Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: [Mesh PAN Alliance (MPA)]

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Re: [IEEE P802.15.5 WPAN MESH Networking Call For Proposals IEEE 802.15-5/0071, January 2005]

Abstract: [The document describes a distributed, decentralized Mesh WPAN MAC proposal.]

Purpose: [Decentralized technology is an important aspect for future Mesh networks. We identify major issues in current wireless technology and present a distributed approach that supports a high speed Mesh WPAN.]

This version has been edited for publication as PDF file at ComNets, RWTH Aachen University.

Some animations may not be displayed correctly in PDF format.

Please see http://802wirelessworld.com for the original version in PowerPoint format.

Mesh PAN Alliance (MPA)

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Overview

- Radio propagation basics
  - Interference range
  - Carrier over Interference ratio
  - Reception range
  - Hidden nodes
  - RTS/CTS handshake
  - Exposed nodes
- Mesh PAN Alliance
  - Superframe structure
  - Beacon Period
  - Data Transmission Period
  - Frame Aggregation
  - Multi-Channel extension

Radio wave propagation

- Received (Rx) power (P_{Rx})
  - Transmitter (Tx) power @ isotropic antenna ($P_{Isotrop}$)
  - Non free space attenuation (α)
- g_{Rx}, g_{Tx} antenna gain (compared to isotropic antenna)
- Attenuation
  - Distance (d)
  - Frequency (f_c)

$$P_{Rx} = \frac{P_{Isotrop} * g_{Tx} * g_{Rx} * \alpha}{d^2} * \left(\frac{c}{f_c * 4\pi} \right)^2$$

General path loss

- Let
  - $P_{Tx} = \beta * P_{Isotrop}$
    - β, Antenna form factor
  - $d^{2-\gamma} = \alpha * \beta * g_{Tx} * g_{Rx}$
    - γ, generalized damping factor
- $\gamma = 2$
  - Free space, isotropic radiation
  - Theoretical value & far distances
  - Line of Sight (LOS)
- $\gamma > 2$
  - More realistic
  - Non LOS
  - Indoor
  - Valid for one location tuple (x,y,z) only

$$P_{Rx} = \frac{P_{Tx}}{d^{\gamma}} * \left(\frac{c}{f_c * 4\pi} \right)^2$$

Noise

- Random process
  - Boltzmann constant, k_B
  - Temperature (here: 300K)

$$P_N = k_B T * \Delta f$$

$$N(dBm) = 10 * \log_{10}(\frac{P_N}{10^{-3} W})$$

Carrier over interference ratio (CoI)

- Carrier (C) = $P_{Rx,\ wanted}$
- Interference (I) = $P_{Rx,\ unwanted,\ i}$
  - i interferer
  - Noise (N)

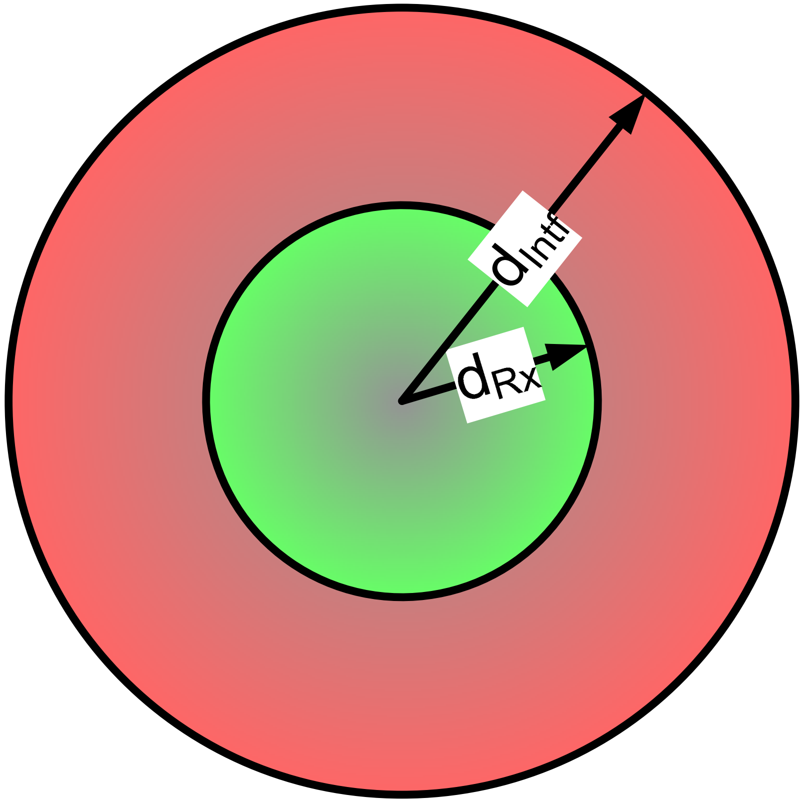
$$i \in \mathbb{N}_0 \qquad CoI = \frac{C}{N + \sum_i I}$$

Reception and intereference range

- Tx power defines interference range
- P_{Rx} & CoI define Rx range

$$d_{Intf} = w * d_{Rx}$$

$$w \gg 1$$

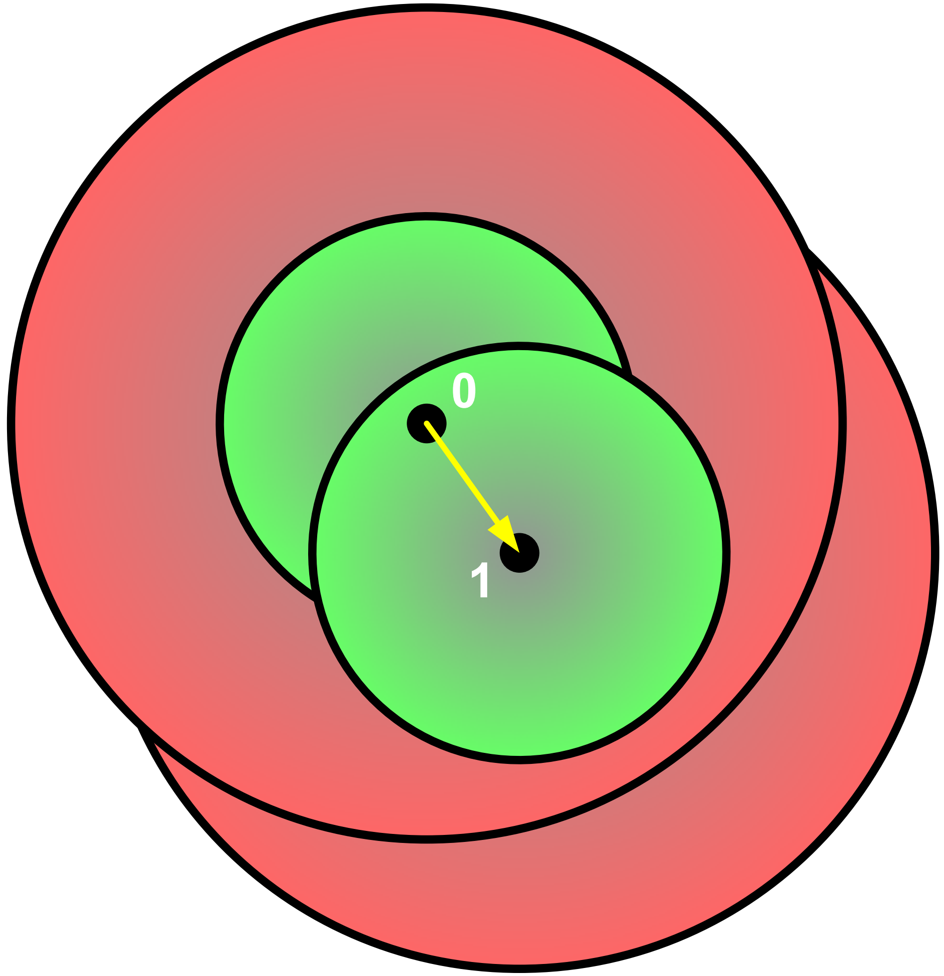


Limitations in Mesh networks

- Hidden nodes
  - Devices unaware of current neighbors receiving data
  - Collisions
  - Mutual interference
- Exposed nodes
  - Devices unaware of their position relative to receiver
  - Concurrent transmission in same time period possible but unused
  - Inefficient spatial frequency reuse

