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

**Submission Title:** **MedWiN MAC and Security Proposal – Part 1 of 2**
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**Re:** Response to IEEE 802.15.6 call for proposals

**Abstract:** This presentation illustrates the major MAC aspects of a joint MAC and security proposal detailed in an accompanying normative text document doc. IEEE 802.15-09-0327-01-0006.

**Purpose:** To submit a joint proposal on MAC and security to the IEEE 802.15.6 task group

# MedWiN MAC and Security Proposal

*Part 1 of 2 – MAC Sublayer*


| | |
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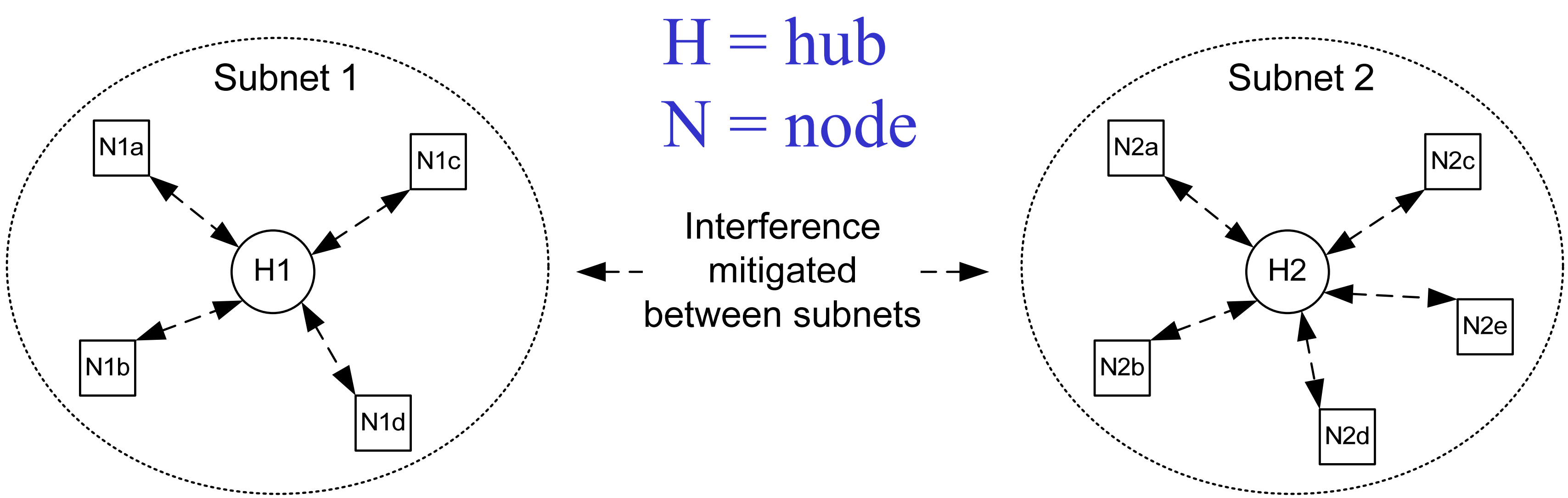
# Outline

- Network topology
- Scalable access mechanisms
  - Time partitioning and beacon transmission
  - Addresses and IDs
  - Scheduled access (one-periodic & multi-periodic allocations)
  - Improvised access (polls & posts)
  - Random access (CSMA/CA contention)
- Joining a Body Area Network
- Reliability and QoS
  - Acknowledgement policies
  - Urgent alarm access (<1 sec)
- Interference and Coexistence
- Power efficiency
- Implementation estimates
- Summary

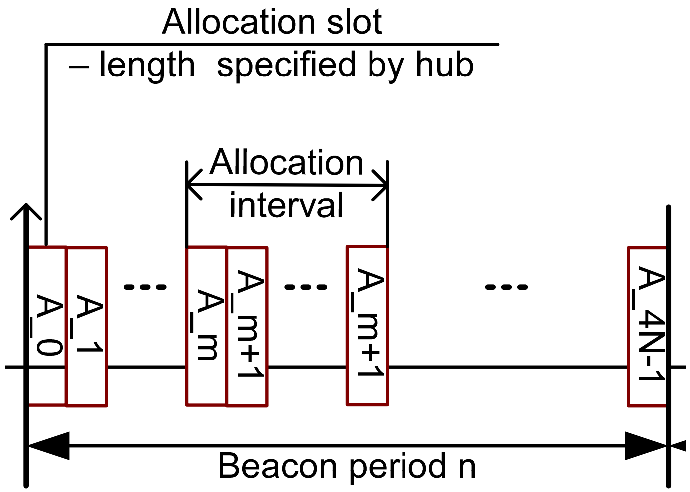
# Centralized, Star Network Topology

- Enable Medical Body Area Network (BAN) applications
- Support simple, effective access methods
- Reduce network management overhead & power consumption
- Simplify creation of a secure network



# Time Partitioning and Beacon Transmission

- Beacon period
  - Hub transmits beacon every period
  - Length = 4N allocation slots, N determined by hub
  - Maximum 4N = 256 allocation slots
- Allocation slot
  - Slot length determined by hub
  - Slot length 1 to 256 msec
  - Time units for access intervals
- Allocation interval
  - Consecutive allocation slots (≥ 1 slot)
  - Interval length determined by hub or negotiated with node

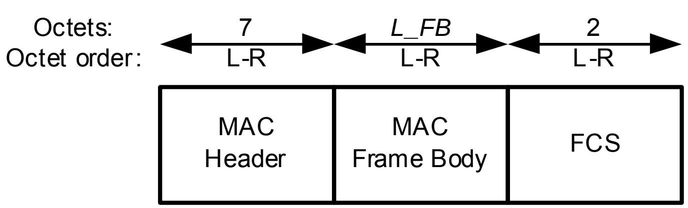


# Addresses and IDs

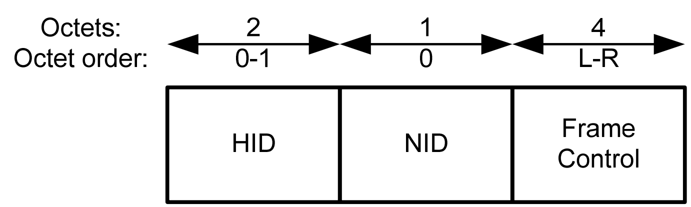
- Every device assigned 48 bit address at manufacture
  - Uniquely identifies each node and hub
  - Exchanged in management frames to unambiguously identify connecting devices

- Abbreviated addresses Identifier exchanged in MAC header of all frames
  - Hub uses lowest 16 of 48 bit address as its HID

    $2^{16}$ = 65,536 HIDs sufficient for hospital environment
  - Node assigned its 8 bit NID by hub at connection
  - MAC header requires only 7 bytes



MAC Frame format



MAC Header format

# Medical Body Area Network Access

- **Medical application requirements**
  - Continuous patient monitoring needs periodic, deterministic access for bounded latency and loss
  - Home and other environments need infrequent, robust access for episodic data traffic
  - Sensor node type, quantity change over time for a patient
- Access mechanisms supported
  - Scheduled access (1-periodic, m-periodic allocations)
  - Improvised access (polls & posts)
  - Random access (CSMA/CA contention)

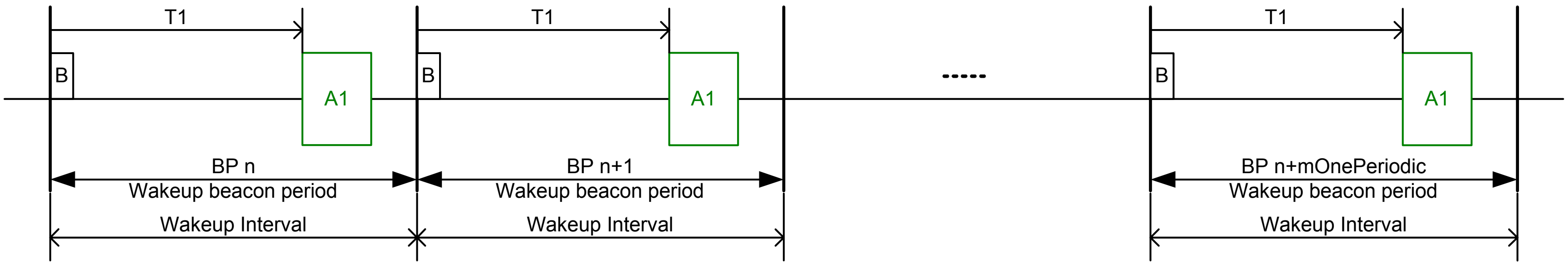
# Scheduled Access

## Enables continuous and periodic medical patient monitoring

- Mandatory for hub, optional for node
- Node or hub obtains one or more recurring allocation intervals to initiate frame transactions
  - 1-periodic: allocation interval in every beacon period
  - m-periodic: allocation interval every multiple beacon periods
  - Single allocation interval may be shared among several m-periodic nodes
  - Allocation interval includes acknowledgements
- Scheduled access enables periodic
  - Hub to node downlink traffic
  - Node to hub uplink traffic
- Requested by node's Connection Request frame
- Granted via hub's Connection Assignment frame

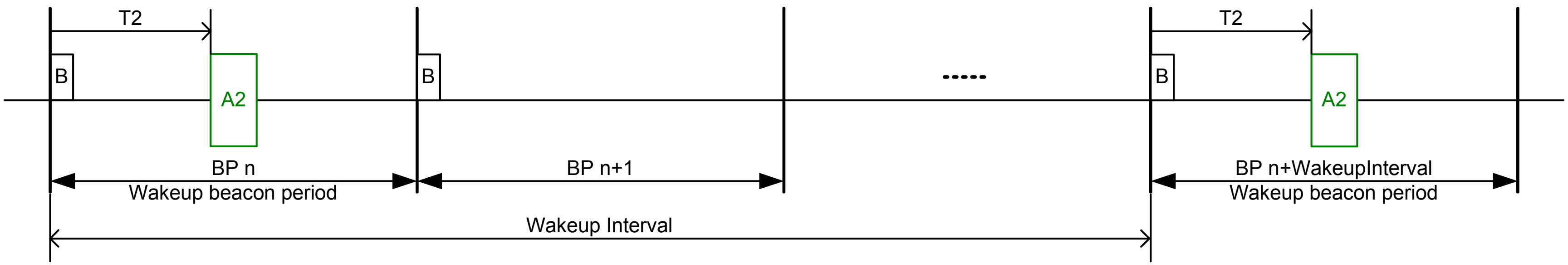
# Scheduled Access (2)

B = beacon BP = beacon period
A1 = 1-periodic allocation interval of node 1 T1 = interval start of A1 relative to beacon transmission time




**(a) 1-periodic allocation of node 1**

B = beacon BP = beacon period
A2 = m-periodic allocation interval of node 2 T2 = interval start of A2 relative to beacon transmission time



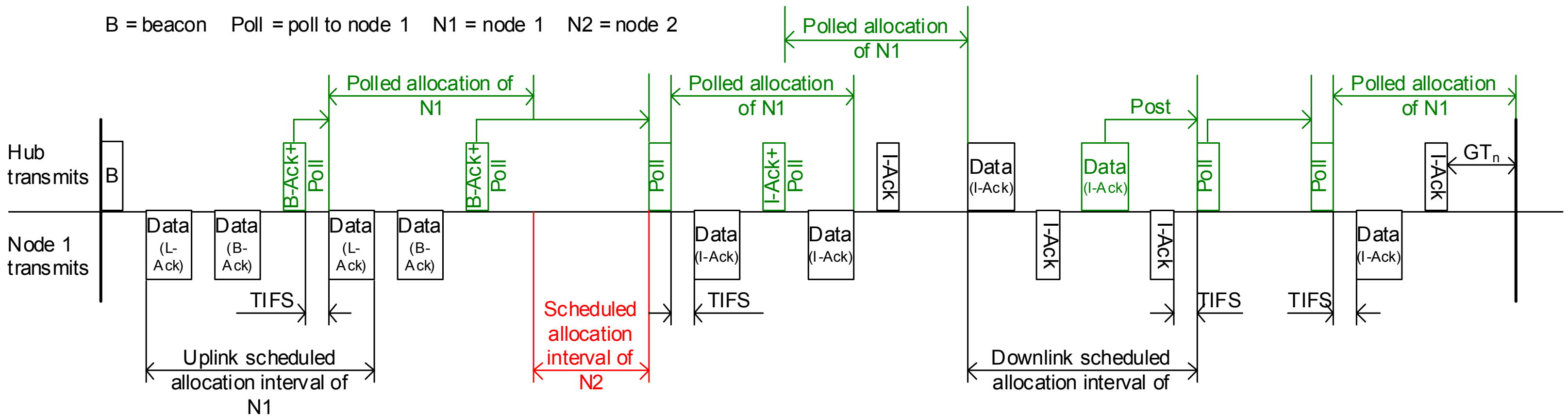

**(b) m-periodic allocation of node 2**

# Improvised Access

## Enables impromptu exchange for medical alarms, variable data quantities, configuration and network construction

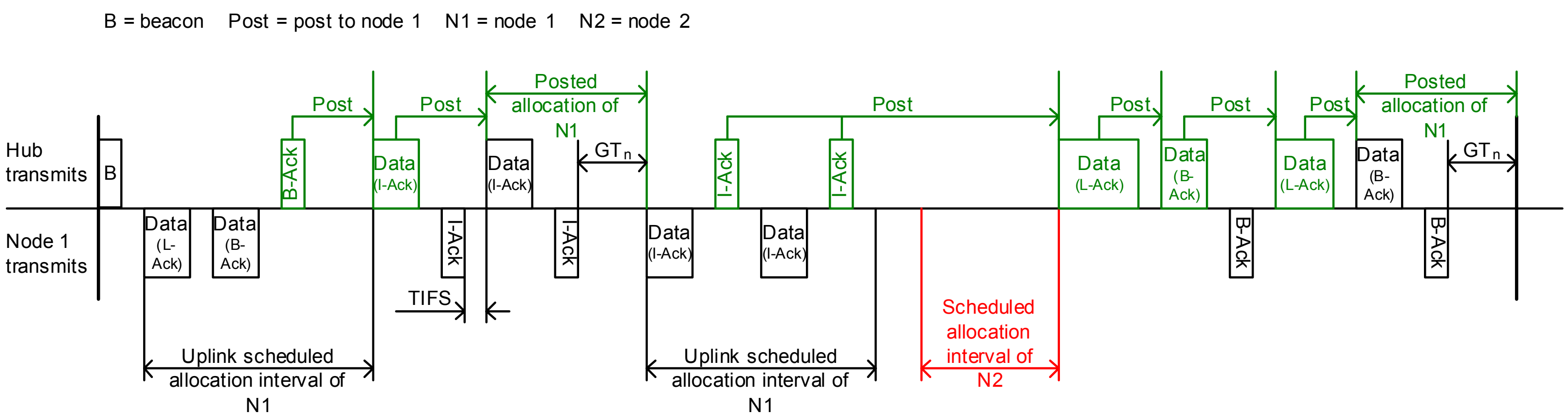
- Improvised access yields allocation interval for a single beacon period
  - Short-distance: improvised allocation immediately following
  - Long-distance: improvised allocation later in the beacon period
    - Allows node to sleep and save power within beacon period
- Hub with data for a node
  - Essential for network management
  - Informs node of pending Post via Acknowledgement frame
  - Post: hub to node (Mandatory for hub and node)
- Node needs bandwidth beyond its scheduled allocation
  - Requests Poll with More Data bit in MAC header frame control field
  - If short-distance: Acknowledgement + Poll sent to allow node to continue
  - If long-distance: Poll frame sent by hub to indicate start of improvised interval
  - Poll: node to hub (Optional for hub and node)

