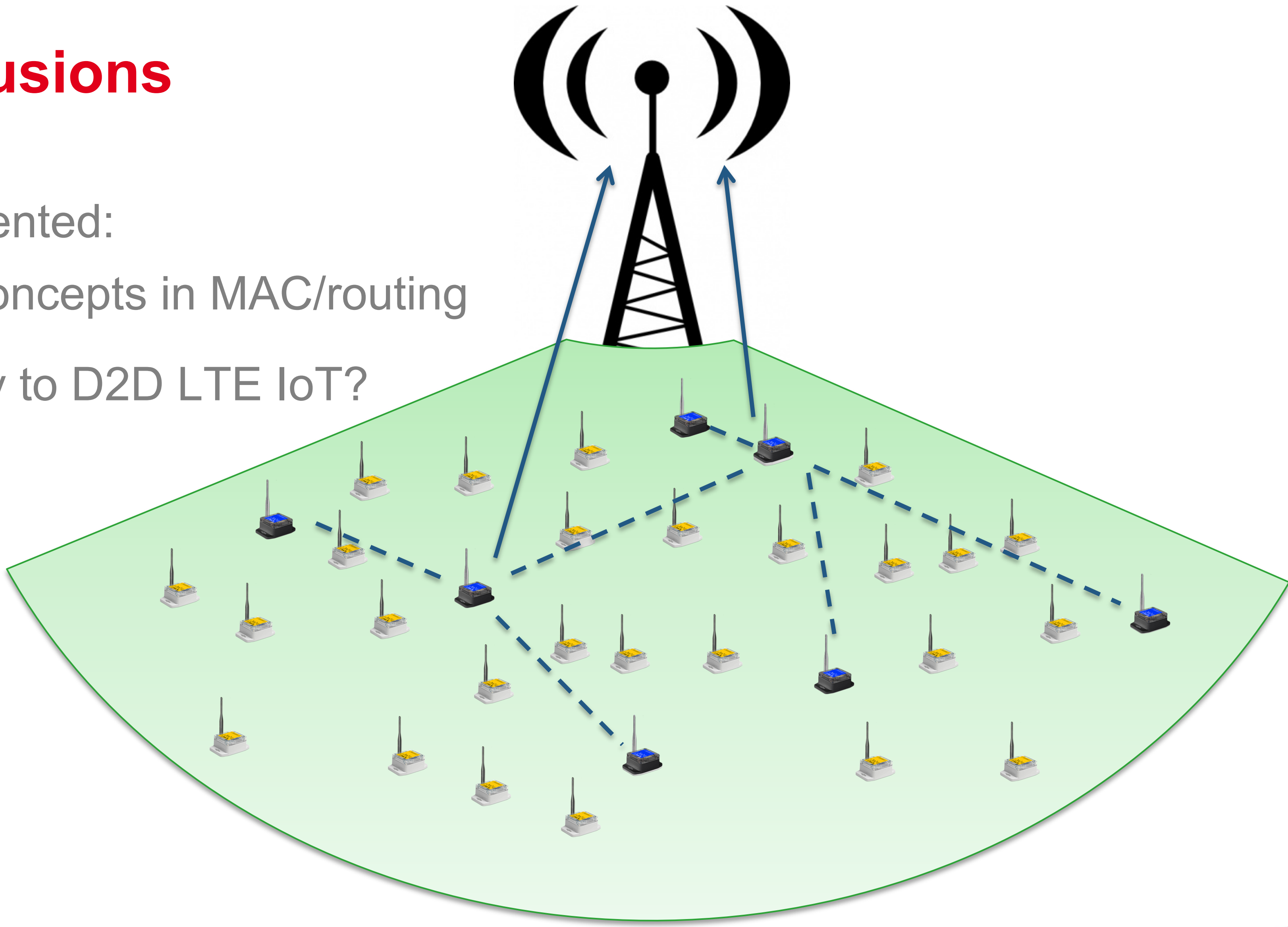
[1] Zhang L, Luo J, Guo D. "Compressed neighbor discovery for wireless networks". Preprint, http://arxiv. org/abs/1012.1007. 2010.

[2] Zhang, L. and Guo, D., 2011, May. "Neighbor discovery in wireless networks using compressed sensing with Reed-Muller codes". In Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt), 2011

[3] Wu X, Tavildar S, Shakkottai S, Richardson T, Li J, Laroia R, Jovicic A. FlashLinQ: A synchronous distributed scheduler for peer-to-peer ad hoc networks. IEEE/ACM Transactions on Networking (TON). 2013 Aug 1;21(4):1215-28.

Conclusions

- Presented:
  - Concepts in MAC/routing
- Apply to D2D LTE IoT?



[1] Zihan, E., Choi, K. W., & Kim, D. I. (2015). "Distributed random access scheme for collision avoidance in cellular device-to-device communication". *IEEE Transactions on Wireless Communications*, *14*(7), 3571-3585.

Thank you, धन्यवाद !

Questions?