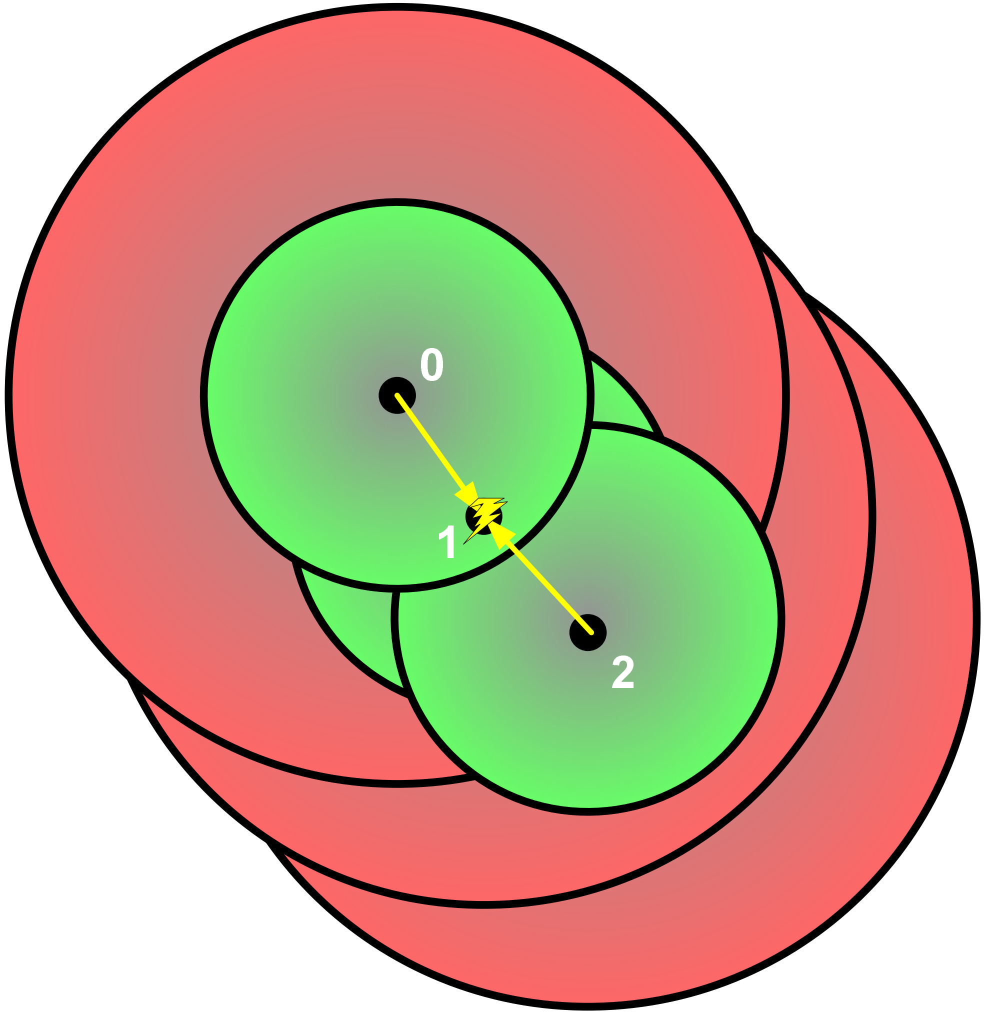
Example set-up

- Device 0 = transmitter
- Device 1 = receiver
- Rx range
- Interference range



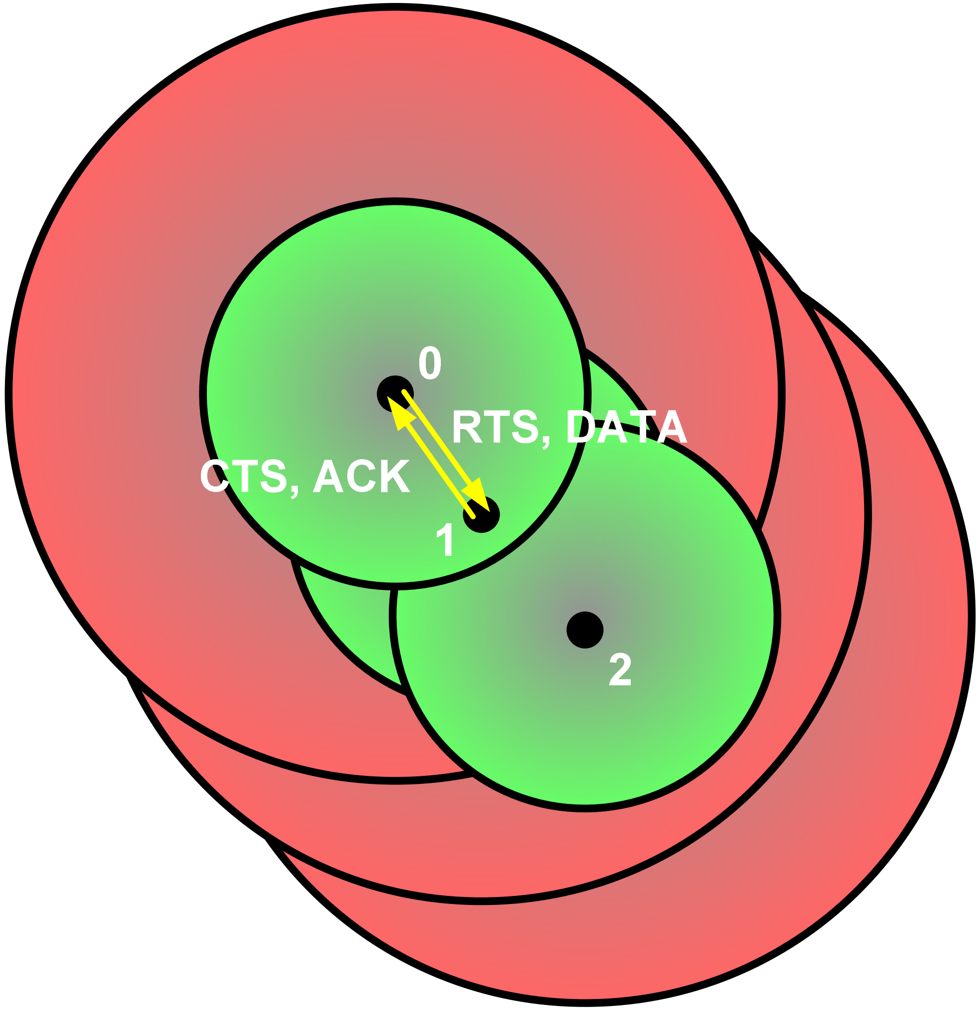
Hidden nodes

- Concurrent transmission of device 0 & 2
- Collision at device 1



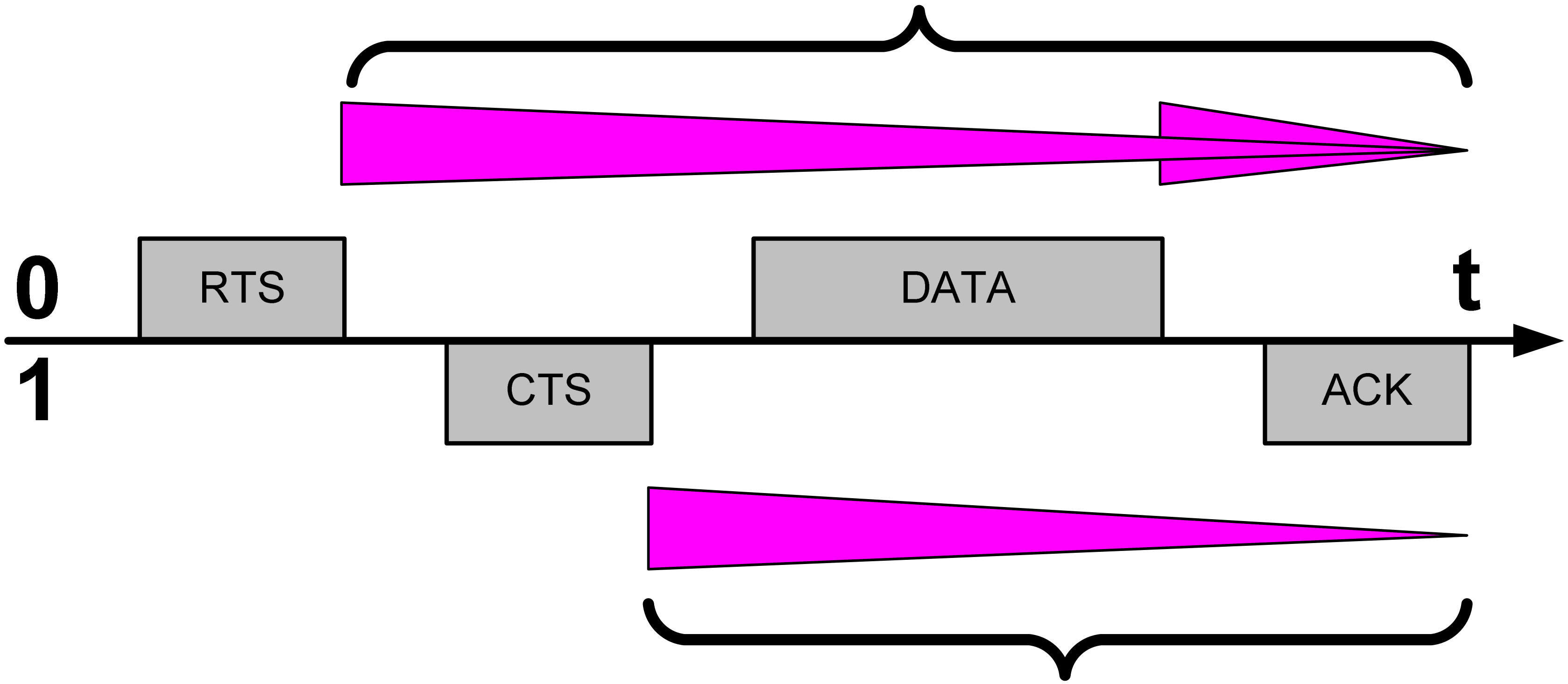
Hidden Nodes: RTS/CTS handshake

- Handshake
  - Request to Send (RTS)
  - Clear to Send (CTS)
- Provide information on duration of upcoming DATA transmission



RTS/CTS

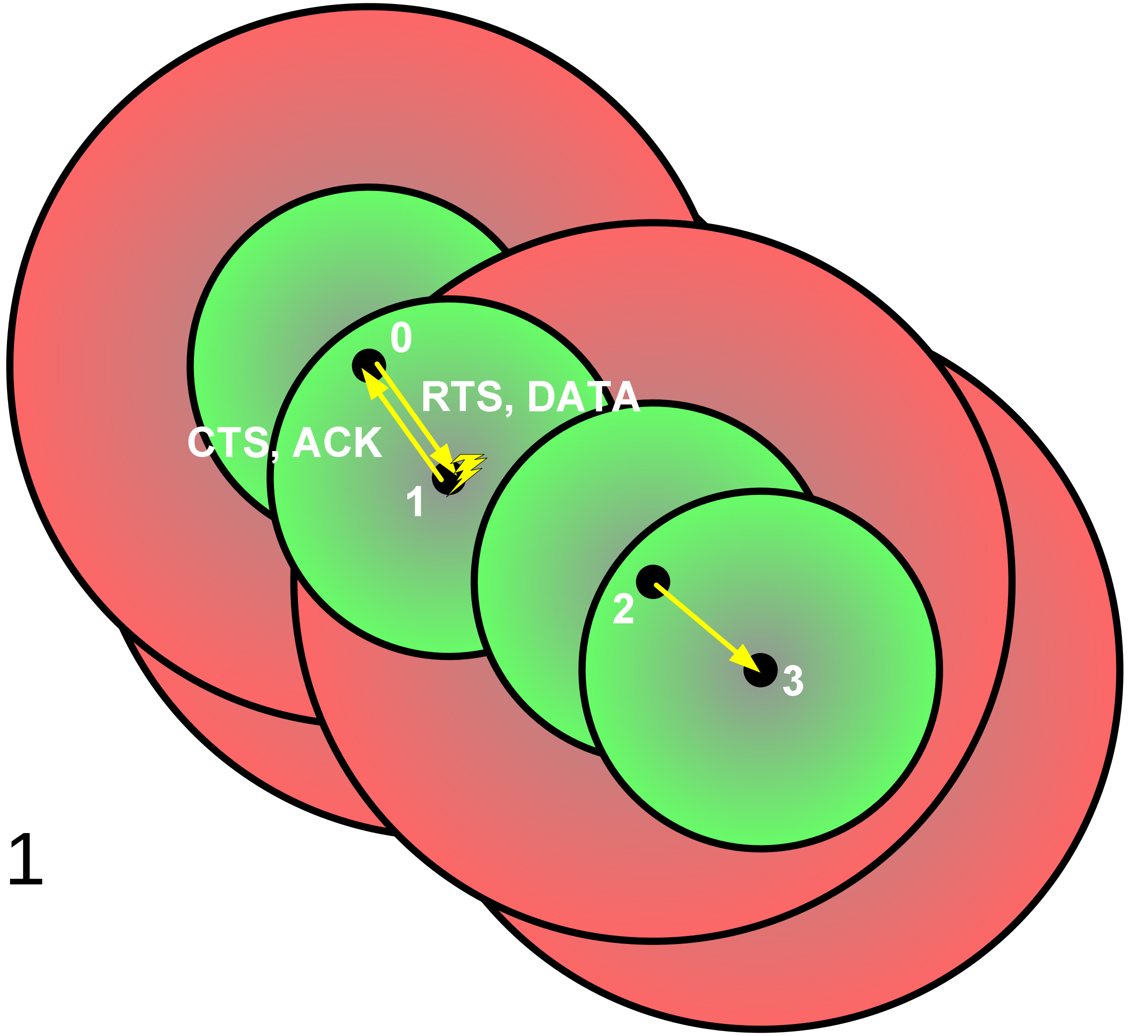
RTS informs devices around transmitter (0) about duration of the following data exchange incl. Acknowledgment (ACK). DATA informs about ACK duration.



CTS informs devices around receiver (1) about duration of the following data exchange including Acknowledgment (ACK).

RTS/CTS drawbacks

- Interference range >> Rx range
  - RTS/CTS not received at 2
  - Transmission from 2 to 3 interferes 0 to 1

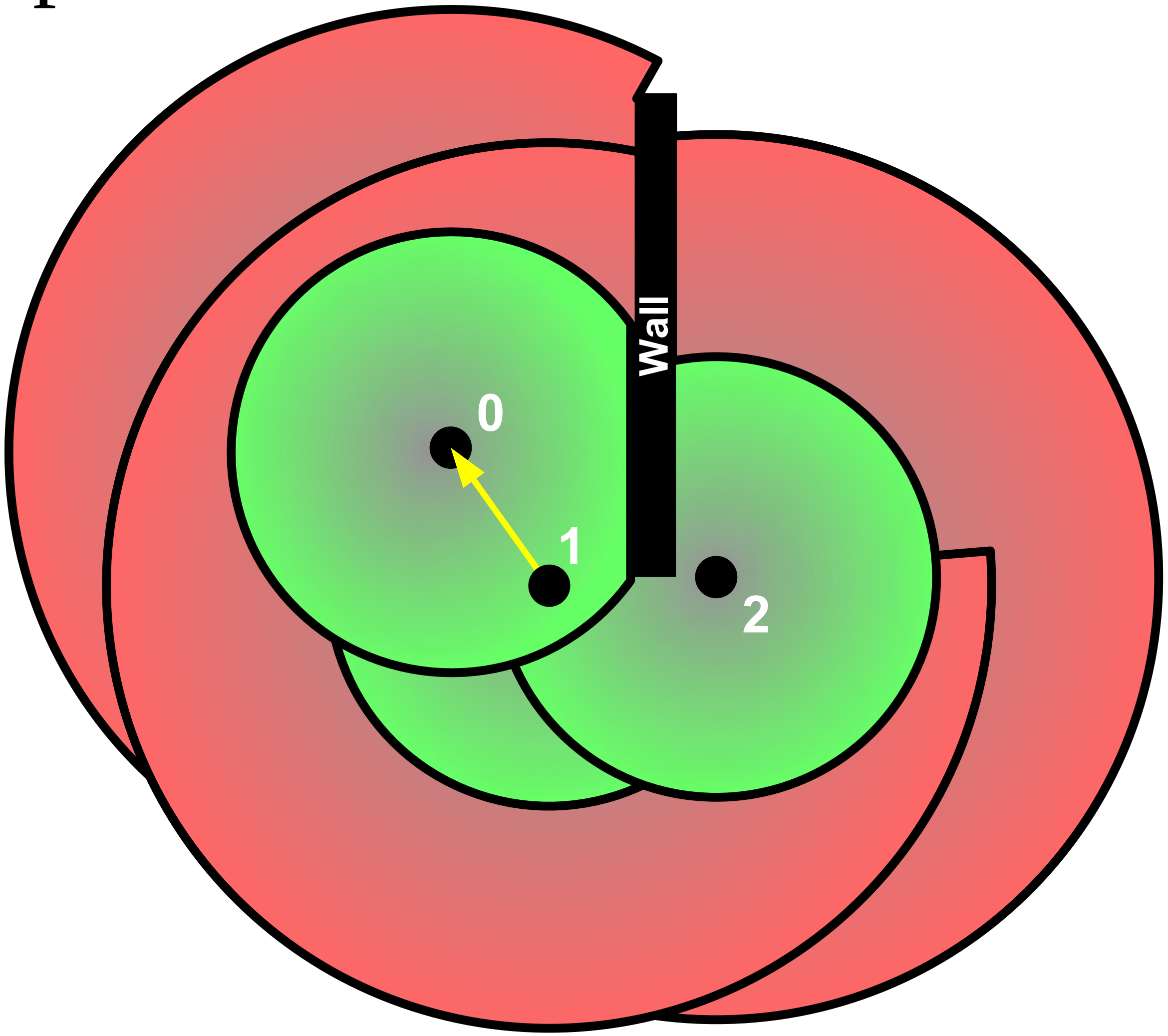


Hidden nodes: Conclusions

- Simple handshake not sufficient
  - Differences in Rx and interference range
  - RTS/CTS itself may collide
- Additional carrier sensing not sufficient
- Severe problem in Mesh networks
  - Device density high
  - Non-Mesh MAC unaware of neighbors' neighbors