# Improvised Access (2)




**Example Polls and Polled Allocations**

# Improvised Access (3)




**Example Posts and Posted Allocations**

# Improvised Access (4)

## Frames and fields sent by a hub enabling polls and posts

| | Short distance | Long distance |
|---|---|---|
| Poll | Poll, I-Ack+Poll, or B-Ack+Poll frame, with More Data = 0, Sequence Number = *A*, Fragment Number = *Reserved* :<br><br>A polled allocation starts TIFS after the end of the current frame, and ends at the end of allocation slot *A* located in the current beacon period. | Poll, I-Ack+Poll, or B-Ack+Poll frame, with More Data = 1, Sequence Number = *A*, Fragment Number = *B* :<br><br>No polled allocation follows this frame, but another poll starts at the start of allocation slot *A* located in the current beacon period if $B = 0$ or in the next *B*th beacon period if $B > 0$. |
| Post | Non-beacon management or data type frame, with More Data = 1 :<br><br>A post starts TIFS after the end of the current frame transaction. A poll providing another poll but not a polled allocation may be considered a post. | I-Ack or B-Ack frame, with More Data = 1, Sequence Number = *A*, Fragment Number = *B* :<br><br>A post starts at the start of allocation slot *A* located in the current beacon period if $B = 0$ or in the next *B*th beacon period if $B > 0$. |

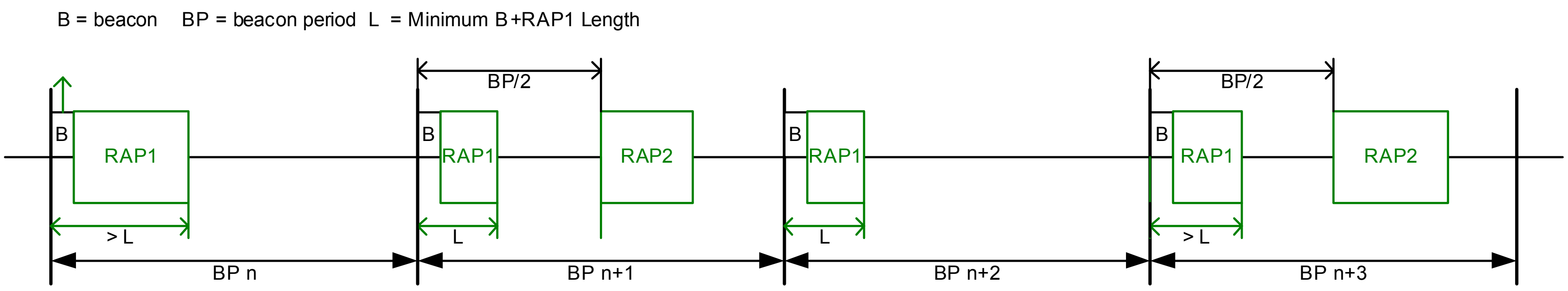
# Random Access

**Enables episodic medical applications like home and fitness monitoring, medical alerts and alarms**

- Hub's beacon advertises two random access phases within the beacon period
  - First phase immediately after beacon (RAP1)
  - Second phase at half beacon interval (RAP2)
  - Width of random access phases specified by RAP1 and RAP2 ≥ 0 slots
- Mandatory for hub
  - Hub has to listen only, does not need to perform CSMA/CA
  - RAP1 and RAP2 can be set to zero, effectively disabling Random Access
- Random access support is optional for node

# Random Access (2)

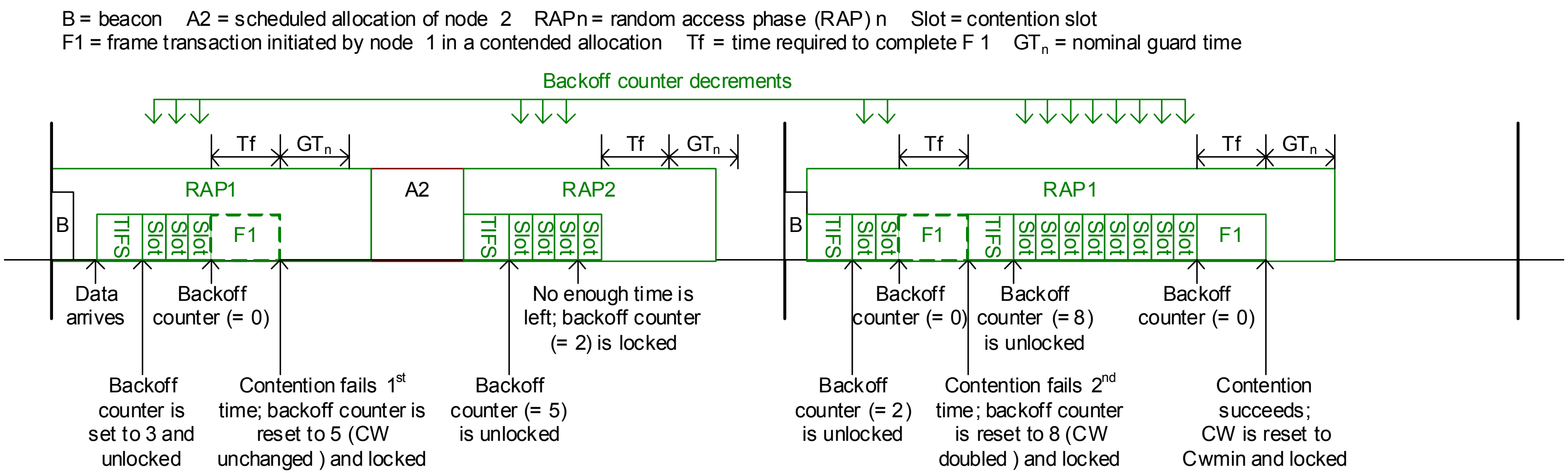
- Random Access based on CSMA/CA
  - If enabled (RAP > zero), minimum value of RAP1 provided via Connection Assignment
    - RAP1 can be larger, but no smaller than L
    - RAP2 can be any size including zero
  - Hub can vary width of RAP1 and RAP2 across beacon periods




**Random access phases (RAPs)**

# Random Access (3)

- A node sets a back-off counter to a random integer in [1, CW], with CWmin ≤ CW ≤ CWmax, to obtain a contended allocation for one or more frame transactions.
- Alternative doubling of contention window with every other failure; redraw back-off on each failure

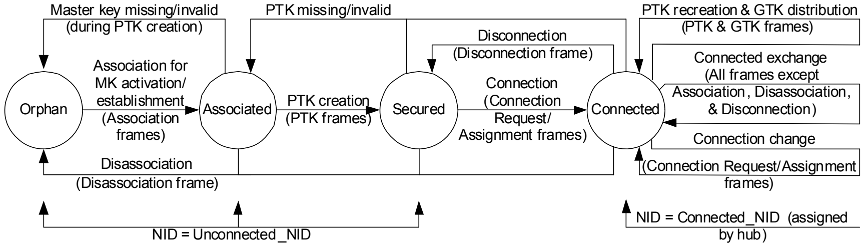



**Random access by node 1 to obtain a contended allocation**

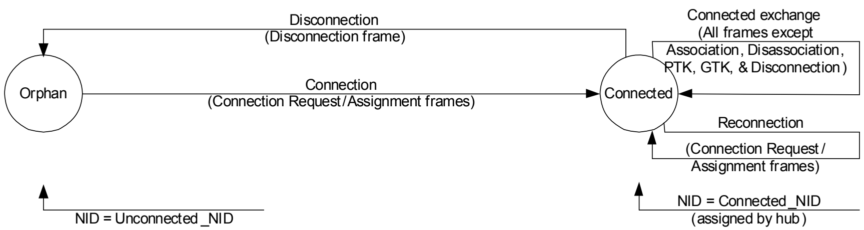
# Joining a Body Area Network

- Node to join a network
  - Node must scan to find a Hub's beacon frame or Unconnected poll frame
  - Node can leverage Random Access or Improvised Access to join

- Node joins via secure or unsecure access mechanisms
  - Association: identify node and hub to each other, establish or activate a master key
  - Connection: relationship between node and hub in the same subnet, substantiated by a Connected_NID assigned to the node by the hub, and by a power management profile and an access allocation contract negotiated between the node and the hub.




**(a) Secured Communication**




**(b) Unsecured Communication**

**Access State Diagram**

# Joining a Body Area Network (2)

- Node to join a network – using Improvised Access
  - Hub provides unconnected poll allocations to Unconnected Broadcast NIDs
  - Node selects an Unconnected NID and sends its first frame to hub in the improvised poll allocation
    - If successful, hub assigns the node a new NID and new, unicast, improvised polls until Connection Request frame received
    - If no acknowledgement from hub, node retries in subsequent unconnected poll allocations with probability = min(1/4, 1-R/4), R = retry number

- Node to join a network – using Random Access
  - Node scans for hub's beacon frame
  - Node supports CSMA/CA and hub advertises RAP1 or RAP2 > 0
  - Node contends for access for its first frame to hub using an Unconnected NID
  - If successful, hub assigns the node a NID and new, unicast, improvised polls until Connection Request frame received

# Joining a Body Area Network (3)

- Hub configuration
  - Determines slot availability for Association and Connection frames
  - Contributes to node scan time given channel hopping, beacons interval and use of Unconnected broadcast Polls
- Illustrative examples of frames exchanged to join a network
  - Case 1: 863 – 870 MHz band with 125 ksps symbol rate, 64.5 kbps PHY header information rate and 101.2 kbps data information rate
  - Case 2: 2360 – 2483.5 MHz band with 631.58 ksps symbol rate, 81.5 kbps PHY header information rate and 1022.6 kbps data information rate
  - Transfer time/Frame = (8*MAC Octets/Info Rate) + (16 bits/Header Info Rate) + (72 bits/Symbol Rate)
  - Excludes time to perform key computations

| Join Mode | Frames Required | MAC octets | Transfer Time Case 1 | Transfer Time Case 2 |
|---|---|---|---|---|
| **Unsecured Connection** | Connection Request* + I-ACK<br>Connection Assignment* + I-ACK | 48 + 9<br>40 + 9 | 10.73 msec | 2.07 msec |
| **Secured Association & Connection** | 3 (Master Key Association + I-ACK)<br>3 ( PTK Creation + I-ACK)<br>Connection Request* + I-ACK<br>Connection Assignment* + I-ACK | 3 (103 + 9)<br>3 (47 + 9)<br>56 + 9<br>48 + 9 | 62.67 msec | 9.86 msec |

** Assumes 1 uplink and 1 downlink scheduled allocation for node*

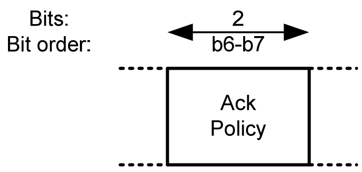
# Reliability and Quality of Service

**Reliable communications is essential for streaming and episodic medical data exchange given bounded data loss and latency requirements**

- Acknowledgement policies support application reliability and latency
  - Immediate Acknowledgement (I-Ack) of preceding frame
  - Block Acknowledgement (B-Ack) of multiple, preceding frames allows for selective retransmission when burst of frames is sent
  - Either Ack message may include Poll allocation grant for the node

- Urgent alarm access (<1 sec) possible via two access methods
  - Improvised access permits conveyance of data outside of scheduled allocations to satisfy latency constraints
    - Node may send data and alarms
    - Hub may send configuration or response to a node
  - Random access with Quality of Service prioritization

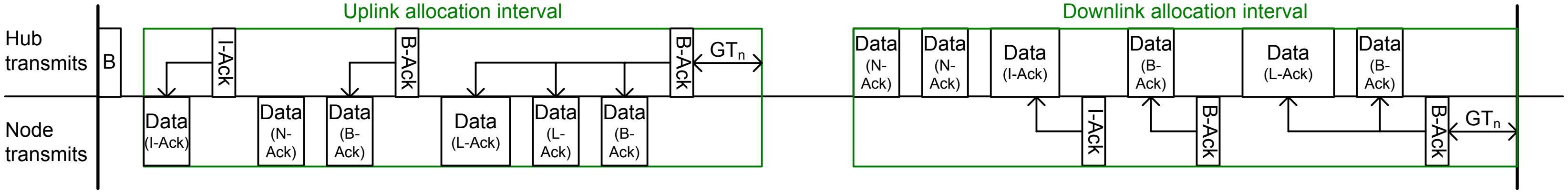
# Acknowledgment Policy




Included in Frame Control field of MAC header

**Table — Acknowledgment (Ack) Policy field encoding**

| Field value b6 b7 | Acknowledgment requirement |
|---|---|
| 00 | No acknowledgment (N-Ack) |
| 10 | Immediate acknowledgment (I-Ack) |
| 11 | Block acknowledgment later (L-Ack) |
| 01 | Block acknowledgment (B-Ack) |




Transmissions in uplink and downlink allocation intervals

# Random Access – Prioritization

## CWmin and CWmax values

| Priority | User Priority | Traffic designation | CWmin | CWmax |
|---|---|---|---|---|
| Lowest | 0 | t.b.d. | 16 | 64 |
| | 1 | t.b.d. | 16 | 32 |
| | 2 | t.b.d. | 8 | 32 |
| | 3 | t.b.d. | 8 | 16 |
| | 4 | t.b.d. | 4 | 16 |
| | 5 | t.b.d. | 4 | 8 |
| | 6 | t.b.d. | 2 | 8 |
| Highest | 7 | Emergency message | 1 | 4 |

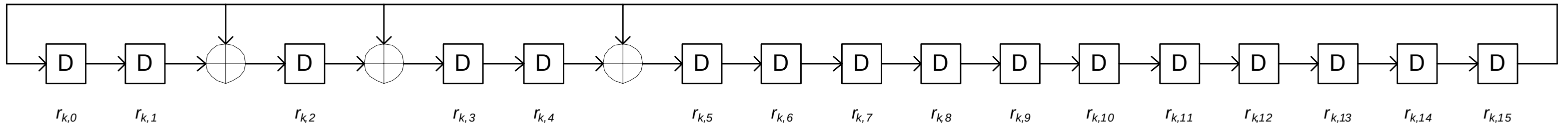
# Coexistence and Interference Mitigation

**Medical use cases involve many collocated patients, each with their own BAN, and other radio services. Medical BANs require effective coexistence and interference mitigation.**

- Coexistence among uncoordinated BANs
  - Collocated BANs do not synchronize amongst each other or via an infrastructure
  - Channel hopping and beacon shifting are mandatory for hub and node
- Channel Hopping of each BAN enables frequency diversity
  - Random frequency hopping, uniformly across available channels
  - Minimum frequency separation based on channel coherence bandwidth
- Beacon Shifting of each BAN in time domain enables temporal diversity
  - Dithering of beacon message transmission among 4 quarters of beacon period
  - Cyclical shift of activity within the beacon period