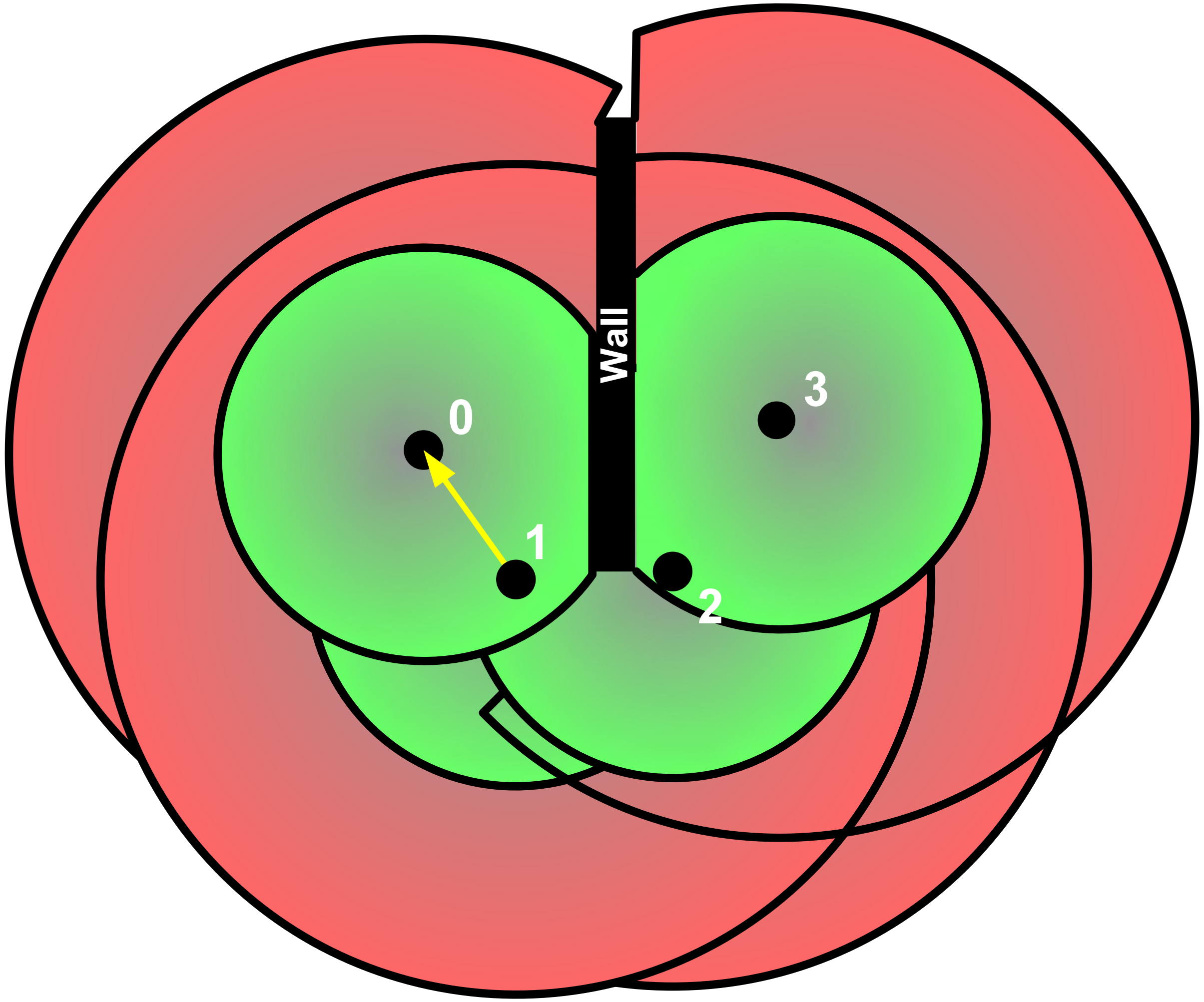
Exposed nodes

- Device 0 & 2 mutually hidden
  - Interference impossible
- Device 1 transmits to 0



Exposed node problem

- Tx from 2 to 3 possible
  - No inter-ference to 0
- RTS/CTS prevents tx from 2



Exposed nodes: Conclusions

- RTS/CTS handshake blocks large area
- Additional channel sensing not sufficient
  - Devices cannot differentiate between rx and tx device
- Severe capacity waste in Mesh networks
  - Low spatial frequency reuse
  - Large area blocked by single transmission

Mesh network capacity

- Limited by mutual interference
  - Severe problem
  - Exposed nodes
  - Hidden nodes
- Solution needed

→ Interference awareness

→ Interference horizon

Mesh PAN Alliance

Philips Research Laboratories
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MAC design

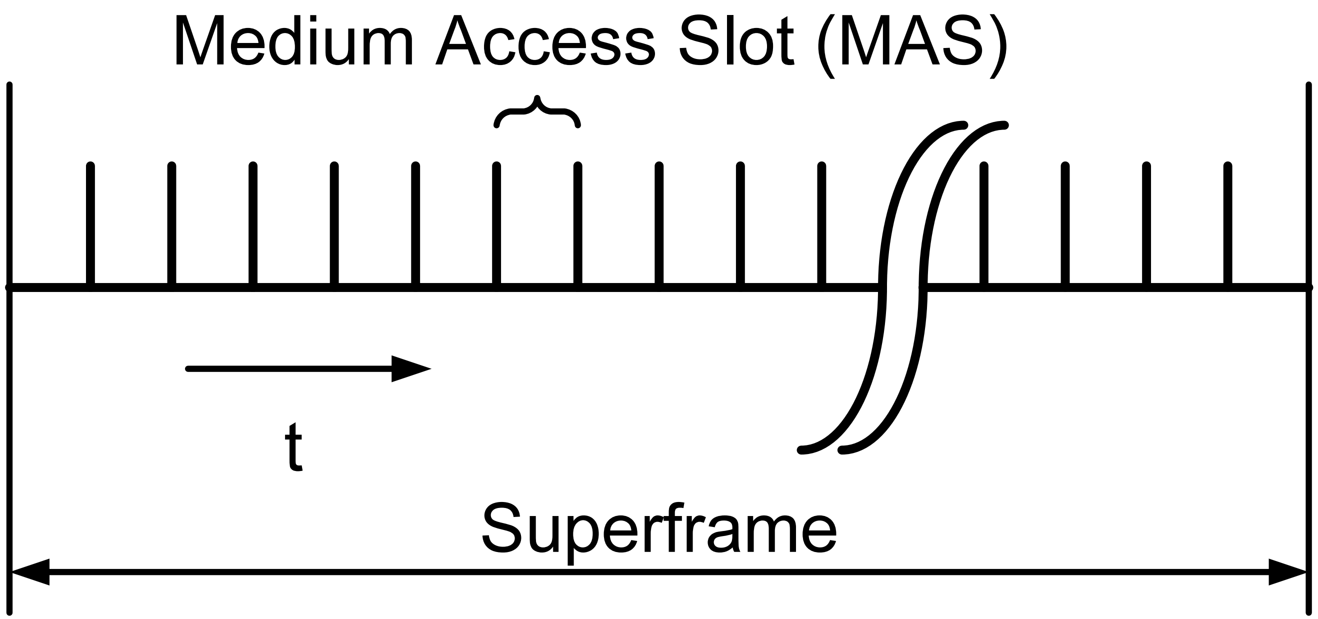
http://mpa.comnets.rwth-aachen.de

Mesh WPAN design criteria

- High speed WPAN
  - High throughput
  - Low latency
- Easy set-up
- Cheap devices
  - Single transceiver/radio solution
- Decentralized
- Data services
  - Isochronous
  - Asynchronous
- High spatial frequency reuse
  - Support for single/multiple frequency

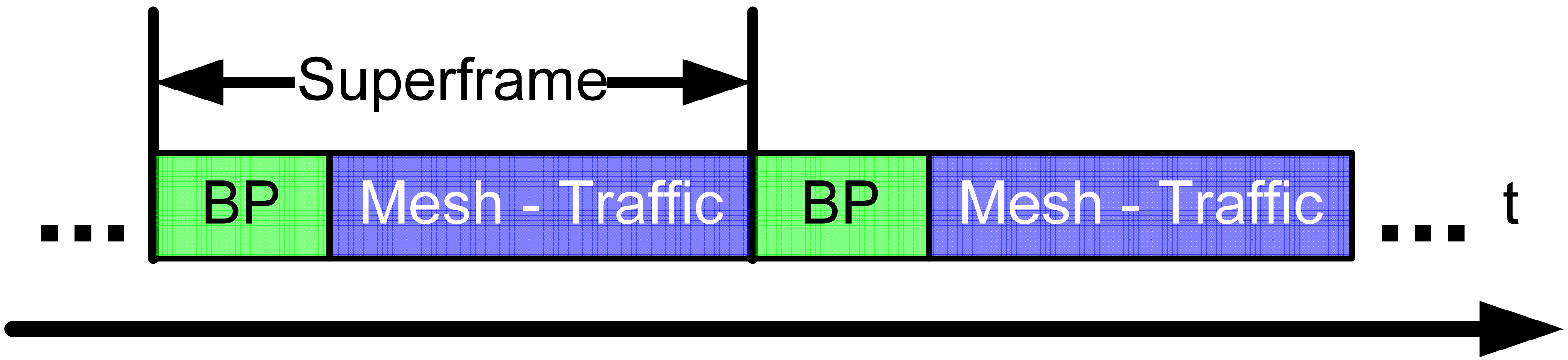
Timing structure

- Superframe
  - Slotted structure
- Medium Access Slots (MAS)



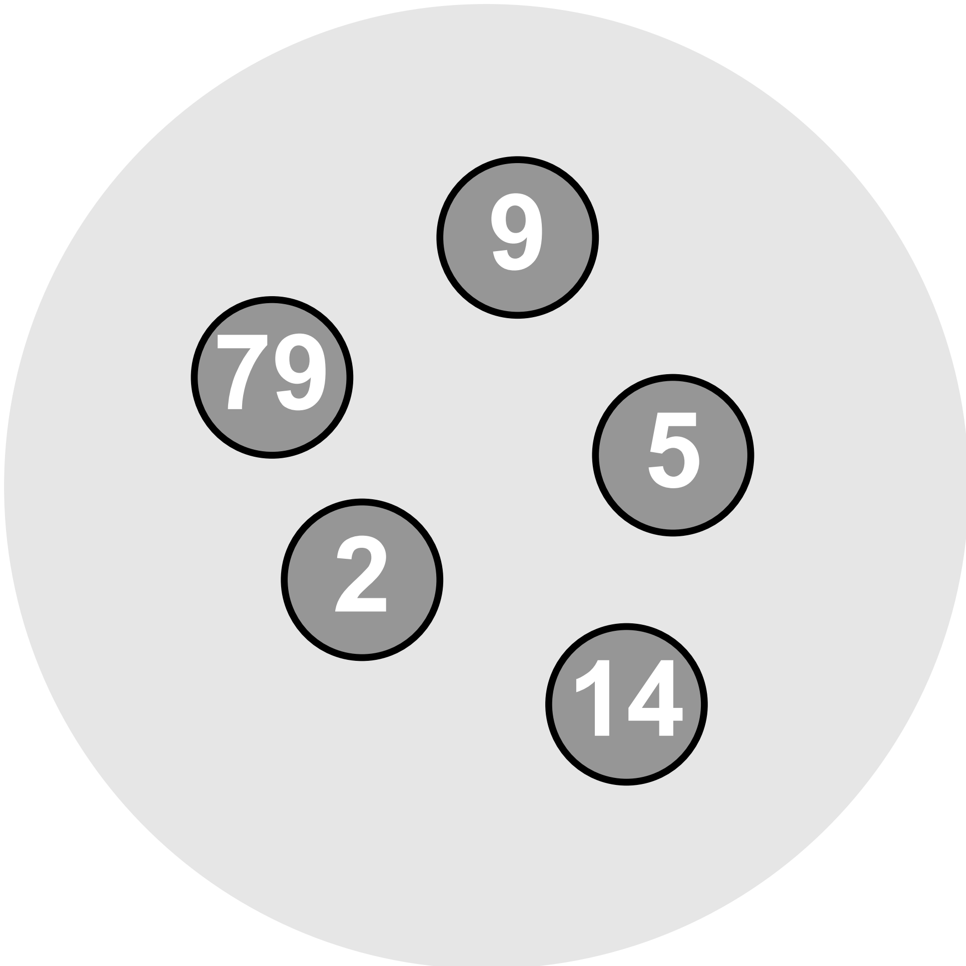
Superframe structure

- Beacon Period (BP)
  - Network and topology management
- Mesh Traffic Period (MTP)
  - Data exchange



Example setup

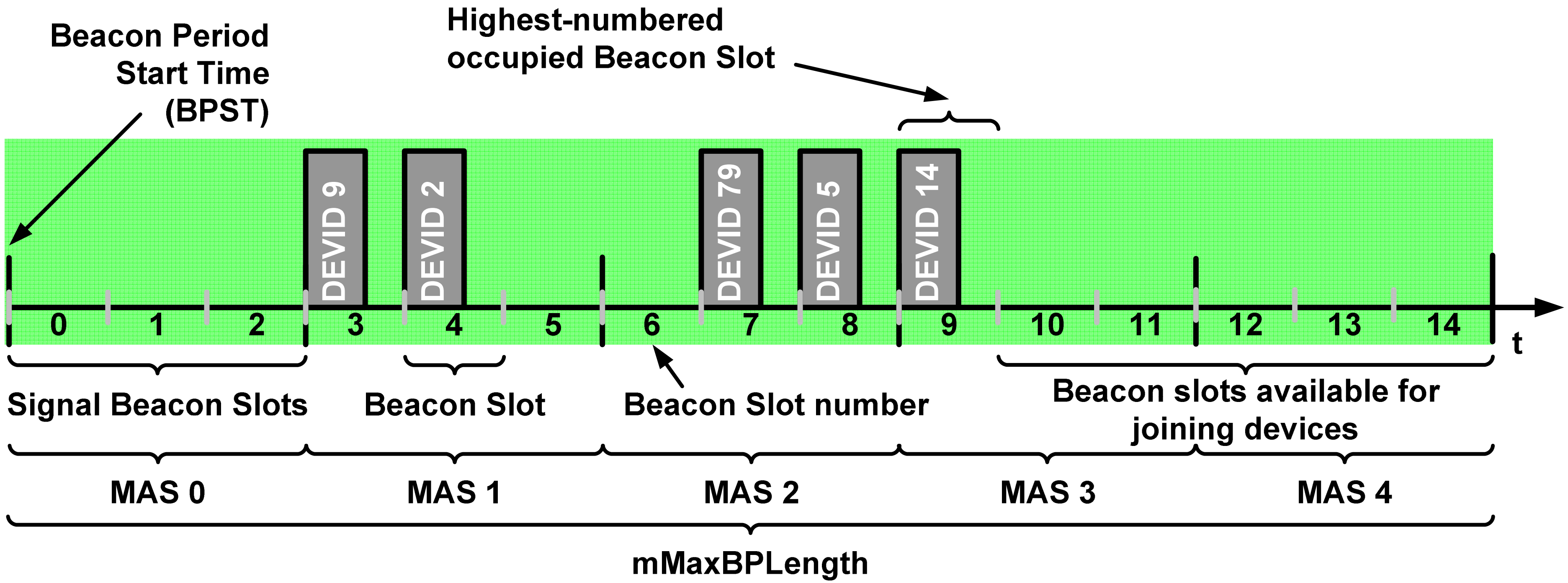
- 5 devices in mutual rx range
- Device ID as indicated



Beacon Period (BP)

Beacon Period

- Used for coordination
- Every device transmits beacon

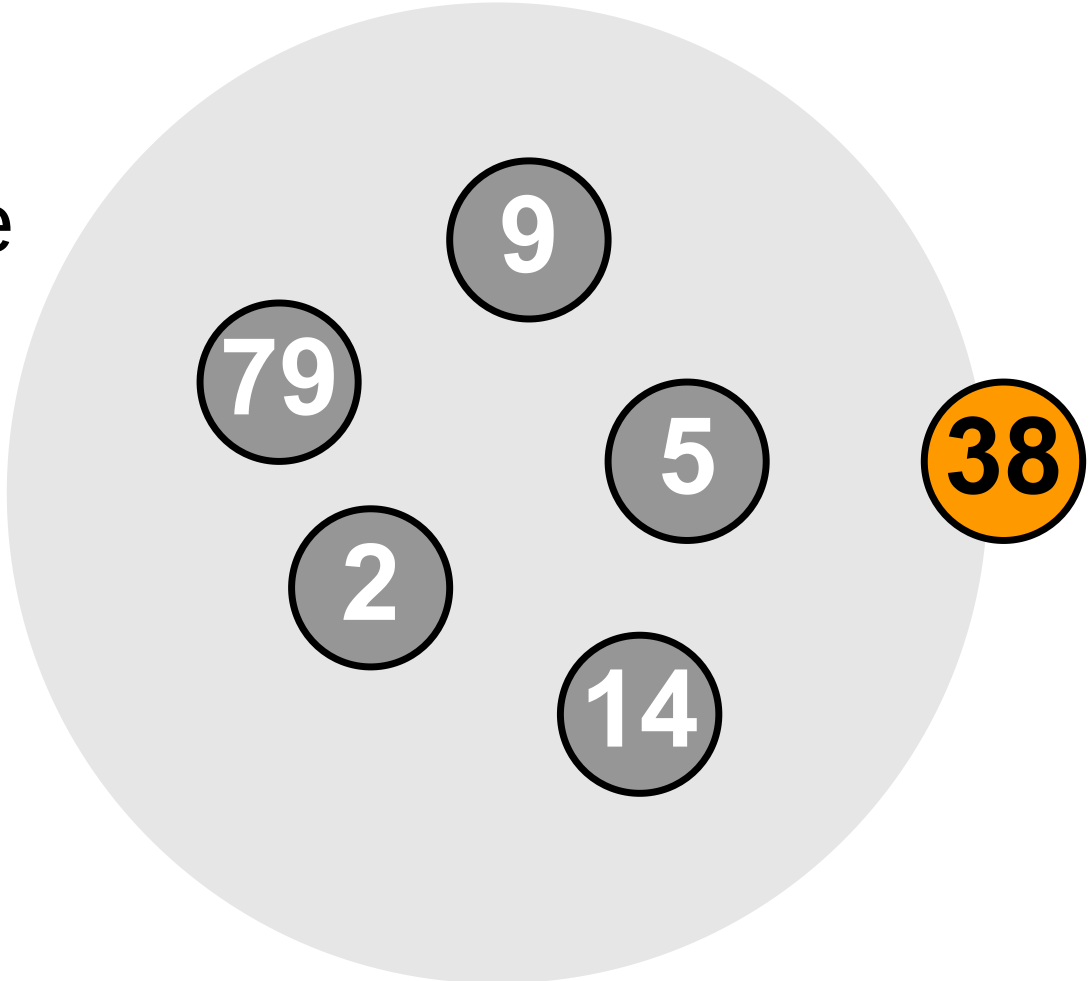


Beacon Period (BP)

- Three Beacon slots per Medium Access Slot (MAS)
  - Beacon size may vary
  - Adaptive Beacon protocol allows flexible number of beacons per MAS
- Beacon carry
  - Device ID
  - Synchronization information
  - Neighborhood information
  - Neighbor‘s neighbors
  - Medium Access Information

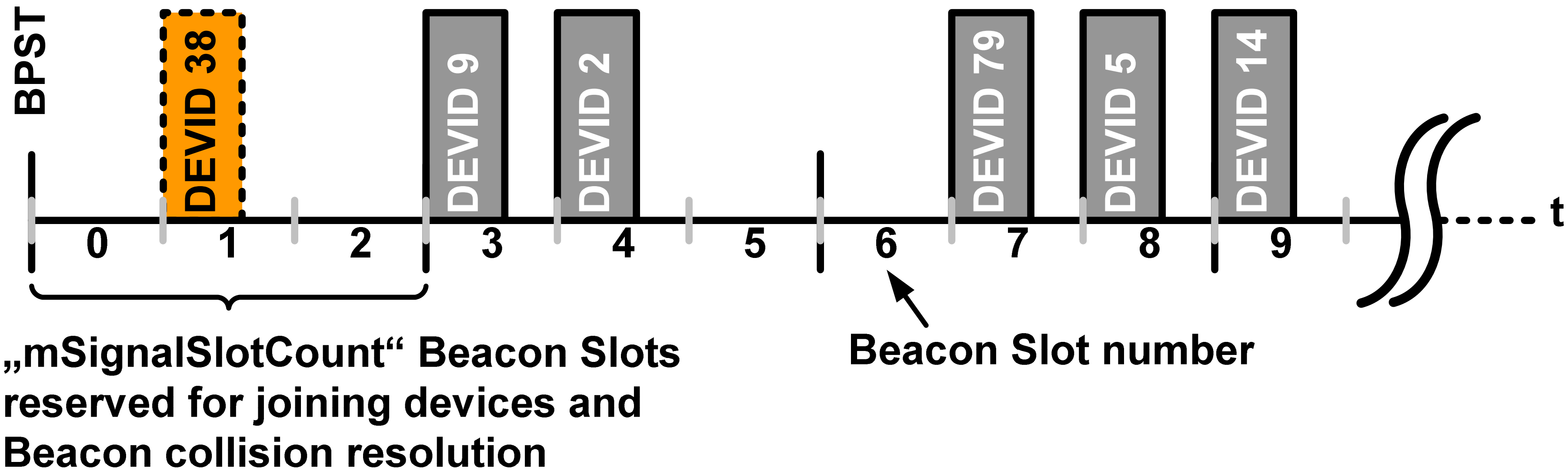
New device joining a group

- Device 38 enters rx range of a group
- 38 scans for beacons
- Select empty beacon slot



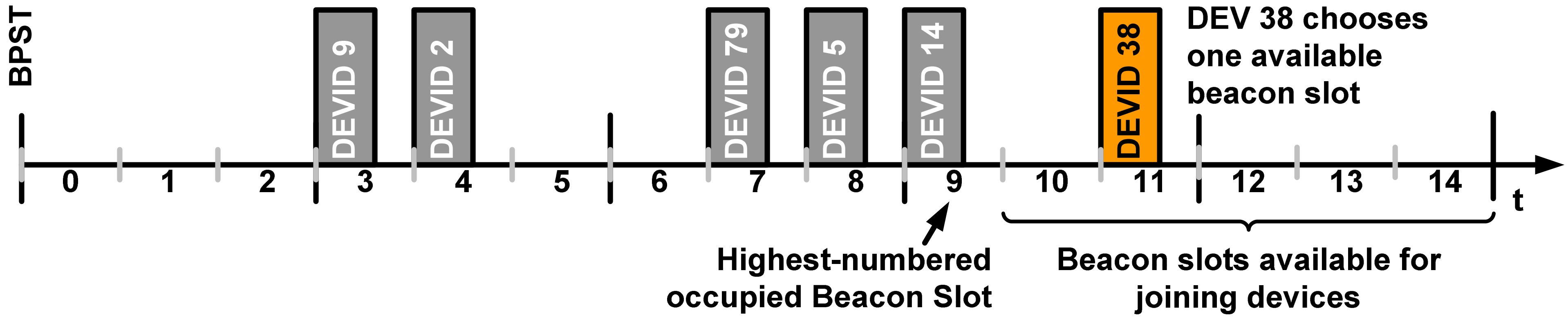
New devices joining Beacon Period

- Device 38 indicates presence in announcement period
- Several slots empty for joining devices



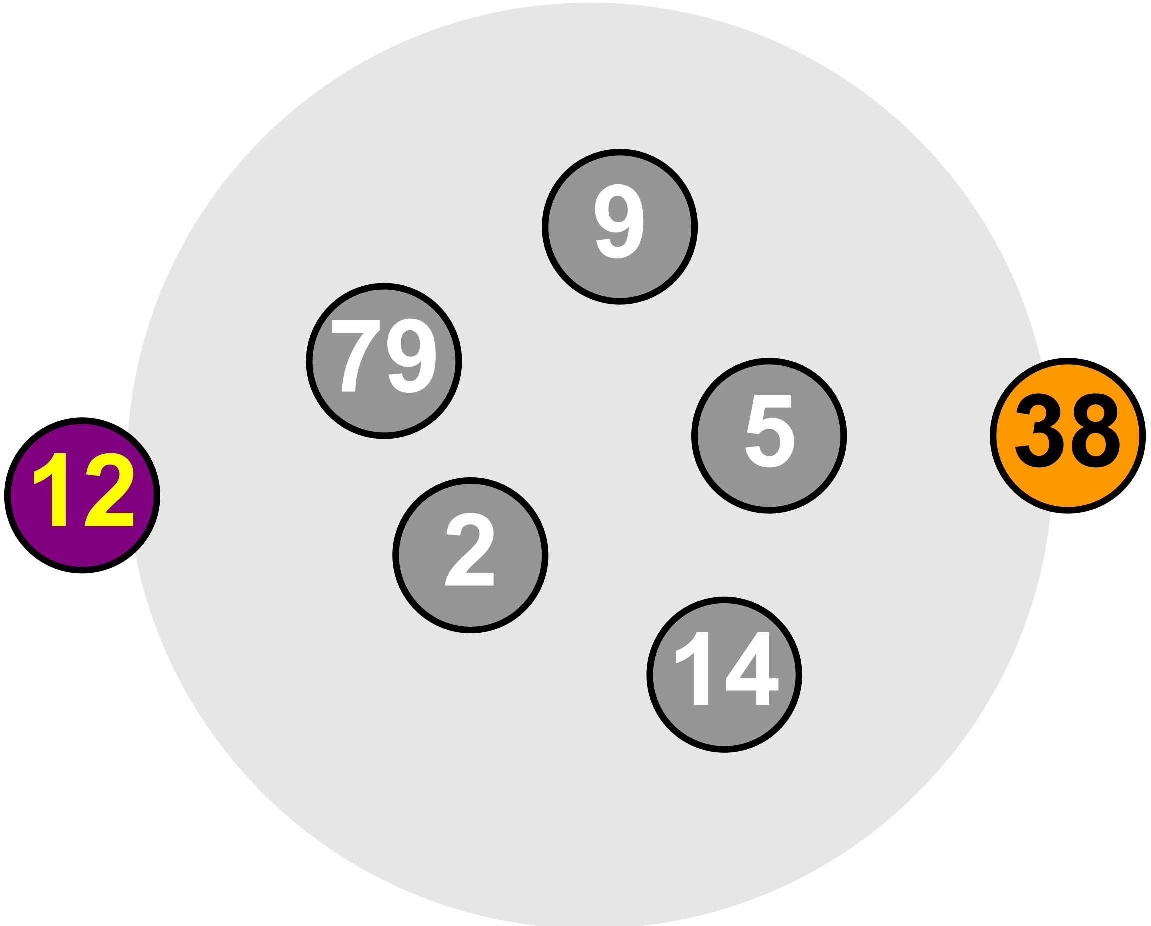
Final beacon period occupancy

- Devices 38 selects final beacon slot
- Neighbors provide knowledge about
  - Empty slots
  - Beacon Period duration