# Coexistence and Interference Mitigation (2)

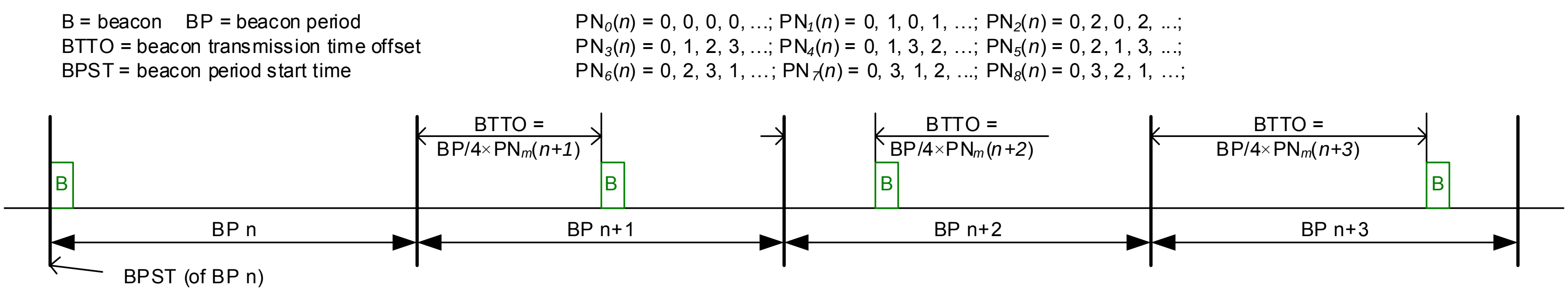
- Channel Hopping of each BAN enables frequency diversity
  - Hub generates channel hop sequence using linear feedback shift register (LFSR)
    - Least significant 16 bits of hub MAC address used to initialize LFSR
    - Beacon messages contain LFSR status and indication of imminent change
  - LFSR mapped to channel ensuring equal probability selection and minimum frequency separation
  - Hub dwells on current channel for fixed number of beacon periods
  - Connection Assignment contains dwell length and phase
  - Can be disabled for single frequency channel operation




**16-bit Galois LFSR for channel hopping sequence generation**

# Coexistence and Interference Mitigation (3)

- Beacon Shifting of each BAN in time domain
  - Hub selects a PN sequence $PN_m(n)$ to shift its beacon transmission time across beacon periods
  - A hub may choose $PN_0(n) = 0$ to transmit its beacon period start
  - Beacon message contains shifting sequence index and phase for the next period
  - Use of quarter beacon period fixed offsets simplifies implementation

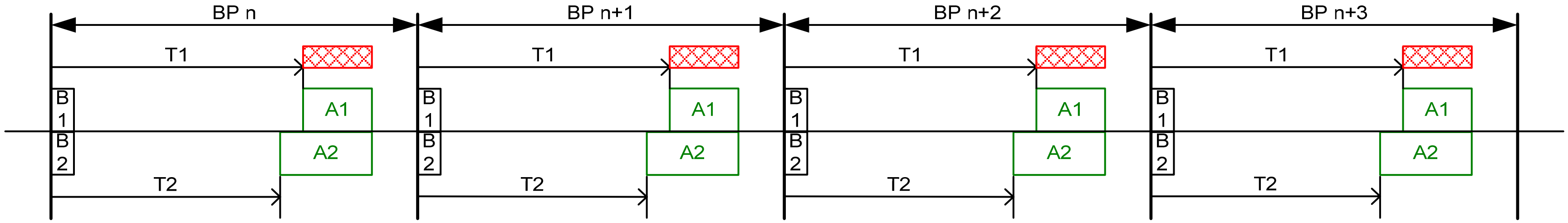



**Beacon transmission with shifting sequence $PN_5(n)$ = 0, 2, 1, 3**

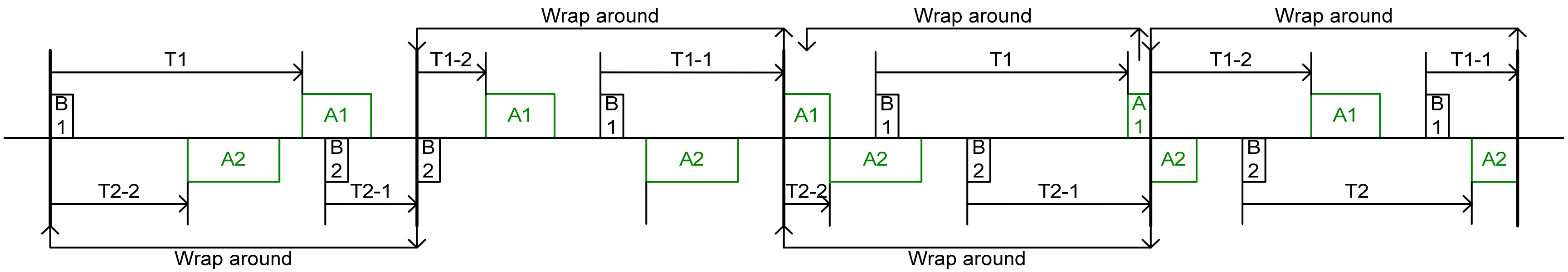
# Coexistence and Interference Mitigation (4)

Bn = beacon transmitted by subnet of node n    BP = beacon period

An = 1-periodic allocation interval of node n    Tn = interval start of An relative to beacon transmission time    Tn = Tn-1 + Tn-2




(a) Subnet of node 1: $PN_0(n)$ = 0, 0, 0, 0, ...; subnet of node 2: $PN_0(n)$ = 0, 0, 0, 0, ...




(b) Subnet of node 1: $PN_5(n)$ = 0, 2, 1, 3, ...; subnet of node 2: $PN_5(n-1)$ = 3, 0, 2, 1, ...

**Beacon shifting to mitigate interference between BANs**

# Coexistence and Interference Mitigation (5)

## Support for 10 BANs in 6 by 6 by 6 meter volume

- Proposed PHY affords at least 10 channels in each frequency band

| Frequency Band (MHz) | Relationship between $f_c$ and $n_c$ |
|---|---|
| 2400 – 2483.5 | $f_c = 2402.00 + 1.00 \times n_c$ (MHz), $n_c = 0, \ldots, 78$ |
| 2360 – 2400 | $f_c = 2362.00 + 1.00 \times n_c$ (MHz), $n_c = 0, \ldots, 37$ |
| 402 – 405 | $f_c = 402.15 + 0.30 \times n_c$ (MHz), $n_c = 0, \ldots, 9$ |
| 902 – 928 | $f_c = 903.50 + 0.50 \times n_c$ (MHz), $n_c = 0, \ldots, 47$ |
| 950 – 956 | $f_c = 951.10 + 0.40 \times n_c$ (MHz), $n_c = 0, \ldots, 11$ |
| 863 – 870 | $f_c = 865.60 + 0.20 \times g(n_c)$ (MHz), $n_c = 0, \ldots, 14$ |

$$g(n_c) = \begin{cases} n_c & 0 \le n_c \le 9 \\ n_c + 3 & 10 \le n_c \le 11 \\ n_c + 4 & 12 \le n_c \le 13 \\ n_c + 7 & n_c = 14 \end{cases}$$

- Channel hopping distributes probability of collision across channels
- Beacon shifting distributes probability of temporal collisions across a BAN’s nodes
- Acknowledgements and improvised access provide for retransmission due to collisions as well as channel impairments
- Maximum BAN deployment density supported by dedicated frequency spectrum with sufficient bandwidth for channelization and retransmissions when needed (*proposed 2360-2400 MHz band for USA*)

# Enabling MedRadio / MICS

## Proposal provides tools to enable MedRadio applications

- Star topology suitable for implant to programmer permitted communications
  - Channelization plan based on 300 kHz bandwidth
- Frequency monitoring per FCC 95.628
  - Utilize MedWiN's proposed PHY energy detection and clear channel assessment
  - Disable channel hopping for single channel operation
- Simple, exemplary scenarios leveraging proposed access methods
  - Monitoring of MedRadio device within 402-405 MHz
    - Hub performs frequency monitoring (PHY ED, CCA), selects primary channel, disables channel hopping and defines an appropriate beacon period and slots
    - Hub transmits beacon message and Unconnected Polls for unconnected NIDs.
    - Node joins BAN, exchanges data and disconnects, ending the MedRadio communication session
  - Event alert from MedRadio device
    - FCC 95.1209(b) permits implants to transmit given medical implant event absent programmer.
    - Node joins hub as previous example, ends MedRadio communication session then sleeps
    - Hub monitors the previous channel for a future event, leveraging random access phase to avoid inefficient messages over the air

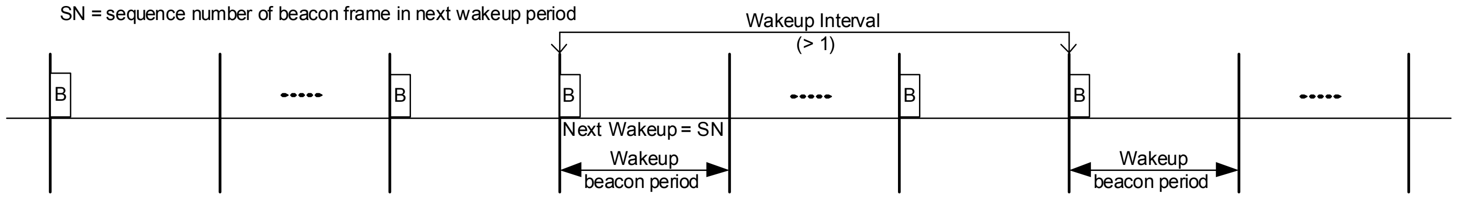
# Power Management

## Medical applications require power efficiency for battery operated devices

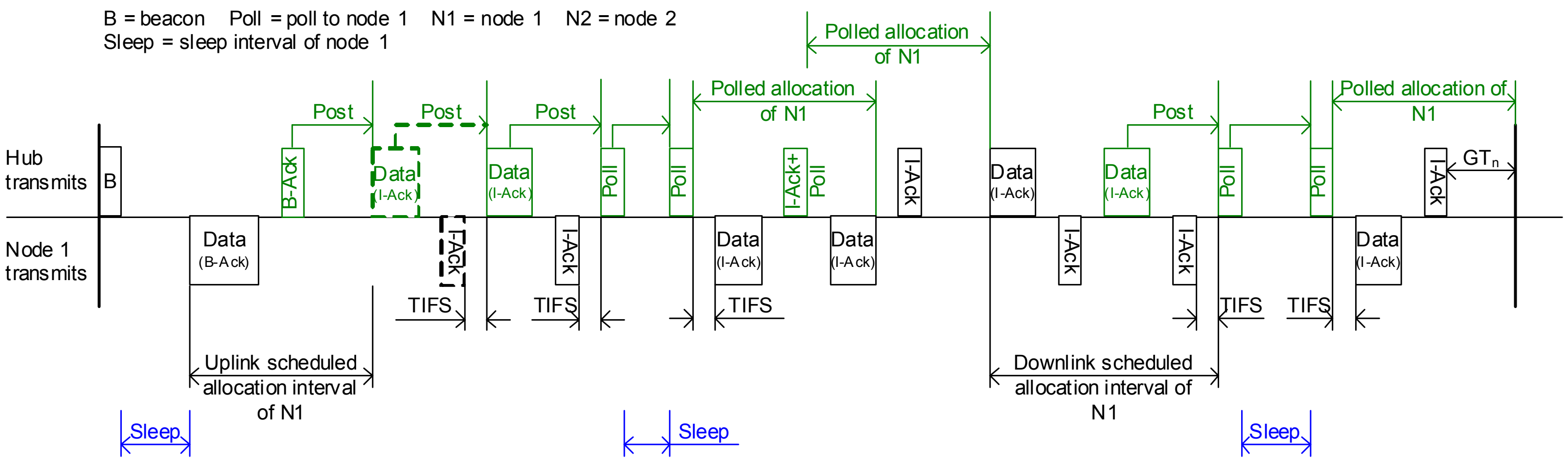
- Hibernation—macroscopic power management
  - Across beacon periods
    - Synchronization interval ($SI_n$) determined by system parameters and beacon's allocation slot length
    - Minimum allocation slot length (1msec), $SI_n$ = 1.5 seconds
    - Maximum allocation slot length (256 msec), $SI_n$ = 639 seconds
  - Node negotiates its wakeup interval with a hub through Connection Request
  - Independent of whether scheduled allocation is desired by node

- Sleep—microscopic power management
  - Within beacon period
  - A node may trade power for access by supporting polls and posts
  - Hub and nodes may sleep outside their scheduled, posted, and polled allocations, all of which have their time known to the nodes in advance

# Power Management (2)




**Example: Hibernation**




**Example: Sleep for a node engaged in scheduled, post and poll allocations**

# Complexity

- Solution size would support digital band-aids, medical devices, etc.
  - Solution will be built using a standard CMOS technology
  - Die size estimates
    - Assumption: Hub supporting 16 nodes
    - Memory implemented as registers

| Device | Gate Count (kgates) |
|---|---|
| Hub minimum | 80 |
| Hub maximum | 160 |
| Node minimum | 40 |
| Node maximum | 120 |

- MAC clock
  - Accuracy of 20 ppm, Resolution of 10 usec
  - Two crystal option allows lower power Hibernation
- Power consumption estimates (minimum implementation)
  - Assumptions: Analog = 1 V, Digital = 0.7 V and 1 V

| Device | @ 125 kbps | @ 1 Mbps | Standby | Hibernate (radio XTAL) | Hibernate (32 kHz watch XTAL) |
|---|---|---|---|---|---|
| Node | 35 uW | 280 uW | 50 uW | 50 uW | < 5 uW |
| Hub | 70 uW | 320 uW | 50 uW | 50 uW | < 5 uW |

# Enabling Low Power Operation

**Illustrative example: Continuous monitoring of patient parameter, moderate data rate sensor node**

- Assumed BAN configuration:
  - Beacon period = 80 msec with 40 allocation slots, each of 2 msec width
  - Beacon uses one allocation slot, Node uses one slot for scheduled uplink (1-periodic)
  - Operation at 1 Mbps within 2360-2483.5 MHz band affords 25,000 bps (raw)
  - Node receives for 2 msec, transmits for 2 msec sleeps 76 msec each beacon period

- Average power estimated as:

$$P_{\text{Avg Node}} = (T_{\text{sleep}}/T_{\text{beacon period}}) * (P_{\text{MAC Standby}} + P_{\text{PHY Standby}}) + (T_{\text{transmit}}/T_{\text{beacon period}})*(P_{\text{MAC Active}} + P_{\text{PHY Tx}}) + (T_{\text{receive}}/T_{\text{beacon period}})*(P_{\text{MAC Active}} + P_{\text{PHY Rcv}})$$

$$= (76 \text{ msec} / 80 \text{ msec}) * (50 \text{ uW} + 50 \text{ uW}) + (2 \text{ msec} / 80 \text{ msec}) * (280 \text{ uW} + 2.9 \text{ mW}) + (2 \text{ msec} / 80 \text{ msec}) * (280\text{uW} + 3.1 \text{ mW})$$

$$= (0.95) * (100 \text{ uW}) + (0.025) * (3.18 \text{ mW}) + (0.025) * (3.38 \text{ mW})$$

$$P_{\text{Avg Node}} = 259 \text{ uW}$$

- Compatible with lithium, zinc air batteries and possibly thin film power sources
  - Estimated > 300 hours operation at 1V with CR2016 lithium coin cell (3V, 80 mAhr)
  - Estimated > 170 hours operation at 1V with Power Paper STD-2 battery (1.5 V, 30 mAhr), [http://www.powerpaper.com/index.php?categoryId=33408]