Example setup with hidden node

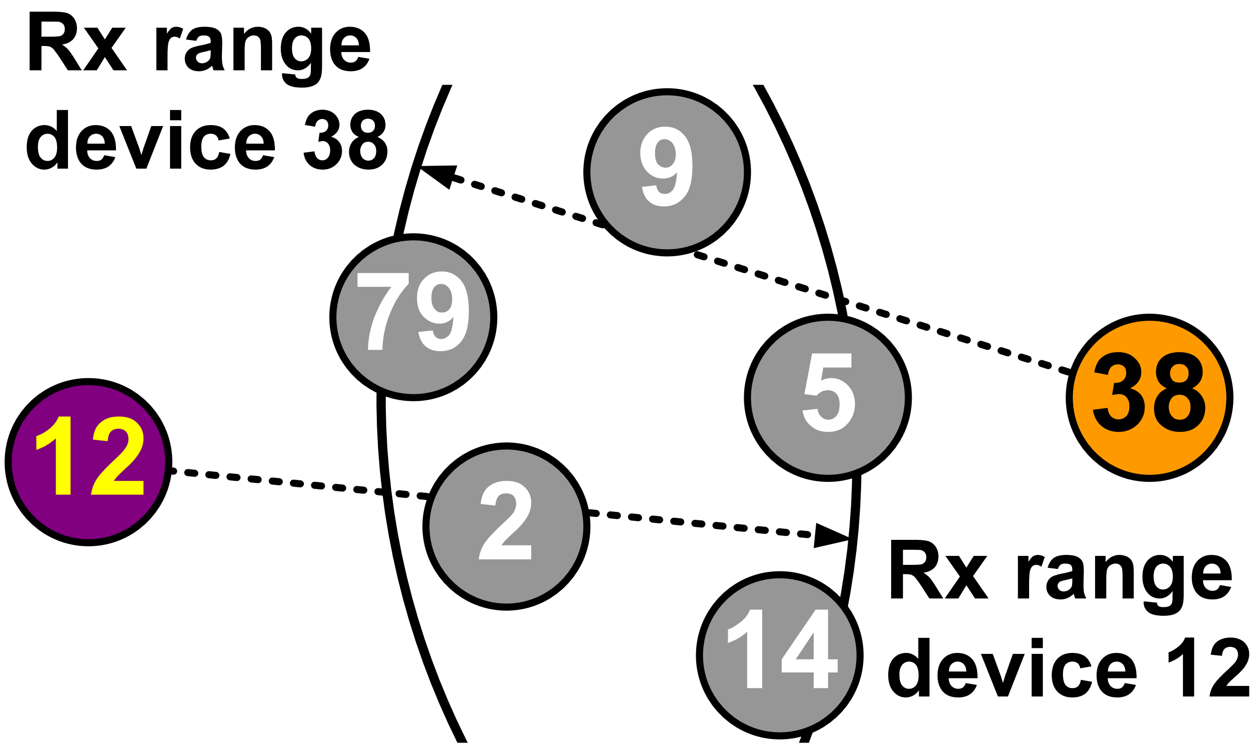
- 12 & 38 mutually cannot rx each other
- Mutual interference possible



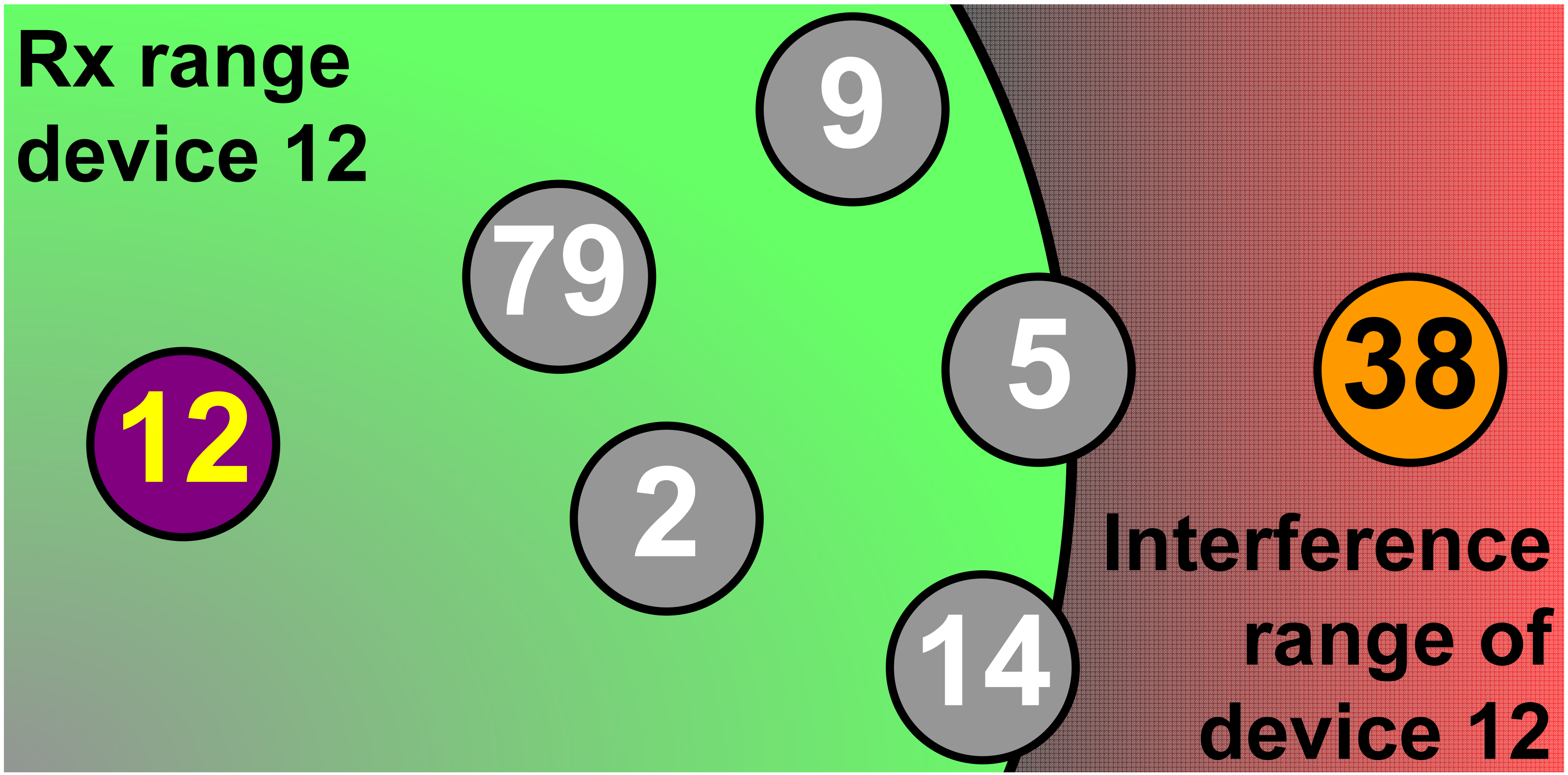
Neighborhood information

Example

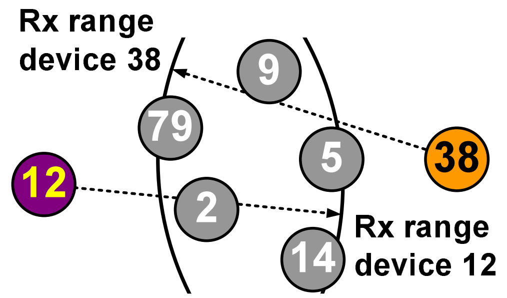
- 12 & 38 mutually hidden
- Common neighbors