*Refer to PHY power consumption values from doc. IEEE 802.15-09-0328-00-00006.*

# MedWiN MAC Proposal Enables Medical and Consumer Applications per TG6 PAR

*Illustrative examples – not a comprehensive list*

| Application Area - Use Case | PHY Frequency Bands and Data Rates | Scheduled Access Mechanism | Improvised Access Mechanism | Random Access Mechanism |
|---|---|---|---|---|
| **Medical Applications – Continuous Patient Monitoring**<br>*physiological waveforms, vital signs, location, body motion and posture, etc.* | ● | ● | ◐ | ◐ |
| **Medical Application – Episodic Home Monitoring**<br>*weight scale, blood pressure, fall and impact, environment and context sensing, etc.* | ● | ◐ | ● | ● |
| **Consumer Application – Entertainment & Gaming**<br>*Streaming audio, visual with controller response input* | ◐ | ● | ◐ | ◐ |
| **Consumer Application – Social Interaction & Networking**<br>*Friend finder, business card exchange, etc.* | ● | ○ | ● | ● |

*Key: Enabling applicability* ● *HIGH* ◐ *MEDIUM* ○ *LOW*

# MedWiN MAC Proposal Summary

- Star topology – suitable to medical applications
- Time partitioning – simple but adjustable time slot structure
- Beacon – network management and interference mitigation
- Channel migration – frequency diversity & interference mitigation
- Access methods – flexible, scalable reservation & contention
  - Scheduled access (1-periodic & multi-periodic allocations)
  - Improvised access (polls & posts)
  - Random access (CSMA/CA contention) with priorities
- Acknowledgment policy – versatile but simple
- Power management – for both within and across beacon periods
- MAC frame structure – simple, effective header and body
- Frame types & subtypes – orthogonal, effective

***Details are provided in the accompanying normative text doc. IEEE 802.15-09-0327-00-00006.***

# Comparison Criteria

| Criteria | Proposed Capability |
|---|---|
| 1. Regulatory | Compliant with TG6 regulatory document in multiple frequency bands |
| 2. Raw PHY data rate | 100 kbps to 1 Mbps supported between node and hub |
| 3. Transmission distance<br>4. Packet error rate<br>5. Link budget | PER and link budget shown to support 10% PER for 255 octet PSDU at 3 meters within all operating frequency bands proposed. |
| 6. Power emission level | -10 dBm / -16 dBm maximum EIRP |
| 7. Interference and coexistence | MAC: Channel hopping, Beacon shifting, Acknowledgements, Poll/Post for additional retransmission if necessary. PHY: Channelization ≥ 10 channels, same channel bandwidth for all modulations at each frequency band, low sidelobes of selected modulation |
| 8. Security | MAC provides 3 levels of security (none, authentication, authentication + encryption) based on AES-128. Association protocols provided for master key setup. |
| 9. Reliability | Acknowledged traffic, guard time and node synchronization to beacon provided. Unique identifications used to distinguish between collocated BANs. Link margin sufficient given TG6 channel models variations. |
| 10. Quality of Service | MAC: Time to join a network ~ 63 msec for message exchange. Fast (<1sec) channel access available via prioritized CSMA/CA random access as well as scheduled or improvised access mechanisms. |
| 11. Scalability | PHY: Scalable data rate from common symbol rates. MAC: Multiple nodes supported via m-periodic scheduled, improvised and random access methods. Prioritized QoS and beacon configuration. |
| 12. MAC transparency | MAC transparent across multiple frequency bands proposed |
| 13. Power Efficiency | MAC: Sleep and Hibernate modes. PHY: ≤ 3.1 mW (active), 50 uW (standby), 250/125 nW (deep sleep) |
| 14. Topology | Star topology, broadcast beacon supported.<br>Maximum number of nodes supported via multiple access mechanisms. |
| 15. Bonus Point | **Merged proposal focused on satisfying needs of medical BAN applications as defined by TG6 PAR.** |

# Bonus Material

# Beacon Transmission

Hub transmits beacon message each beacon period

| Octets: | 6 | 1 | 1 | 1 | 1 | 1 |
|---|---|---|---|---|---|---|
| Octet order: | 0-5 | 0 | 0 | 0 | 0 | 0 |
| | Sender Address | Beacon Shifting Sequence | Beacon Period Length | Allocation Slot Length | B+RAP1 Length | RAP2 Length |

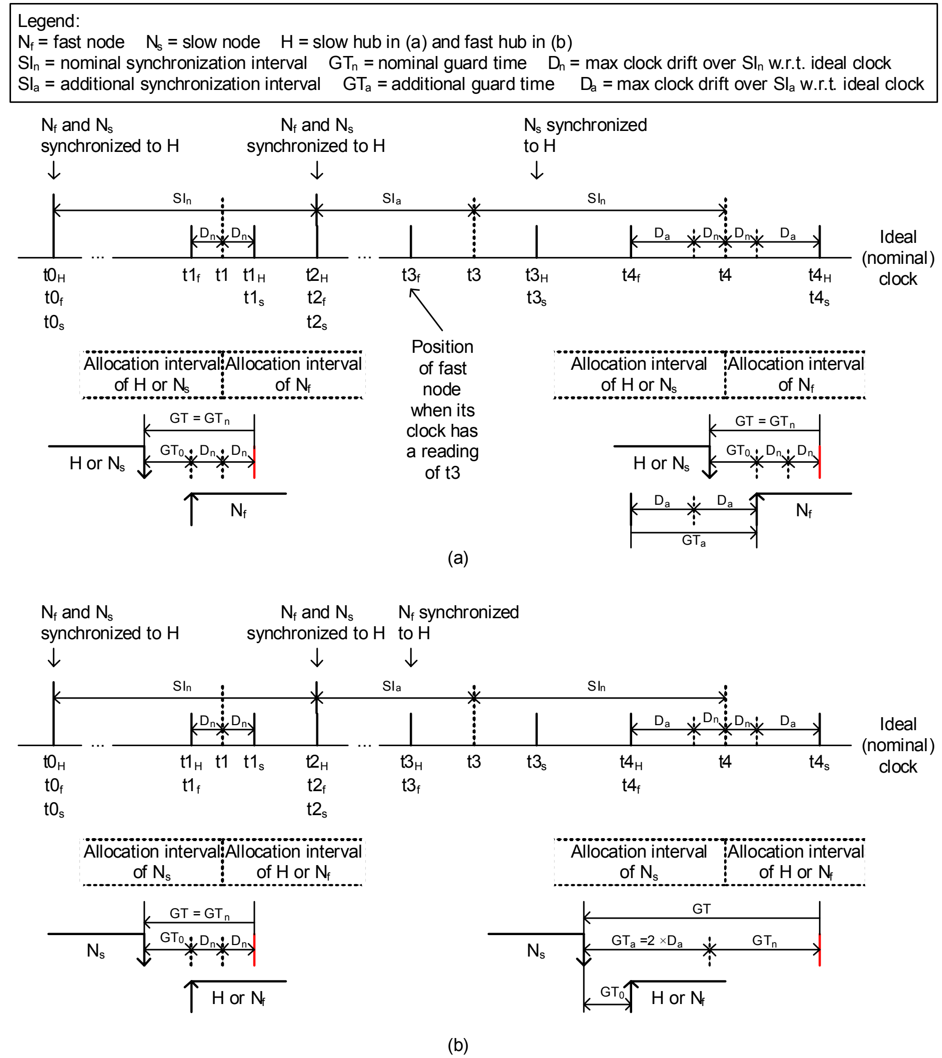
| Octets: | 1 | 1 | 1 | 1 | 2 |
|---|---|---|---|---|---|
| Octet order: | 0 | 0 | 0 | 0 | 0-1 |
| | Security Requirement | Security Capability | MAC Capability | PHY Capability | Channel Hopping State |

| Bits: | 4 | 4 |
|---|---|---|
| Bit order: | b0-b3 | b4-b7 |
| | Beacon PN Sequence Index | Beacon PN Sequence Phase |

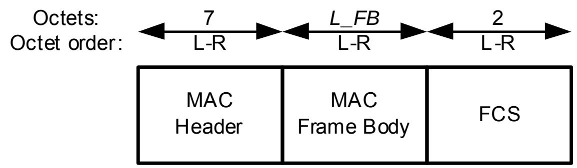
Beacon PN Sequence format

# Clock Synchronization & Guard Time Provisioning

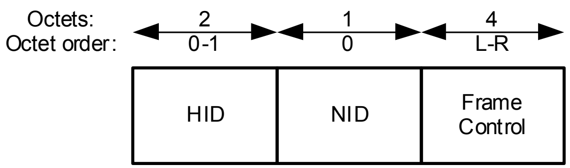
- All nodes synchronize to their hub through the beacons or the first frames in their scheduled allocation intervals received from the hub.
- Guard times are set aside at the start and/or end of each allocation interval.
- Synchronization interval (SIn) determined by system parameters and beacon's allocation slot length
  - Minimum allocation slot length (1msec), SIn = 1.5 seconds
  - Maximum allocation slot length (256 msec), SIn = 639 seconds
  - See MAC sublayer parameters
    - mGT_Nominal = Allocation Slot Length / 10
    - mClockAccuracy = 20 ppm
    - mClockResolution = 10 usec
    - mSyncResolution = 10 usec



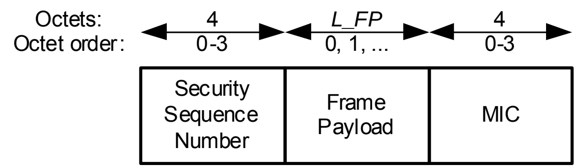
# MAC Frame Format




MAC frame format



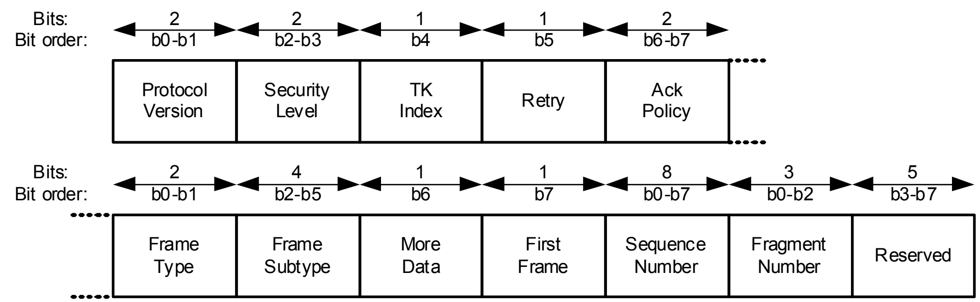

MAC header format




MAC frame body format

NID selection

| NID value in hex | NID notation | NID usage |
|---|---|---|
| x00 | Unconnected_Broad cast_NID | For broadcast to unconnected nodes |
| x01-0F | Unconnected_NID | For unicast to unconnected nodes |
| x10-EF | Connected_NID | For unicast to/from connected nodes |
| xF0-FE | Multicast_NID | For multicast to connected nodes |
| xFF | Broadcast_NID | For broadcast to all nodes |




Frame control format

# Frame Types and Subtypes

| Frame Type value b0 b1 | Frame Type name | Frame Subtype value b2 b3 b4 b5 | Frame Subtype name |
|---|---|---|---|
| 00 | Management | 0000 | Beacon |
| 00 | Management | 1000 | Reserved |
| 00 | Management | 0100 | Association |
| 00 | Management | 1100 | Disassociation |
| 00 | Management | 0010 | PTK |
| 00 | Management | 1010 | GTK |
| 00 | Management | 0110-1110 | Reserved |
| 00 | Management | 0001 | Connection Request |
| 00 | Management | 1001 | Connection Assignment |
| 00 | Management | 0101 | Disconnection |
| 00 | Management | 1101-1111 | Reserved |
| 10 | Control | 0000 | I-Ack |
| 10 | Control | 1000 | B-Ack |
| 10 | Control | 0100 | I-Ack+Poll |
| 10 | Control | 1100 | B-Ack+Poll |
| 10 | Control | 0010 | Poll |
| 10 | Control | 1010-1111 | Reserved |
| 01 | Data | 0000-1111 | User defined data subtype |
| 11 | Reserved | 0000-1111 | Reserved |

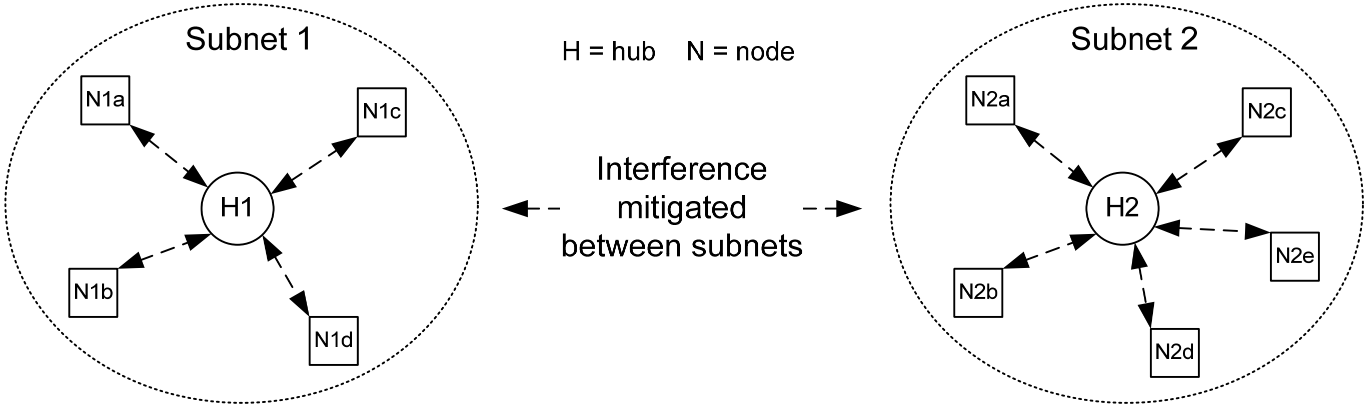
# MedWiN MAC and Security – MAC Presentation Updated from 0327-01

# Outline

- General framework
- Access methods
  - Scheduled access (one-periodic & multi-periodic allocations)
  - Improvised access (polled & posted allocations)
  - Random access (CSMA/CA contented allocations)
  - MICS band communication (no beacon transmission)
- Synchronization & guard time provisioning
- Power management
- Coexistence
- Acknowledgment policy
- MAC frame structure
  - MAC header
  - MAC frame body
  - Frame types & subtypes
  - Management and control frames