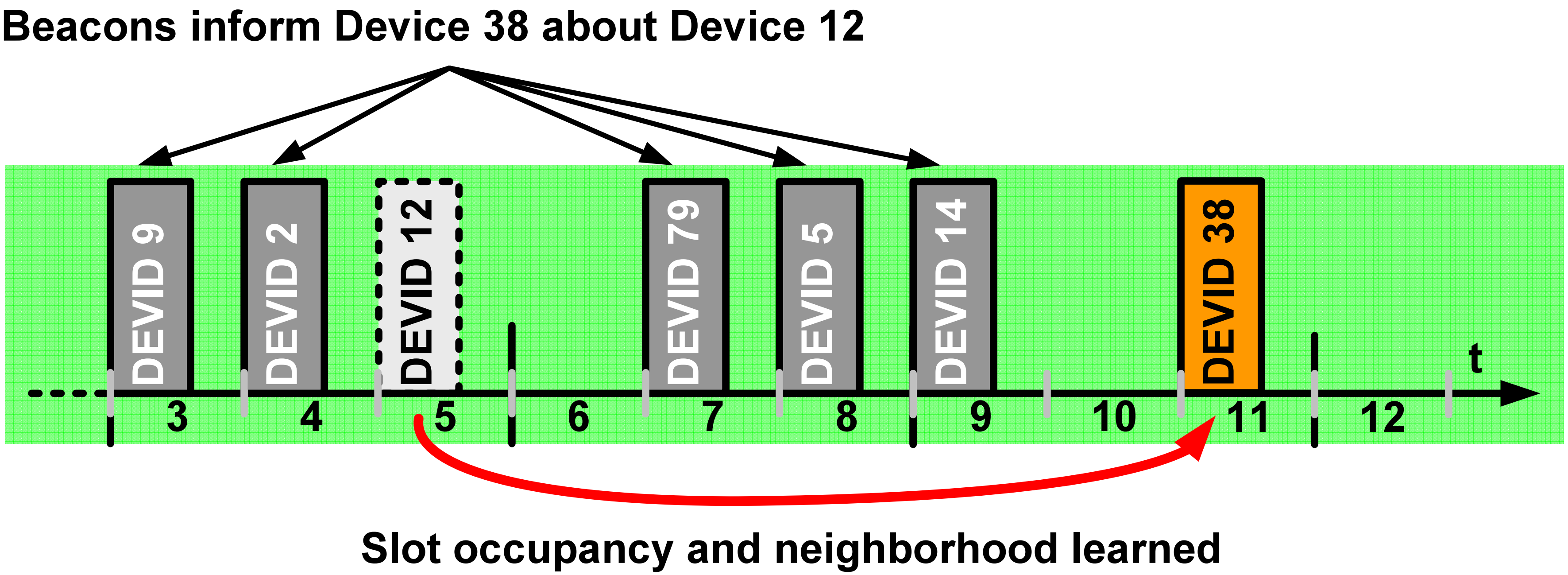


Rx & interference range of device 12

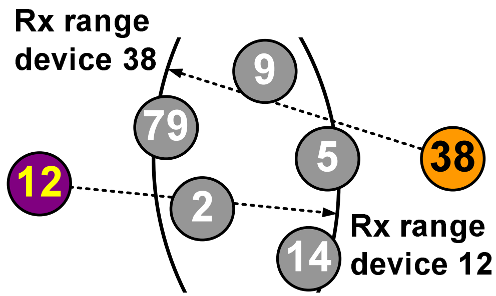


Neighborhood as seen by device 38

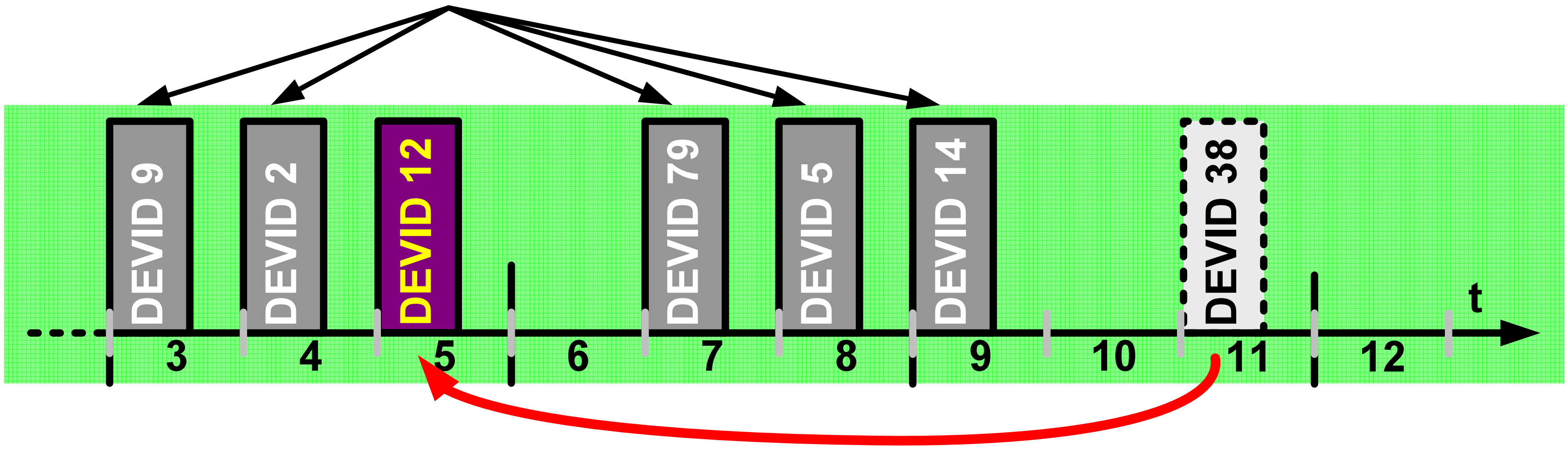




Neighborhood as seen by device 12



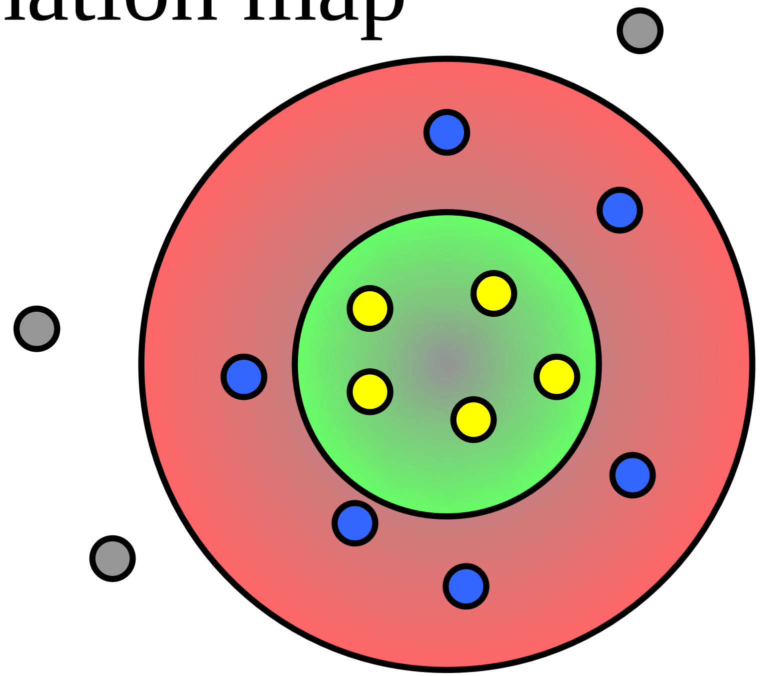
Beacons inform Device 12 about Device 38



Slot occupancy and neighborhood learned

Neighborhood information map

- Beacons send at most robust PHY mode
  - – Reception close to interference range
- Devices store neighborhood information
- → Neighborhood table



Devices in Rx range

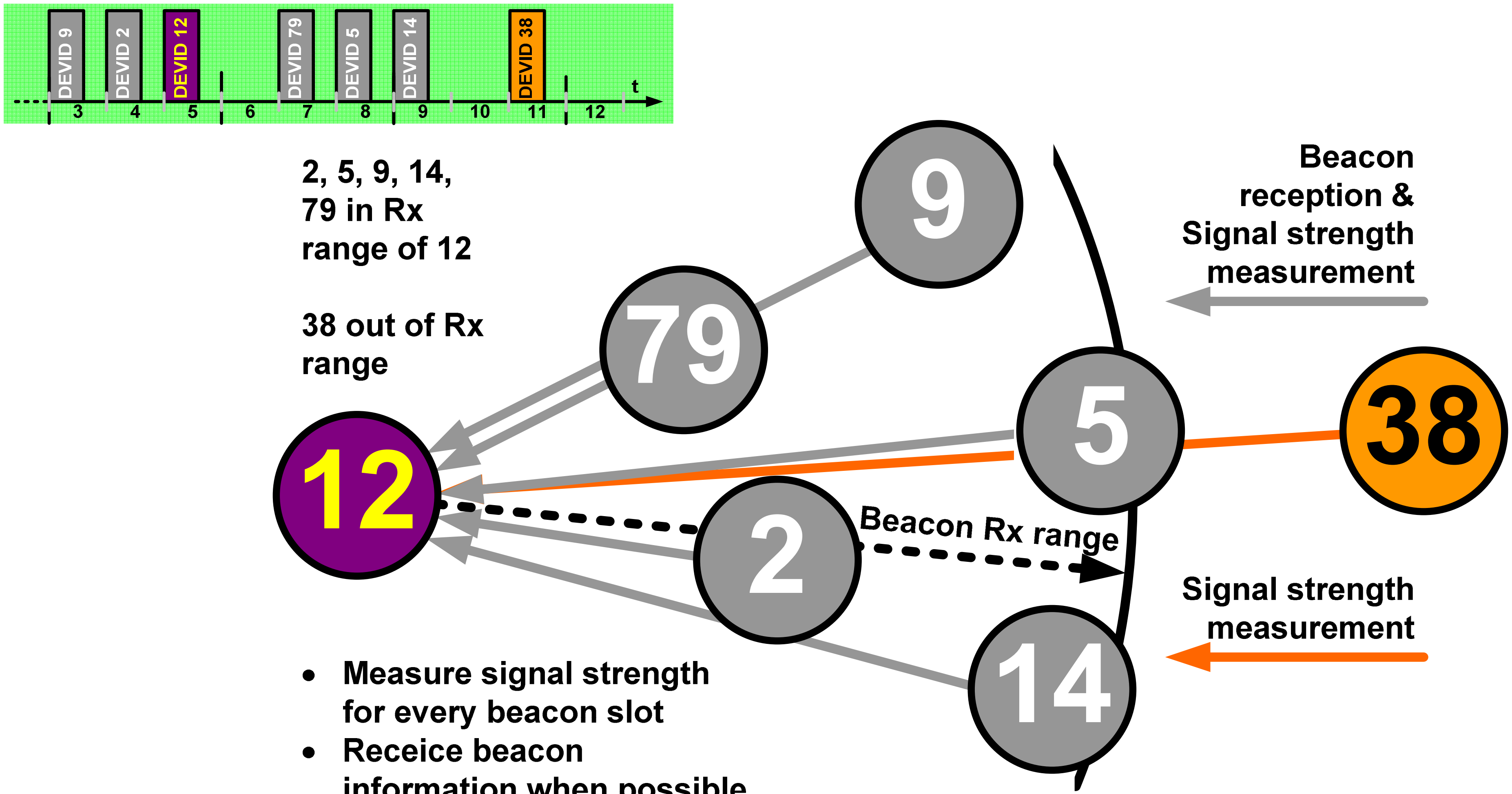
Devices in interference range

Devices outside Rx & interference range

Beacon Period (BP) measurements

- Neighborhood table informs about used Beacon slots
- Devices continuously listen during BP
  - Store received power indication for each beacon
  - Combine power and beacon device ID
  - → Neighborhood and interference graph

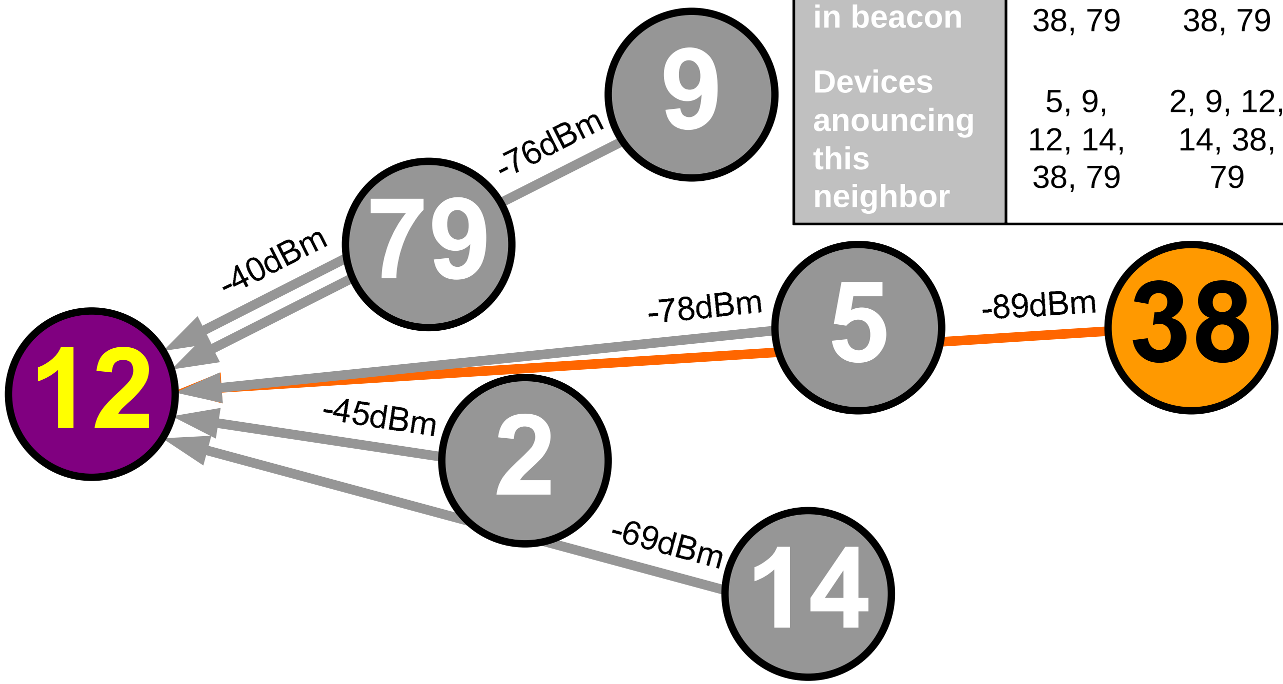
Beacon Period (BP) example



- Measure signal strength for every beacon slot
- Receice beacon information when possible

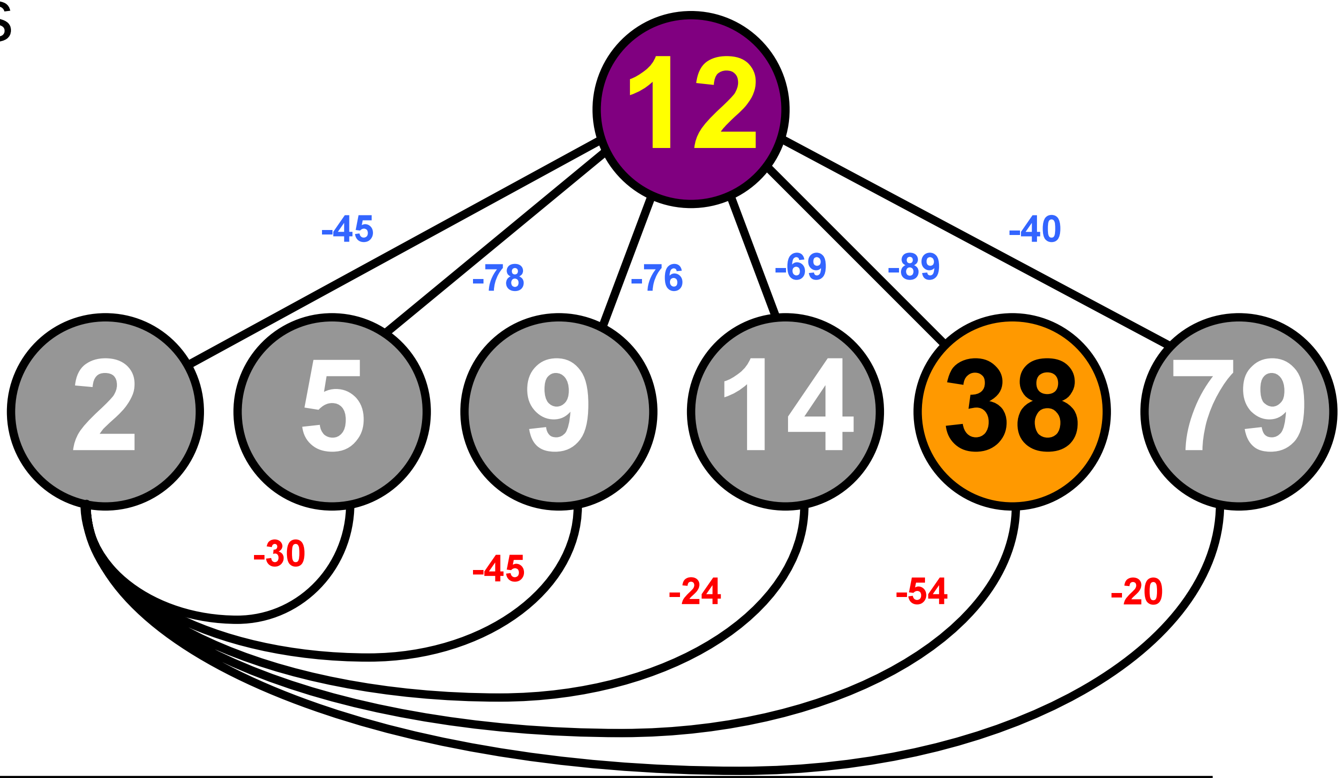
Neighborhood as seen by device 12

Device	2	5	9	14	38	79
RSSI (dBm)	-45	-78	-76	-69	-89	-40
Beacon rxed	✓	✓	✓	✓	✗	✓
Neighbors announced in beacon	2, 5, 9, 12, 14, 38, 79	2, 5, 9, 12, 14, 38, 79	2, 5, 9, 12, 14, 38, 79	2, 5, 9, 12, 14, 38, 79	✗	2, 5, 9, 12, 14, 38, 79
Devices anouncing this neighbor	5, 9, 12, 14, 38, 79	2, 9, 12, 14, 38, 79	2, 5, 12, 14, 38, 79	2, 5, 9, 12, 38, 79	2, 5, 9, 14, 79	2, 5, 9, 12, 14, 38