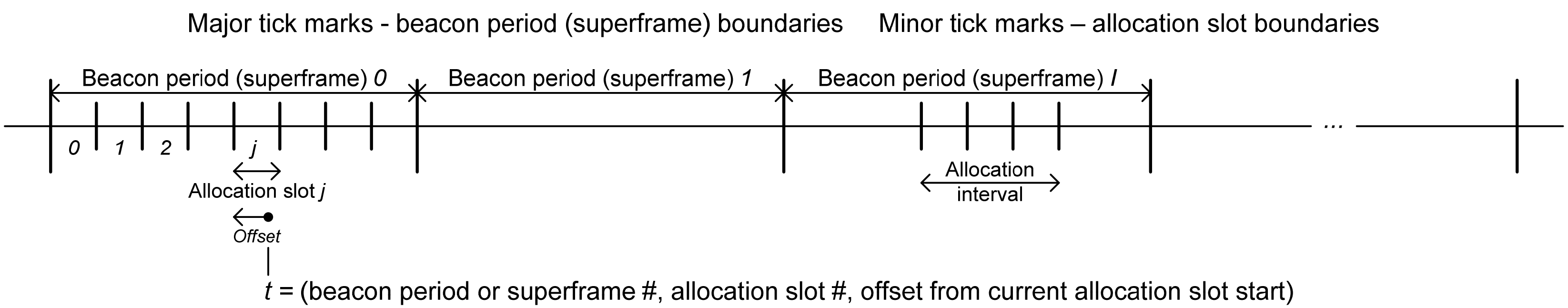
# Star Topology

- Centralized access – warranted for medical use cases
- Point to point – supported as a special case of star topology

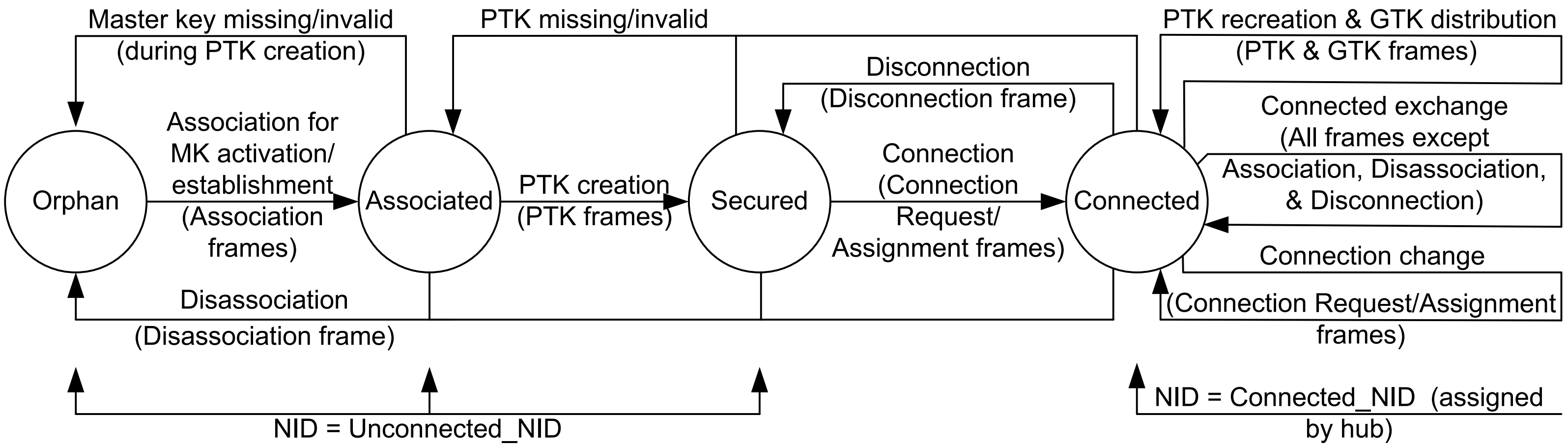


# Time Reference Base

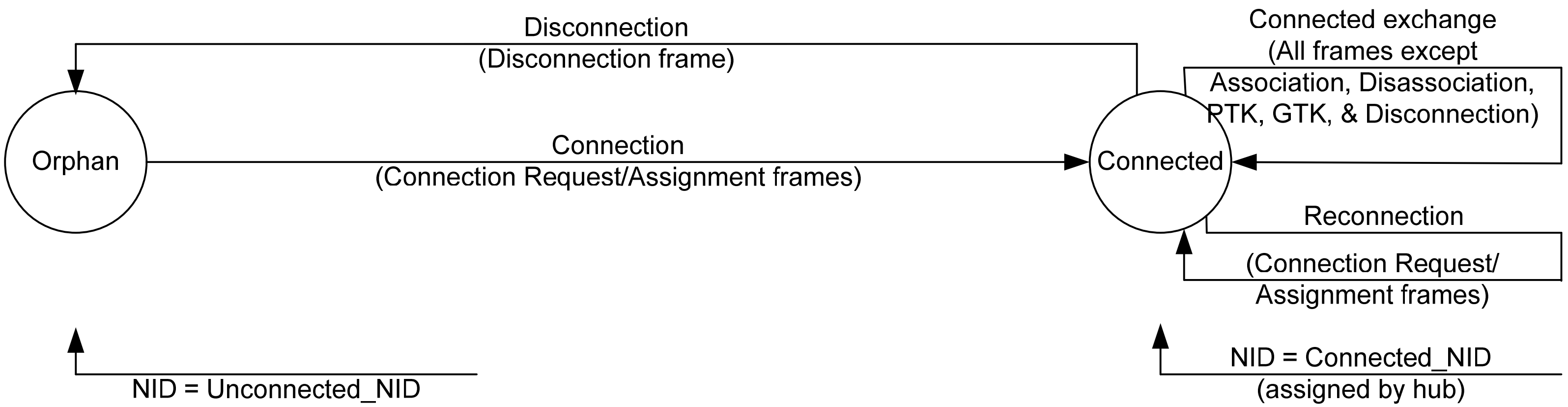
- Hub sets boundaries, and hence lengths, of beacon periods (superframes) and allocation slots
  - via transmission of beacons at specified locations of beacon periods, or/and
  - via transmission of T-Polls containing a timestamp referenced to the boundaries of a specific beacon period (superframe) and allocation slot
- Nodes derive and recalibrate these boundaries
  - via reception of beacons or/and T-Polls
- A node and a hub obtain allocation intervals for frame exchanges
  - by one or more of three access methods (scheduled, improvised, and random)
  - with the start and end of an allocation interval unambiguously specified in reference to the boundaries of specific beacon period and allocation slots



# Access State Diagram



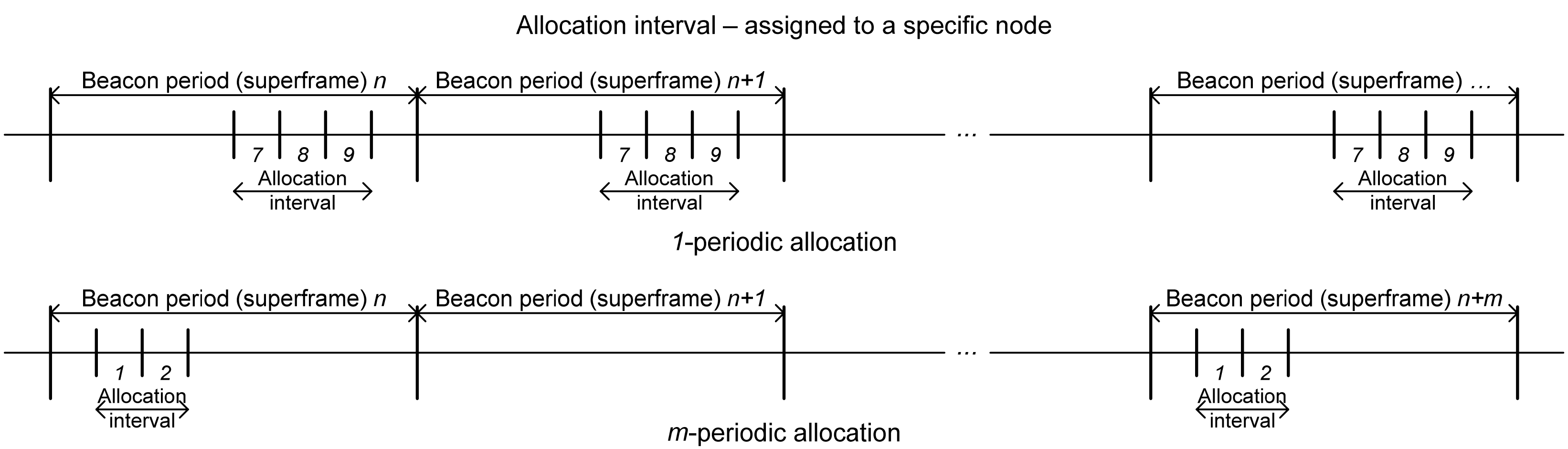

**(a) Secured communication**



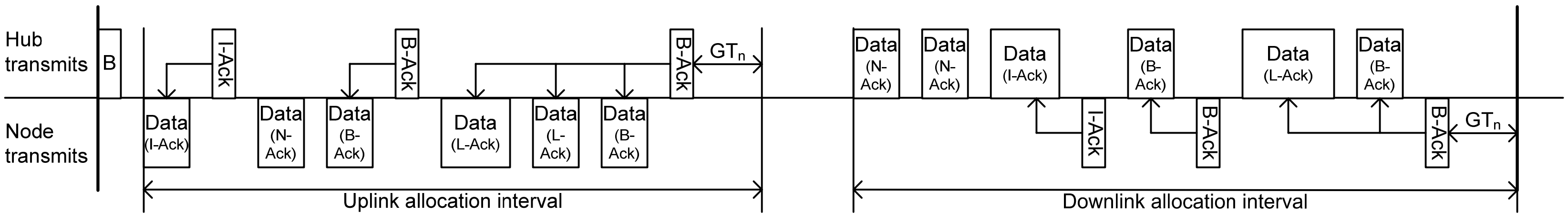

**(b) Unsecured communication**

# Scheduled Access

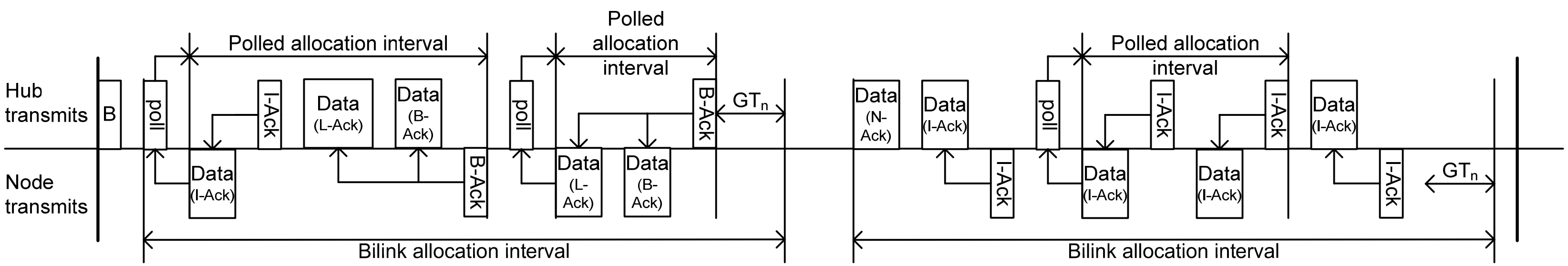
- Periodic allocations are set up via management (connection) frames
  - Node sends Connection Request frame, and hub returns Connection Assignment frame
- Allocation intervals reoccur every beacon period or every *m ( >1)* beacon periods
  - Comprise identically-numbered allocation slots in their reoccurring beacon periods
  - Start and end at allocation slot boundaries
  - Fixed until modified via another Connection Assignment frame
  - Not announced in beacons – node listens to a beacon occasionally for synchronization
- Allocation intervals are for downlink, uplink, or bilink data transfers
  - Uplink: node initiates uplink data transfer and hub acknowledges when required
  - Downlink: hub initiates downlink data transfer and node acknowledges when required
  - Bilink: hub initiates downlink data transfer or polls node for uplink data transfer



# Scheduled Access – Frame Transactions




Transmissions in uplink and downlink allocation intervals




Transmissions in bilink allocation intervals

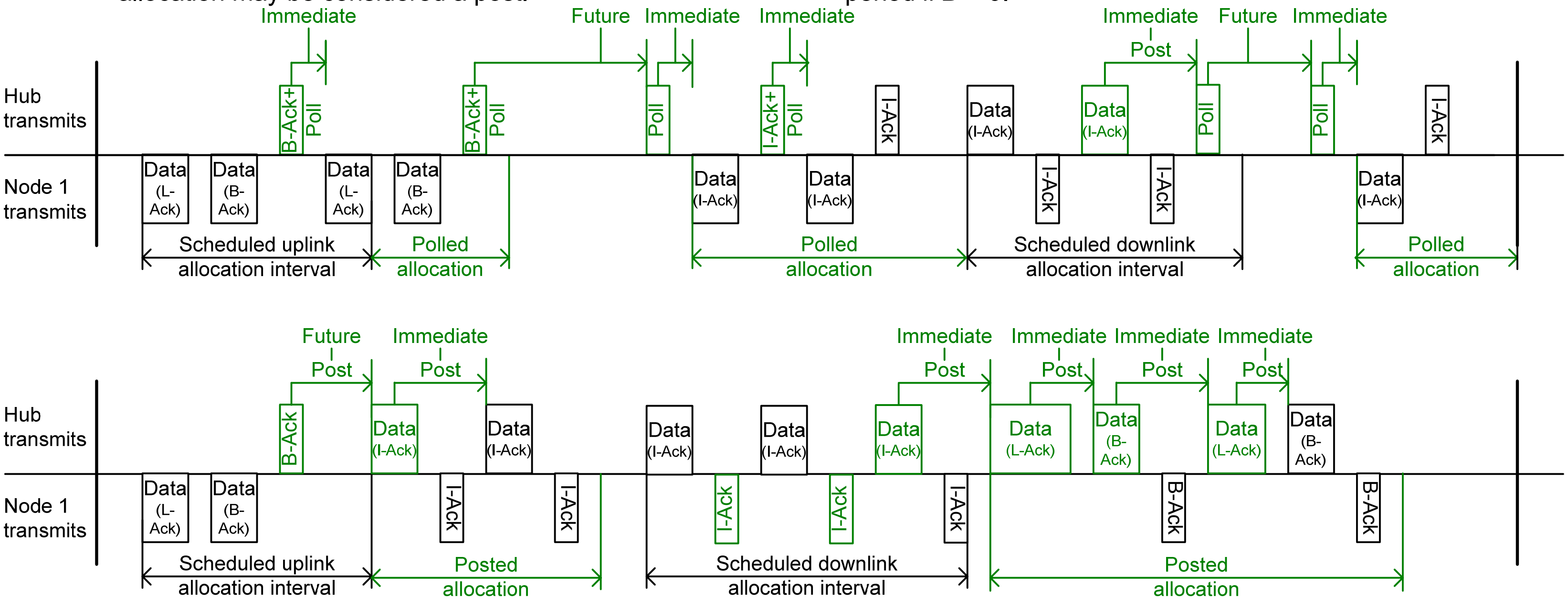
# Improvised Access

- Polled and posted allocations are not set up via management (connection) frames but improvised by hub via piggybacked control or data/management frames
  - Hub grants a polled or posted allocation by piggybacking allocation information into some MAC header fields of a control (I-Ack, B-Ack, Poll, and T-Poll) or data/management frame
  - Node indicates desire to have a polled allocation for uplink data transmission by setting More Data bit in a currently transmitted frame
- Polled and posted allocation intervals are one-time immediate or future grants
  - An immediate polled or posted allocation interval starts immediately after the end of the current frame transaction (ended with I-Ack or B-Ack if required) and ends at an allocation slot in the current beacon period (superframe) as specified in the piggybacked allocation information
  - A future polled or posted allocation interval comprises one or more contiguous allocation slots somewhere in the near future as also specified in the piggybacked allocation information
  - A polled or posted allocation interval may be extended by another immediate polled or posted allocation interval, again via a piggybacked control or data/management frame transmitted in the current interval
- Polled allocations are for uplink and posted allocations are for downlink
  - Uplink: hub sends a poll piggybacked in an I-Ack or B-Ack frame or explicitly via a Poll or T-Poll in the existing allocation interval (not obtained via this poll), which then starts a polled allocation interval, in which the polled node sends data, and hub acknowledges when required
  - Downlink: hub piggybacks a post in a non-beacon management or data frame in the existing allocation interval (not obtained via this post), which then starts a posted allocation interval, in which hub sends data, and node acknowledges when required

# Improvised Access – Frame Transactions

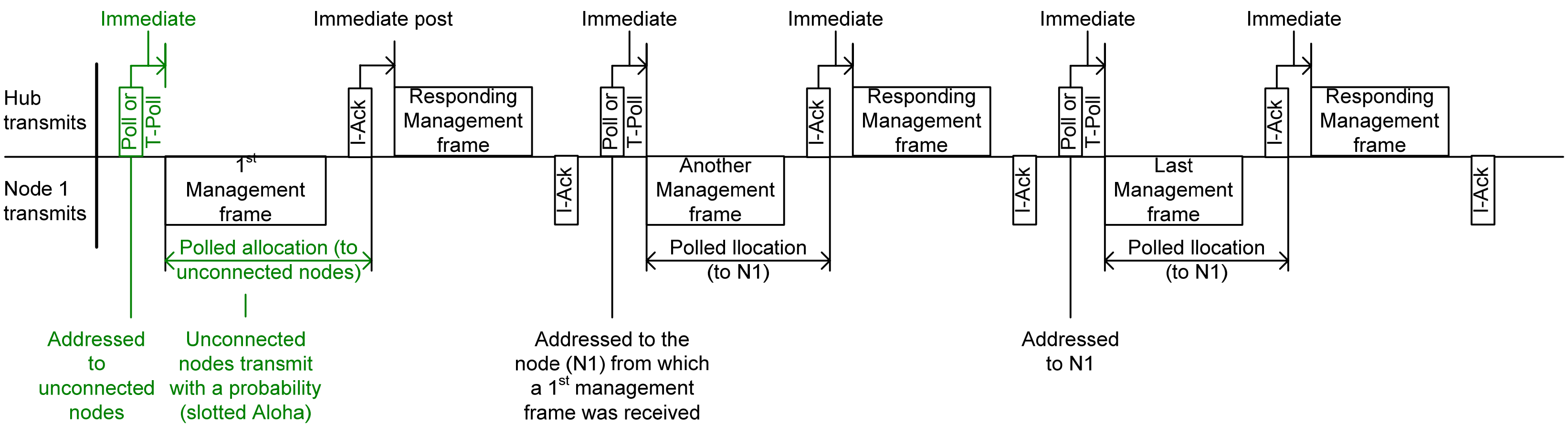
**Table — Frames and fields sent by a hub enabling polls and posts**

| | Short distance (immediate) | Long distance (future) |
|---|---|---|
| Poll | I-Ack+Poll, B-Ack+Poll, Poll, or T-Poll frame, with More Data = 0, Sequence Number = *A*, Fragment Number = *Reserved*: A polled allocation starts pTIFS after the end of the current frame, and ends at the end of allocation slot *A* located in the current beacon period. | I-Ack+Poll, B-Ack+Poll, Poll, or T-Poll frame, with More Data = 1, Sequence Number = *A*, Fragment Number = *B*: No polled allocation follows this frame, but another poll starts at the start of allocation slot *A* located in the current beacon period if *B* = 0 or in the next *B*th beacon period if *B* > 0. |
| Post | Non-beacon management or data type frame, with More Data = 1: A post starts pTIFS after the end of the current frame transaction. A poll providing another poll but not a polled allocation may be considered a post. | I-Ack or B-Ack frame, with More Data = 1, Sequence Number = *A*, Fragment Number = *B*: A post starts at the start of allocation slot *A* located in the current beacon period if *B* = 0 or in the next *B*th beacon period if *B* > 0. |



# Unconnected Exchange

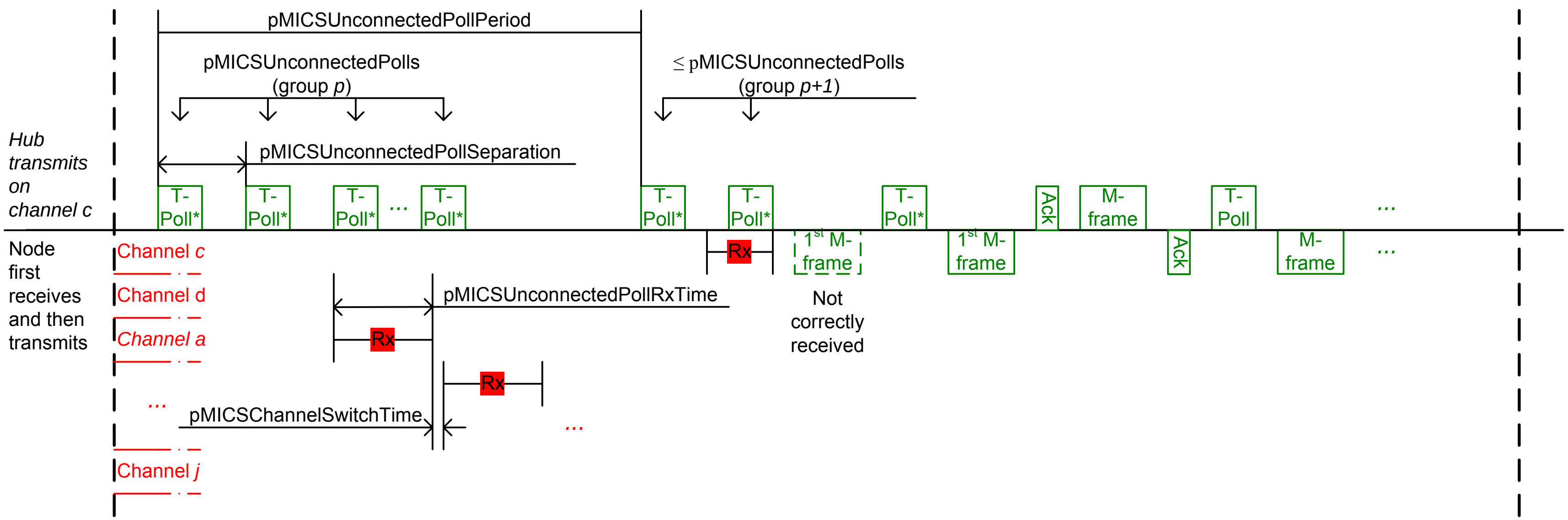
- Polls addressed to unconnected nodes provide polled allocations to unconnected nodes for the transmission of their 1st pre-connection frame to hub
  - Unconnected nodes transmit their 1st pre-connection frame to hub with a probability (slotted aloha contention) to reduce and resolve collisions
  - Hub subsequently sends posts and polls addressed to a specific unconnected node to provide contention-free posted and polled allocations to that node for exchange of the remaining pre-connection frames



# MICS Band Unconnected Exchange

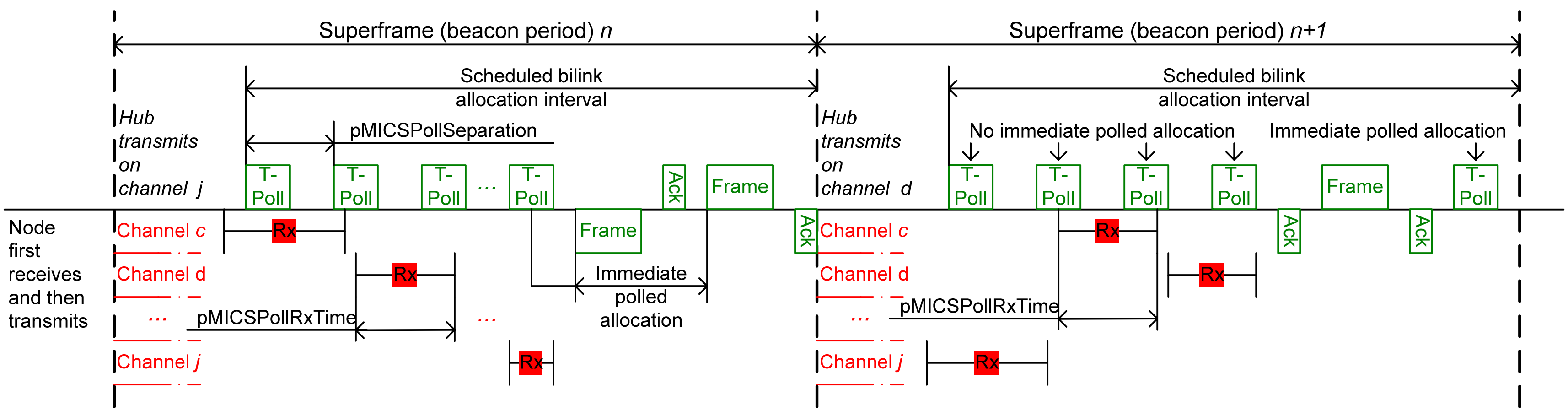
- Once a while hub chooses a channel and sends a group of T-Polls addressed to unconnected nodes
  - T-Polls within a group are separated such that hub can detect a response following the last poll before sending the next poll
  - Enough T-Polls in each group are sent such that a node (implant) can encounter one even in the worst case of having to cycling through all the MICS channels
  - Unconnected nodes use Aloha with a transmit probability to transmit its 1st management to hub following a received T-Poll addressed to unconnected nodes
  - Hub uses improvised access to advance unconnected exchange to connection

T-Poll* = unconnected T-Poll M-frame = management frame prior to connection Ack = I-Ack



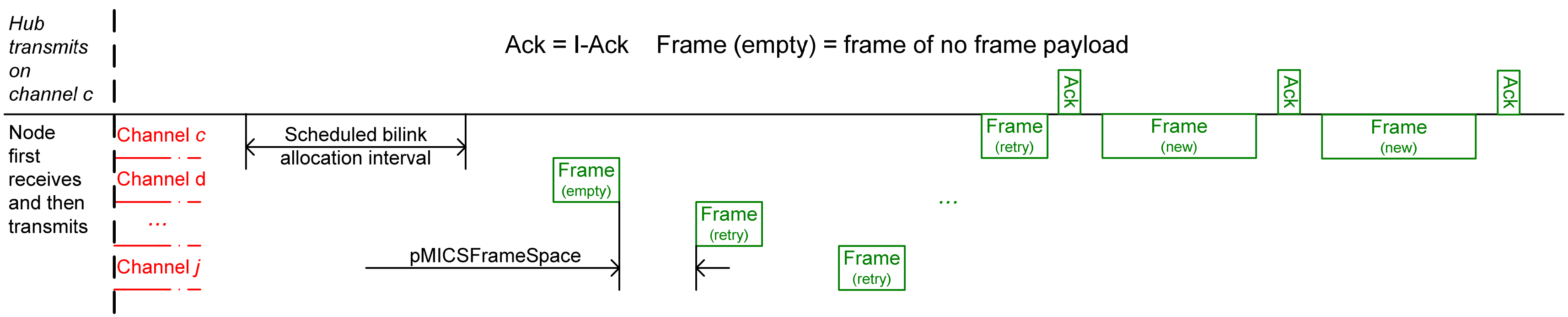
# MICS Band Connected Exchange

- Node (implant) and hub set up a scheduled periodic bilink allocation
  - The period of the allocation intervals is set based on application's service demand
  - Hub sends one or more T-Polls to node at start of each scheduled allocation interval
  - At some guardtime before the start of such an interval, node first tunes to last channel in which it received a frame from hub, cycling through other channels until receiving a frame from hub
  - Hub may send downlink data in or following such an interval



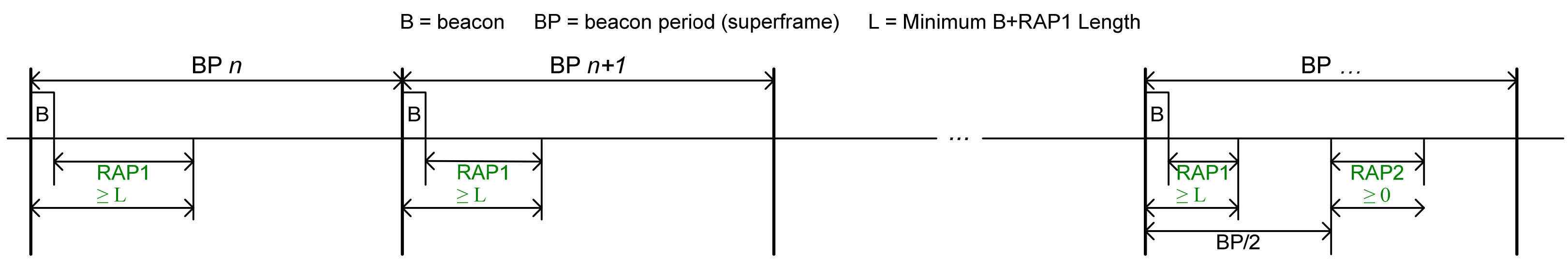
# MICS Band Medical Implant Event Report

- Node (implant) waits for the next scheduled bilink allocation interval
  - if it is not two far away
- Node (implant) initiates transmission outside scheduled allocation intervals
  - Node first sends a frame of no frame payload with a Data Subtype = 7 on the last channel in which it received a frame from hub, switching to another channel after failing to receive an acknowledgment
  - Hub gives node medium access on receiving such a frame, suspending any impending downlink data or management frame transmissions
  - Node then proceeds to send the data frames containing frame payloads generated from the medical implant event