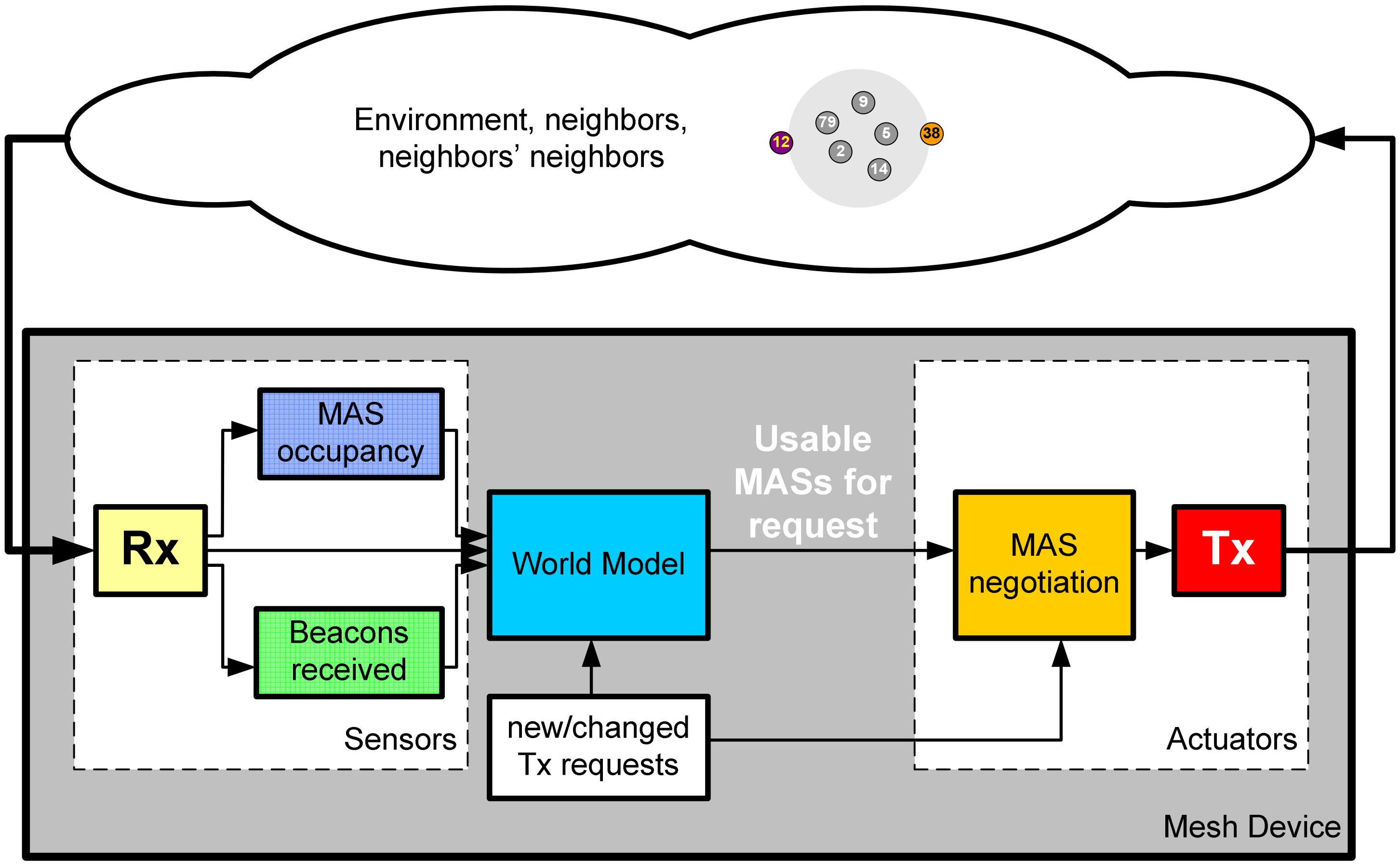
Interference Graph

- Power levels as seen by device 12
- Neighbor's neighbor RSSI
- Here only device 2 displayed



World model

- Devices point of view
- Neighbor-hood
- Signal strength informa-tion
- Constant learning process



Data Transmission Period

Data Transmission Period

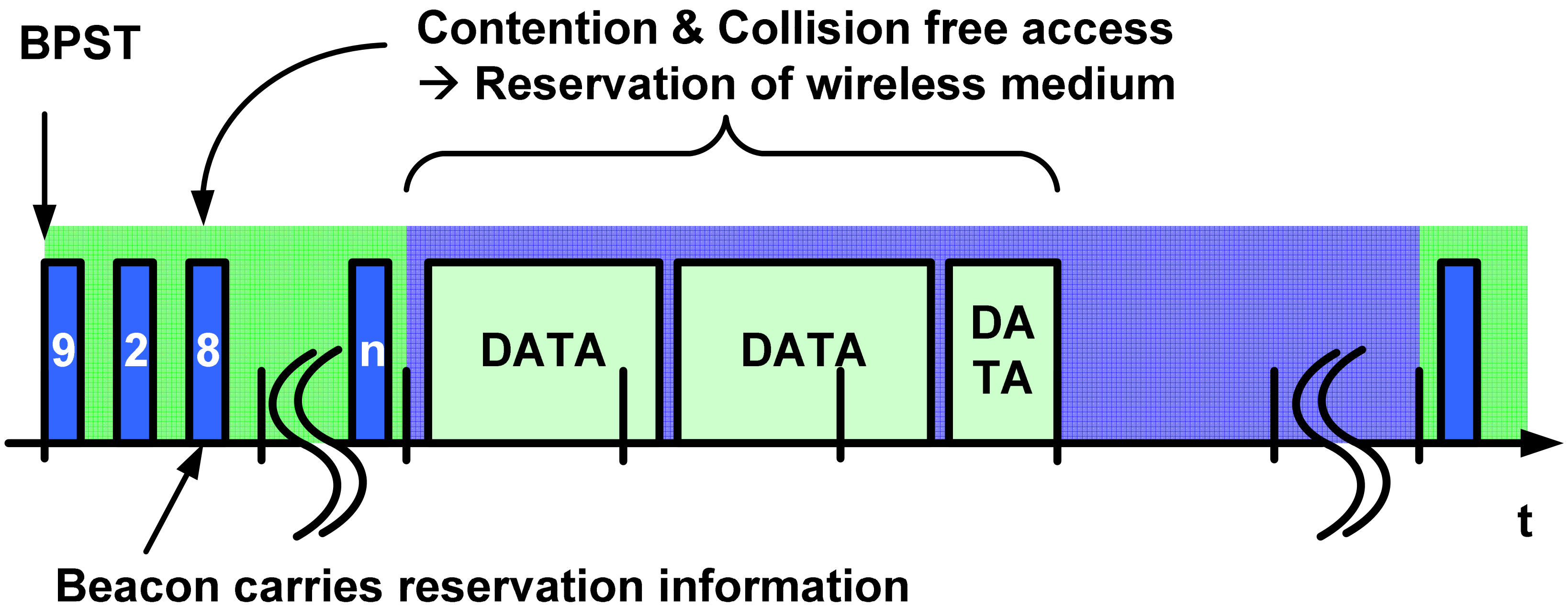
- Scheduled transmissions
  - Contention avoidance
  - Collision avoidance
  - Distributed
  - Mutual interference awareness
  - Efficient spatial frequency reuse

- Support for
  - Distributed Quality of Service
  - A-/synchronous data
    - Wireless USB
    - VoIP
    - Multimedia (Video, Audio) streaming

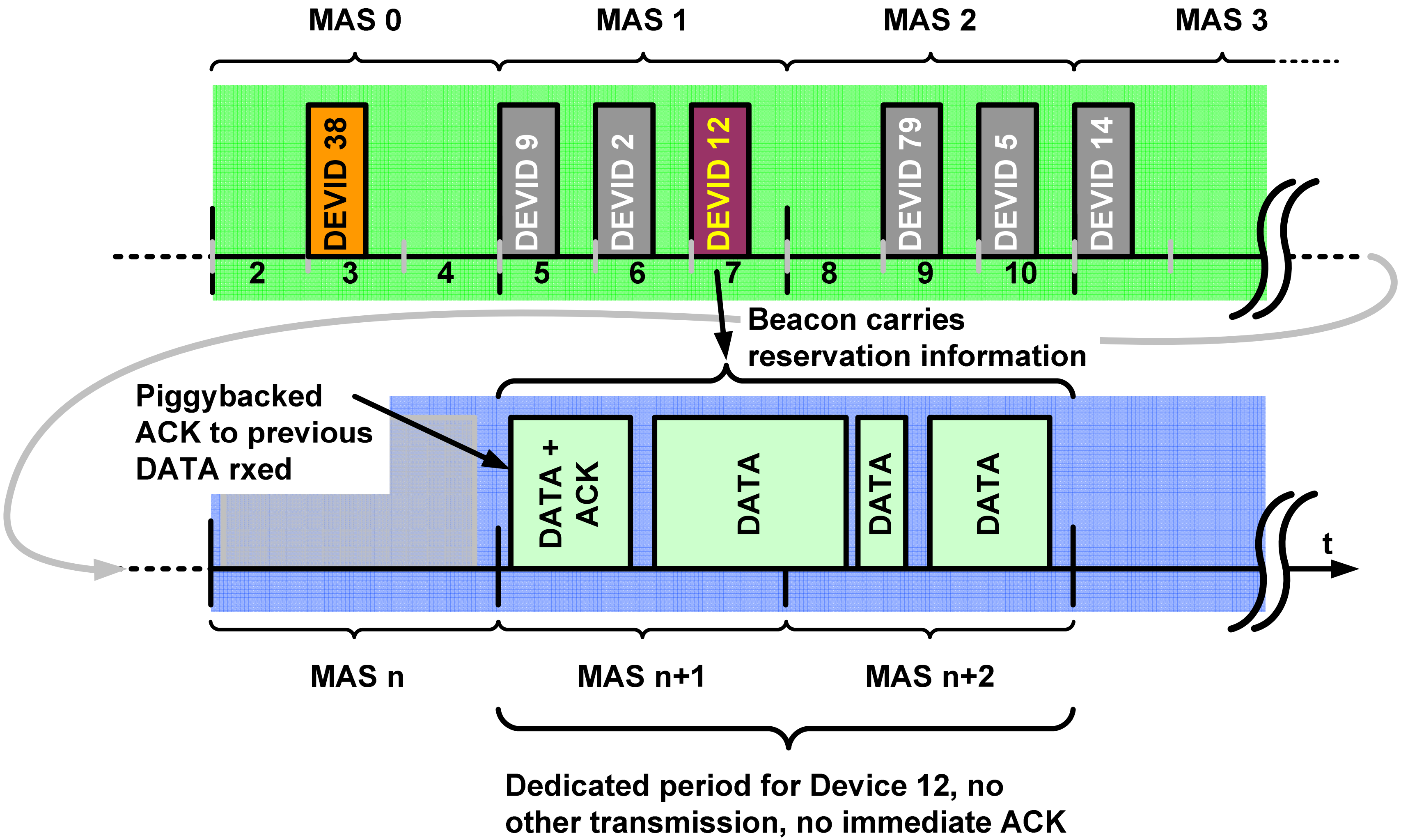
→ **Distributed Reservation Protocol (DRP)**

Distributed Reservation Protocol (DRP)

- Devices announce desired transmissions
- Receiver & transmitter negotiate via beacon
- Beacons carry information on other reservations
- Interference awareness allows parallel transmissions



Data transmission using DRP



Data transmission rules

- Reservations must be accepted by receiver
  - Transmitter announces wish in beacon
  - Receiver accepts or declines wish in its beacon
- Priority support
  - High priority reservations may replace low priority
- All data transmission are unidirectional
  - No immediate ACK
    - DATA and ACK separate
  - Slots assigned to transmitter only
    - Predictable interference
- Delayed ACK
  - Piggyback with DATA
  - Explicit as Block ACK

Delayed Acknowledgment

- Immediate ACK
  - Rx and Tx role interchanged
  - Unpredictable radio transmission
  - Unreliable interference situation
  - Not allowed for MPA
- ACK
  - Explicit
    - Separate MAS
  - Implicit
    - Piggyback on DATA
- Block ACK
  - Several ACKs combined
  - Window oriented