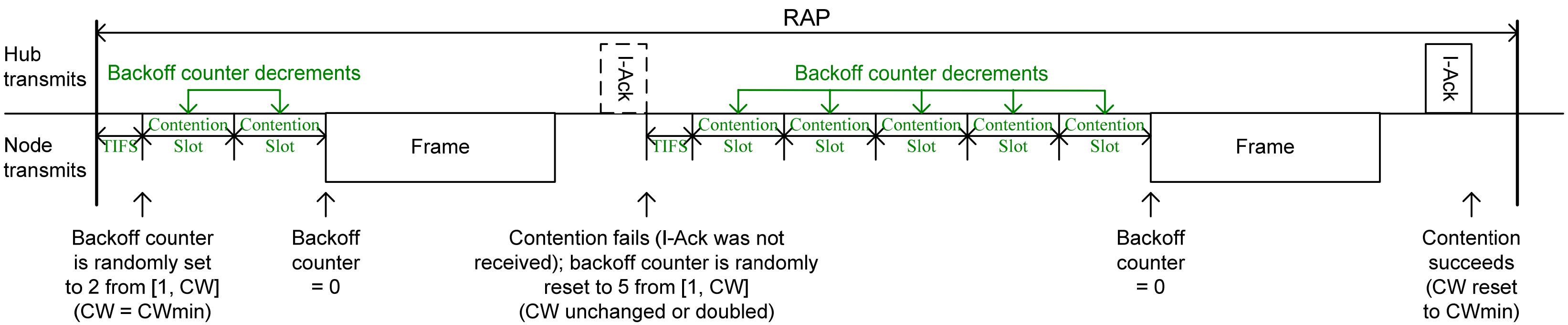
# Random Access

- Up to two random access phases (RAPs) are provided by hub in each beacon period
  - RAP1 follows the beacon immediately and is guaranteed to have at least the minimum length communicated to each node during connection via Connection Assignment frame
  - RAP2 is half beacon period apart from the beacon and is optional in any beacon period
  - The minimum length of RAP1 may be zero →in this case RAP1 is optional as well
  - No beacon or RAPs are allowed in any beacon period in the MICS band
- RAP1 is most power friendly and RAP2 is still acceptable to many devices
  - If RAP1 has a minimum length, it is like a scheduled interval for random access – a node does not need to receive a beacon to use it for contention
  - A node finds the duration of RAP2 by listening to the beacon in the preceding beacon period

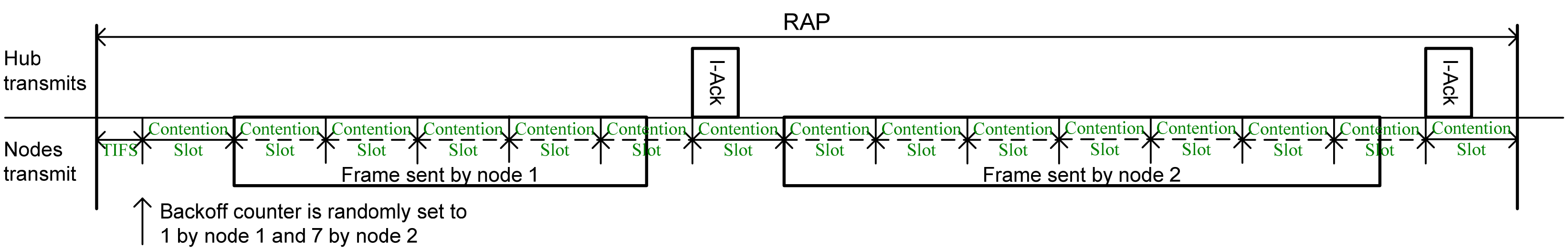


# Random Access – CSMA/CA

- A contended allocation is obtained in a RAP by a node using CSMA with backoff
  - Node sets its backoff counter to an integer randomly drawn from [1, CW], decrementing the counter by one over each idle contention slot, and initiating a transmission when the counter reaches zero
  - CW is set to CWmin initially and doubled (up to CWmax) after 2 consecutive contention failures
  - Node re-randomizes its backoff counter (and hence transmit time) on each contention failure
  - Higher priority traffic is given smaller CWmin and CWmax numbers, and hence smaller backoff counter values and earlier transmit times




- CSMA degenerates to pure aloha when carrier sensing is disabled (shown below)
  - Backoff counter serves to randomize (spread) transmit times of contending nodes



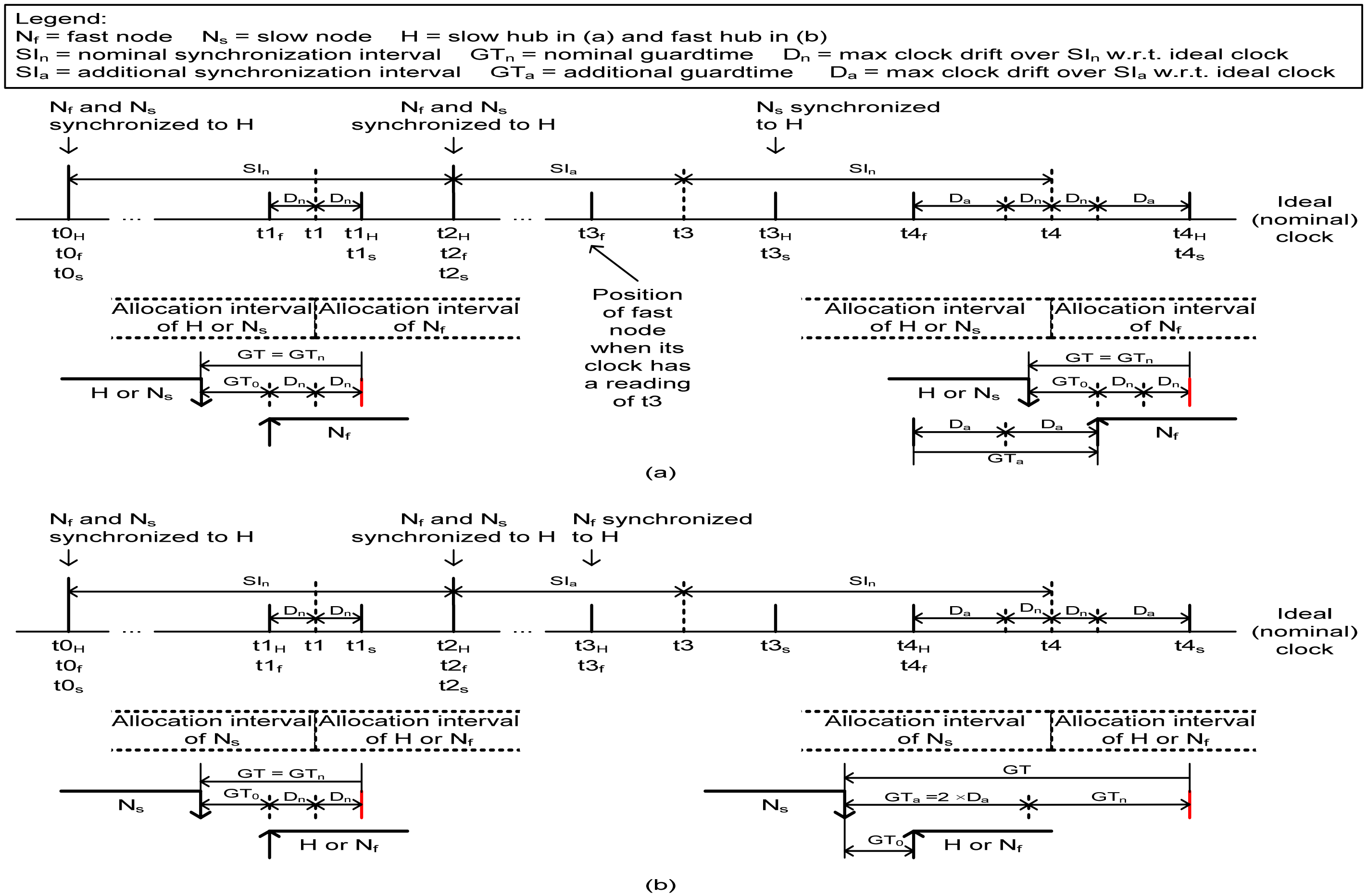
# Random Access – Prioritization

| Priority | User Priority | Traffic designation | CWmin | CWmax |
|---|---|---|---|---|
| Lowest | 0 | Background (BK) | 16 | 64 |
| | 1 | Best effort (BE) | 16 | 32 |
| | 2 | Excellent effort (EE) | 8 | 32 |
| | 3 | Controlled load (CL) | 8 | 16 |
| | 4 | Video (VI) | 4 | 16 |
| | 5 | Voice (VO) | 4 | 8 |
| | 6 | Network control | 2 | 8 |
| Highest | 7 | Emergency or medical event report | 1 | 4 |

# Clock Synchronization & Guardtime Provisioning

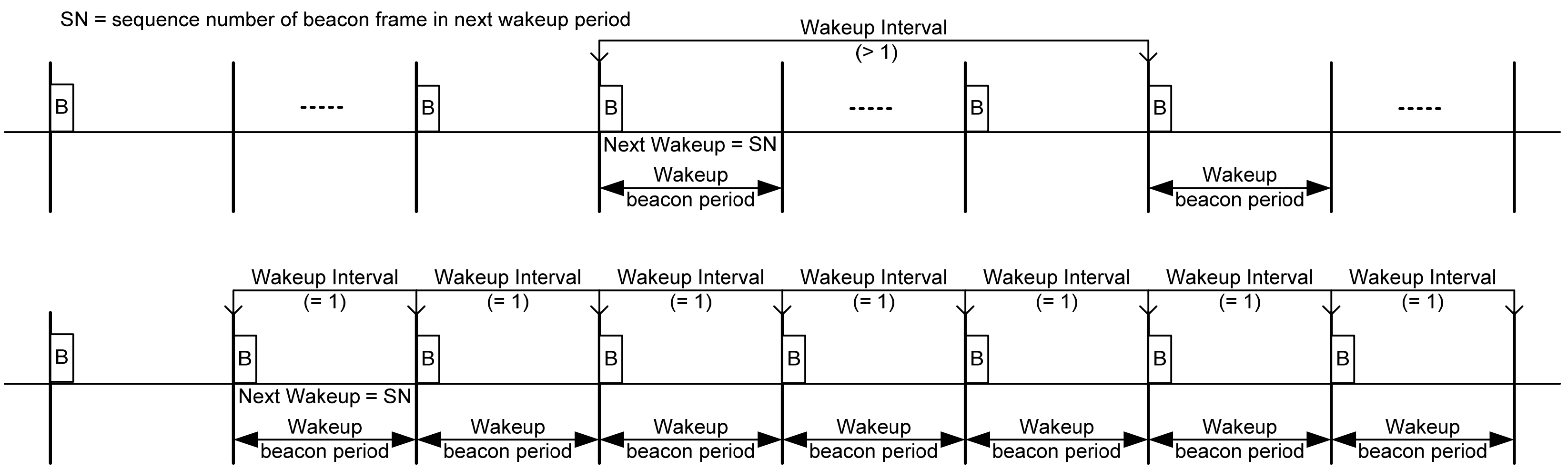
- All nodes synchronize to their hub through the beacons, T-Polls, or the first frames in their scheduled allocation intervals received from the hub.
- Guard times are set aside at the start and/or end of each allocation interval.

Transmission could go all the way to the red line without a guard time, hence colliding with transmission from someone else in next allocation interval.



# Power Management - Macroscopic

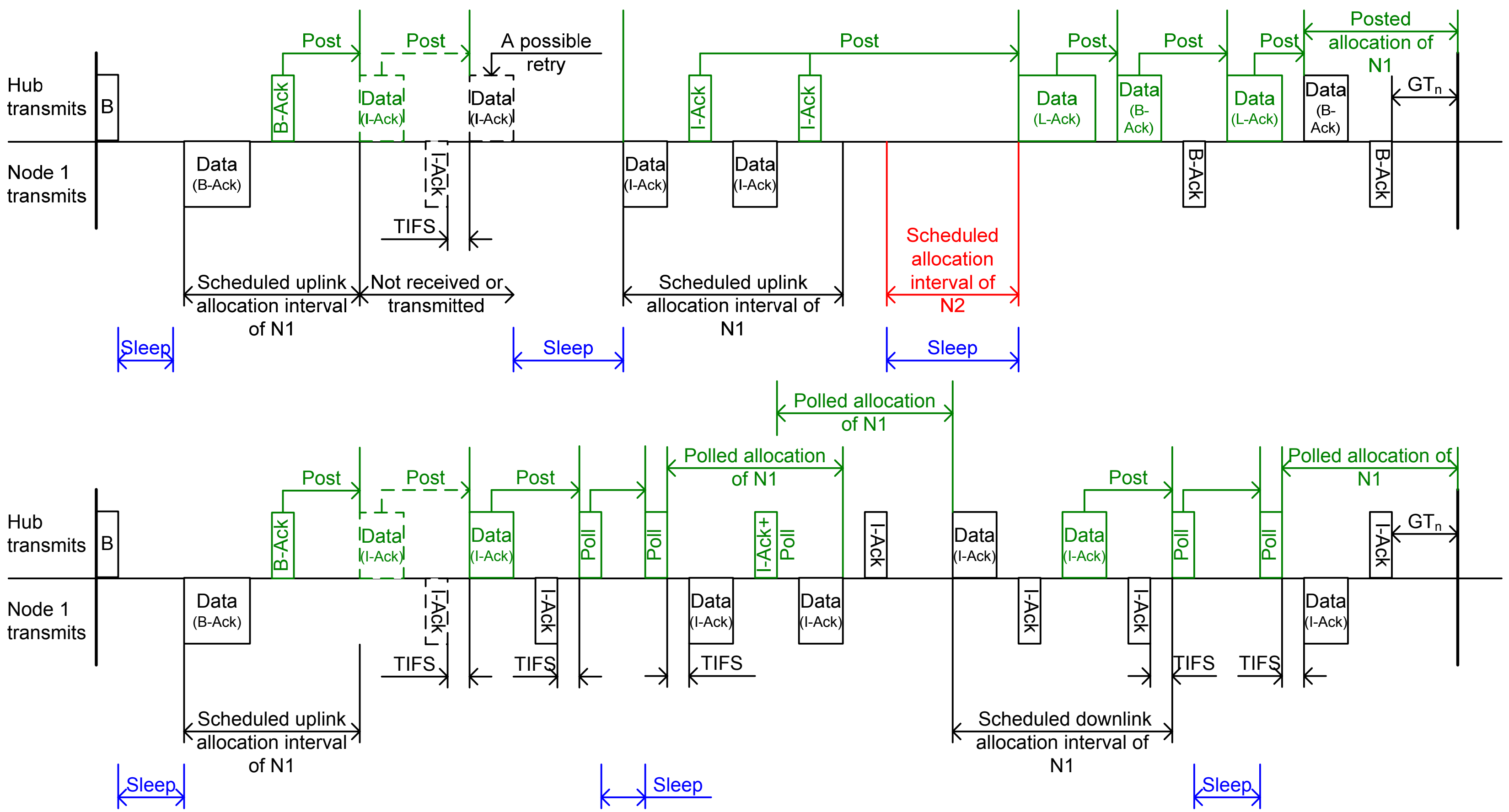
- Hibernation – across beacon periods (superframes)
  - A node negotiates its wakeup beacon period and wakeup interval with a hub through exchanges of Connection Request and Connection Assignment.
  - Wakeup Interval P > 1: a device needs to wake up only in a wakeup beacon period out of P beacon periods
  - Wakeup Interval P = 1: a device needs to wake up in every beacon period



# Power Management - Microscopic

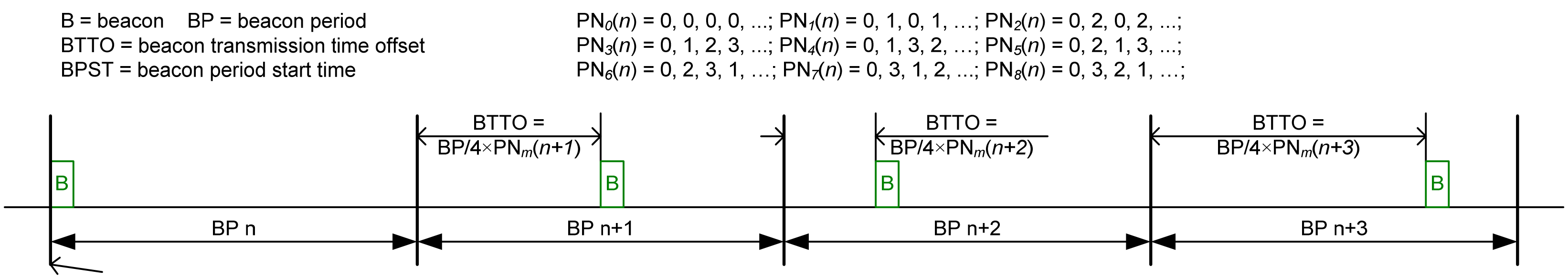
- Sleep – within wakeup beacon period (superframe)
  - A node may sleep outside its allocation intervals in a wakeup beacon period.