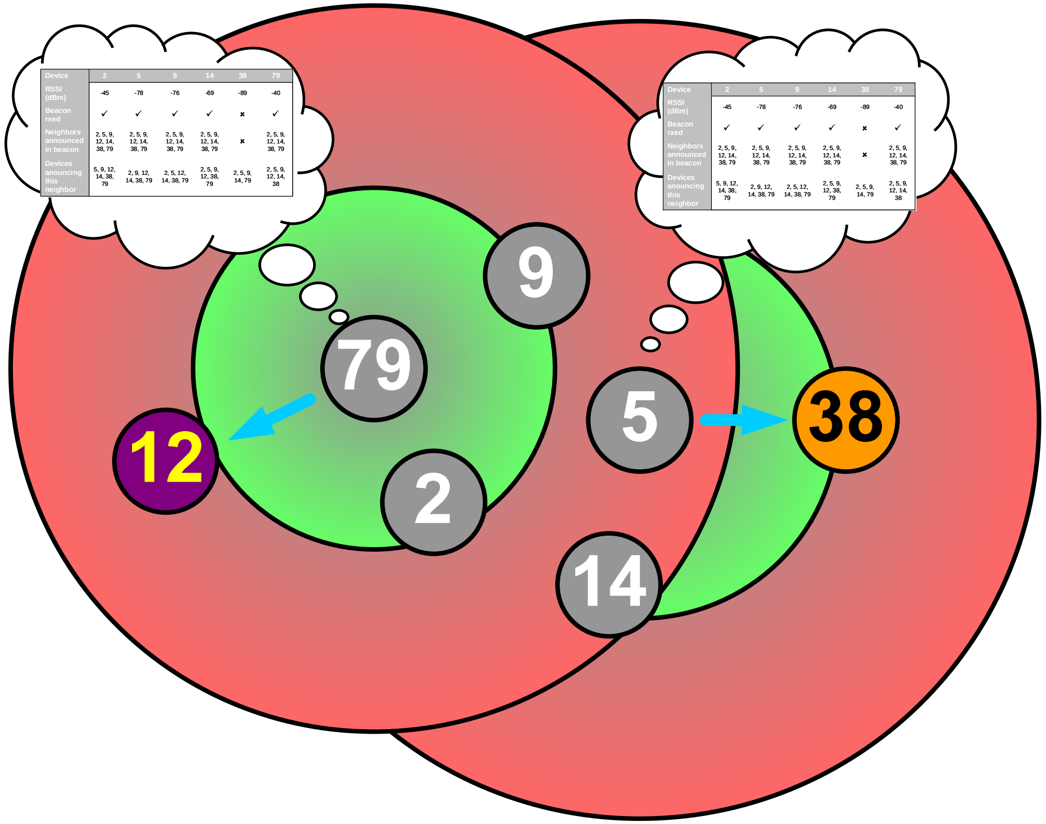
Concurrent data transmission

- Devices learn via beacon about other tx
- Interference table allows prediction

Example:

- Tx (79→12, t_1-t_0)
- Tx (5→38, t_1-t_0)

→ Prediction needed



- High channel reuse

Interference prediction

Tx Device

1. Search table for tx opportunity
2. Indicate proposed MASs to rx device in beacon

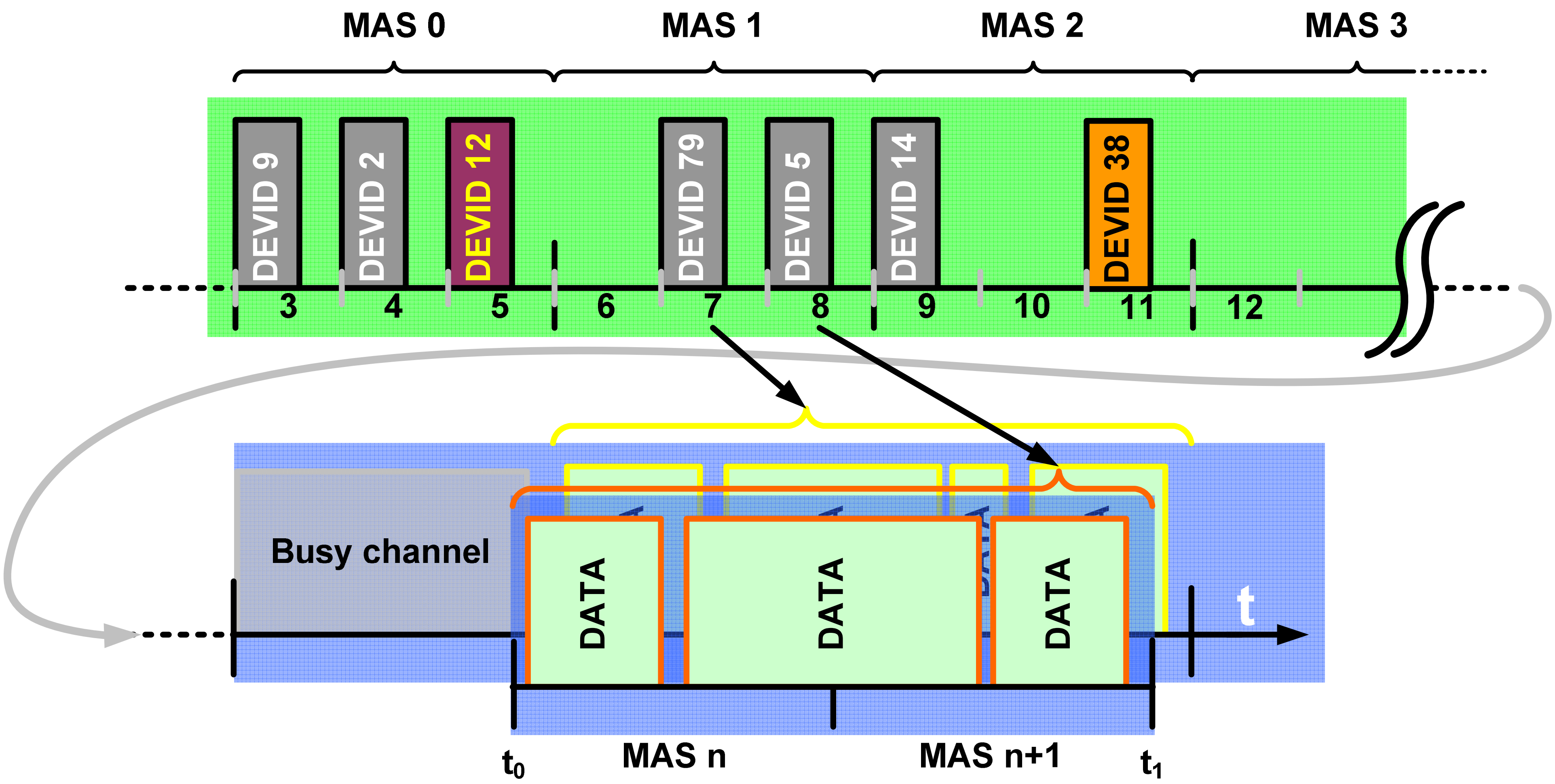
Rx Device

3. Evaluate proposed MAS
4. Search local MAS occupancy map
5. Compute expected interference
6. Accept or propose different MASs

Tx Device

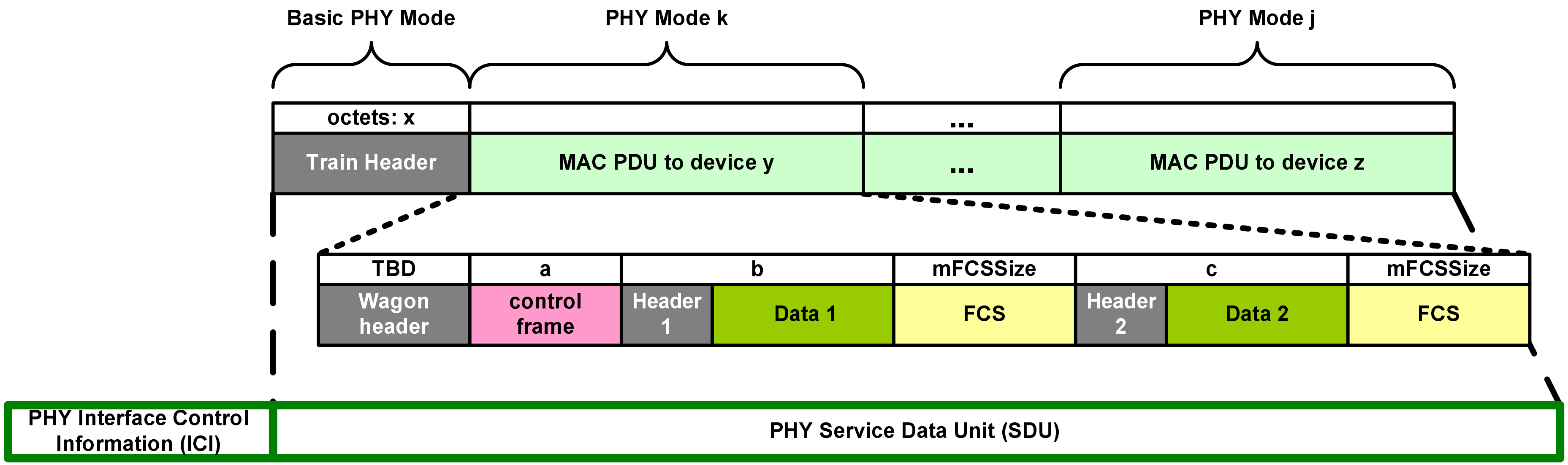
7. Wait for rx respond
8. Accept rx respond or decline

Concurrent data transmission, timing

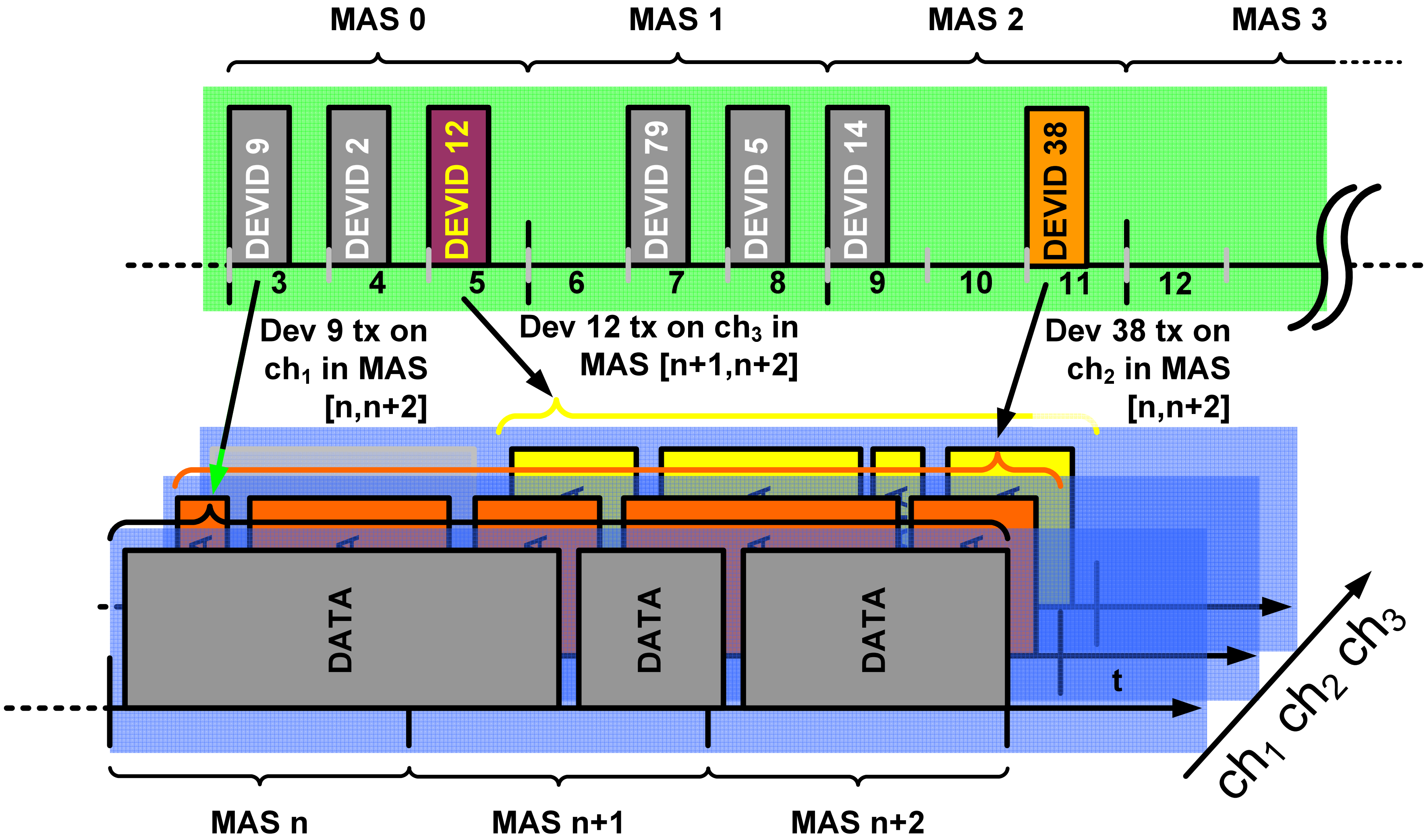


Frame Aggregation

- Aggregate small frames into larger PDU
- Separate Frame Check Sequence
- Multiple receivers possible



Multiband PHY – MAC enhancements



Conclusion

- Mesh PAN Alliance (MPA) proposal
  - Distributed & decentralized
  - Quality of Service support
  - Hidden/Exposed node problem solved
  - High spatial frequency reuse
  - Robust & reliable
- Outlook
  - Simulation results
  - Further details on beaconing
  - World model example
  - Routing procedures

Ready for the next decade of wireless freedom

Thank you for your attention!

http://mpa.comnets.rwth-aachen.de

The Mesh PAN Alliance

Get meshed, get freedom for your Wireless Personal Area Networks