B = beacon Post = post to node 1 N1 = node 1 N2 = node 2 TIFS = pTIFS Sleep = sleep interval of node 1



# Coexistence – Beacon Shifting

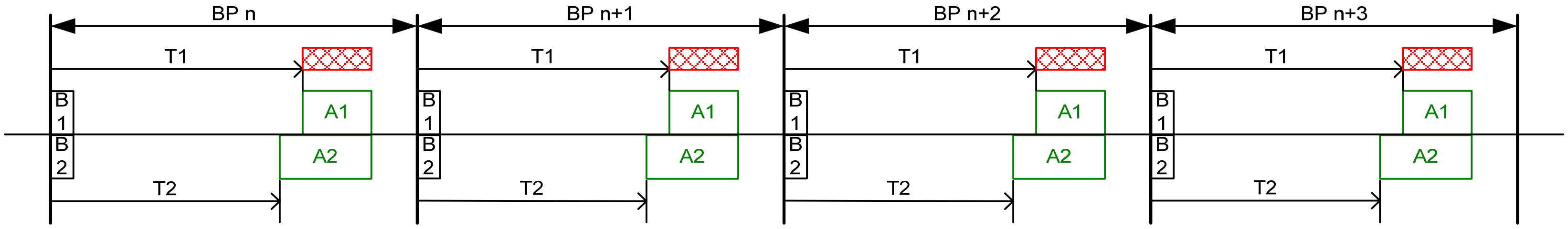
- Beacon shifting of each BAN in time domain
  - Hub selects a PN sequence $PN_m(n)$ to shift its beacon transmission time across beacon periods
  - All scheduled allocation intervals shift cyclically within a beacon period with the shifted beacon transmission time
  - A hub may choose $PN_0(n) = 0$ to transmit its beacon period start
  - Beacon message contains shifting sequence index and phase for the next period
  - Use of quarter beacon period fixed offsets simplifies implementation



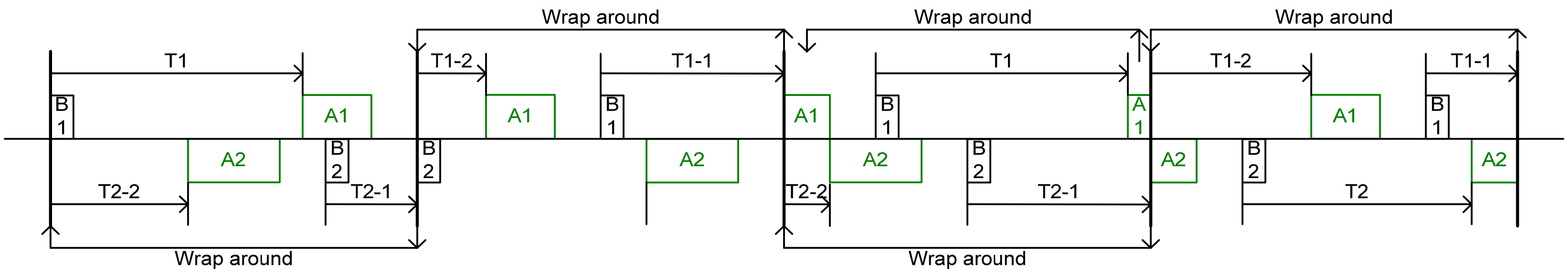

*Beacon transmission with shifting sequence $PN_5(n)$ = 0, 2, 1, 3*

# Beacon Shifting – Interference Mitigation

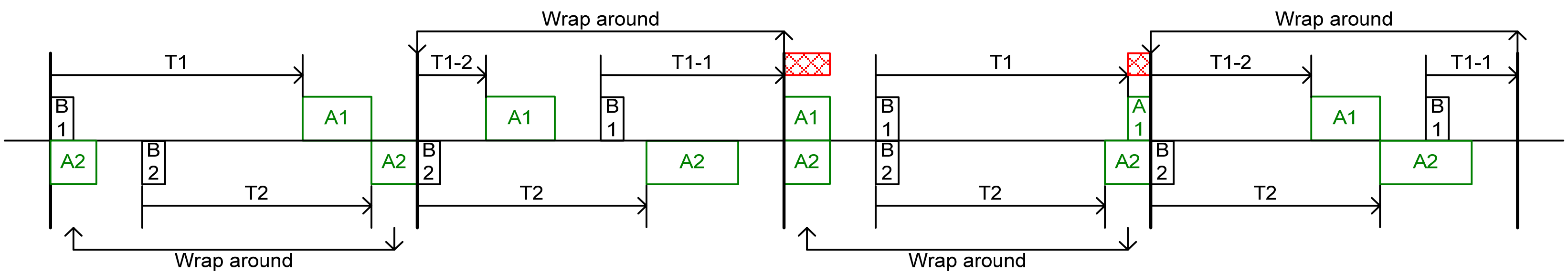
Bn = beacon transmitted by subnet of node n BP = beacon period BTTO = beacon transmission time offset
An = 1-periodic allocation interval of node n Tn = interval start of An relative to beacon transmission time Tn = Tn-1 + Tn-2




(a) Subnet of node 1: $PN_0(n)$ = 0, 0, 0, 0, ...; subnet of node 2: $PN_0(n)$ = 0, 0, 0, 0, ...



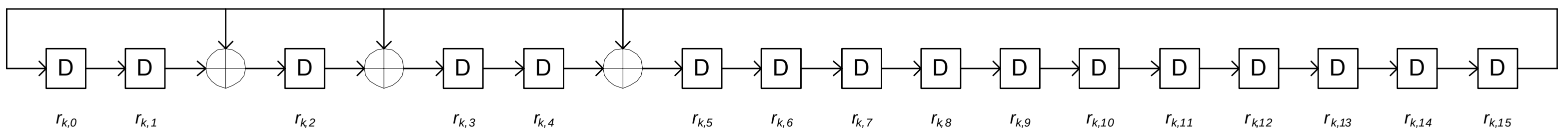

(b) Subnet of node 1: $PN_5(n)$ = 0, 2, 1, 3, ...; subnet of node 2: $PN_5(n-1)$ = 3, 0, 2, 1, ...




(c) Subnet of node 1: $PN_5(n)$ = 0, 2, 1, 3, ...; subnet of node 2: $PN_1(n+1)$ = 1, 0,1, 0, ...

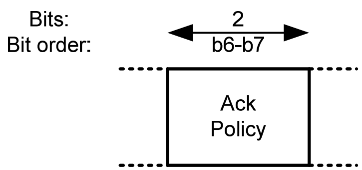
# Coexistence – Channel Hopping

- Channel hopping of each BAN enables frequency diversity
  - Hub generates channel hop sequence using linear feedback shift register (LFSR)
    - Least significant 16 bits of hub MAC address used to initialize LFSR
    - Beacon messages contain LFSR status and indication of imminent change
  - LFSR mapped to channel ensuring equal probability selection and minimum frequency separation
  - Hub dwells on current channel for fixed number of beacon periods
  - Connection Assignment contains dwell length and phase
  - Can be disabled for single frequency channel operation

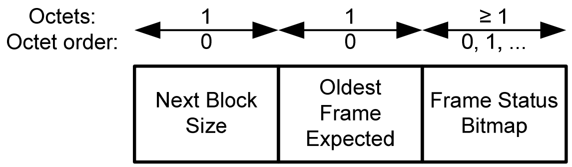



*16-bit Galois LFSR for channel hopping sequence generation*

# Acknowledgment Policy



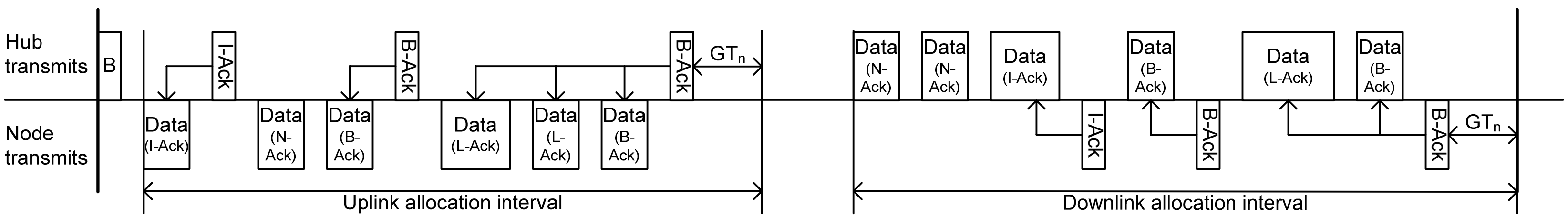

Frame Control format



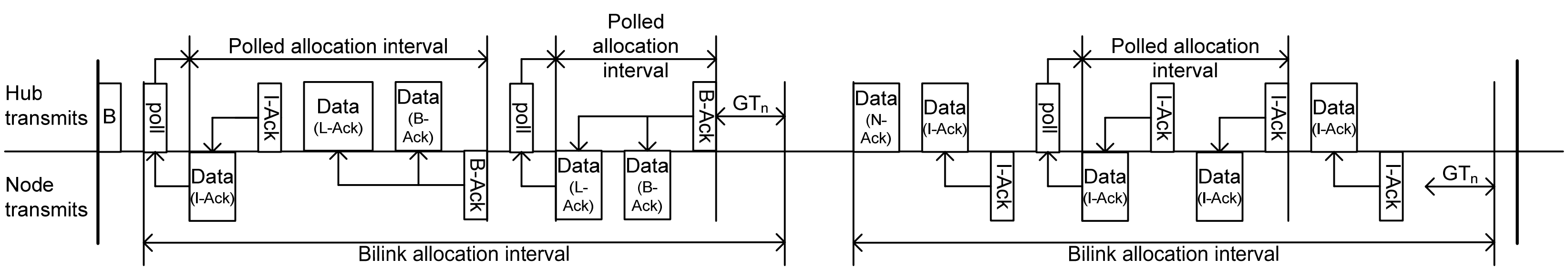

Frame Payload format for B-Ack frames

**Table — Acknowledgment (Ack) Policy field encoding**

| Field value b6 b7 | Acknowledgment requirement |
|---|---|
| 00 | No acknowledgment (N-Ack) |
| 10 | Immediate acknowledgment (I-Ack) |
| 11 | Block acknowledgment later (L-Ack) |
| 01 | Block acknowledgment (B-Ack) |

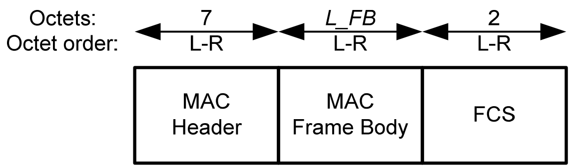



Transmissions in uplink and downlink allocation intervals

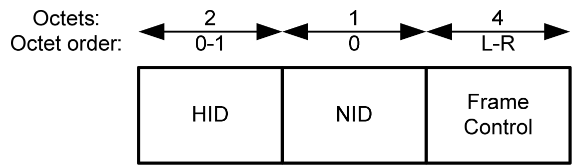



Transmissions in bilink allocation intervals

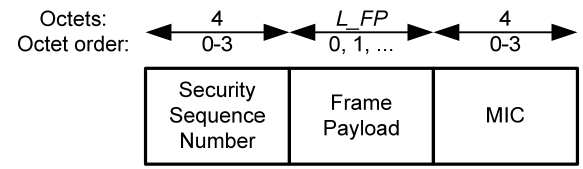
# Frame Format




MAC frame format



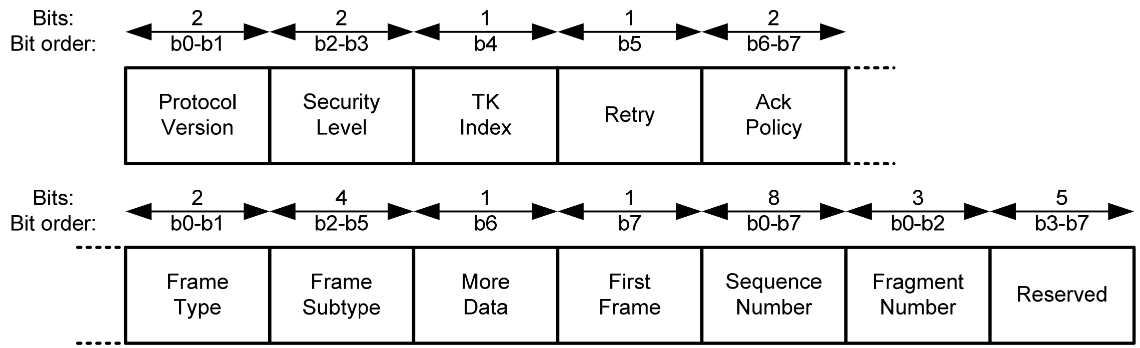

MAC Header format




MAC Frame Body format

**Table — NID selection**

| NID value in hex | NID notation | NID usage |
|---|---|---|
| x00 | Broadcast_Unconnected_NID | For broadcast to unconnected nodes |
| x01-0F | Unconnected_NID | For unicast to unconnected nodes |
| x10-EF | Connected_NID | For unicast to/from connected nodes |
| xF0-FE | Multicast_NID | For multicast to connected nodes |
| xFF | Broadcast_NID | For broadcast to all nodes |




Frame Control format

# Frame Types and Subtypes

| Frame Type value b0 b1 | Frame Type name | Frame Subtype value b2 b3 b4 b5 | Frame Subtype name |
|---|---|---|---|
| 00 | Management | 0000 | Beacon |
| 00 | Management | 1000 | Reserved |
| 00 | Management | 0100 | Association |
| 00 | Management | 1100 | Disassociation |
| 00 | Management | 0010 | PTK |
| 00 | Management | 1010 | GTK |
| 00 | Management | 0110-1110 | Reserved |
| 00 | Management | 0001 | Connection Request |
| 00 | Management | 1001 | Connection Assignment |
| 00 | Management | 0101 | Disconnection |
| 00 | Management | 1101-1111 | Reserved |
| 10 | Control | 0000 | I-Ack |
| 10 | Control | 1000 | B-Ack |
| 10 | Control | 0100 | I-Ack+Poll |
| 10 | Control | 1100 | B-Ack+Poll |
| 10 | Control | 0010 | Poll |
| 10 | Control | 1010 | T-Poll |
| 10 | Control | 0110-1111 | Reserved |
| 01 | Data | 0000-1111 | User defined data subtype |
| 11 | Reserved | 0000-1111 | Reserved |

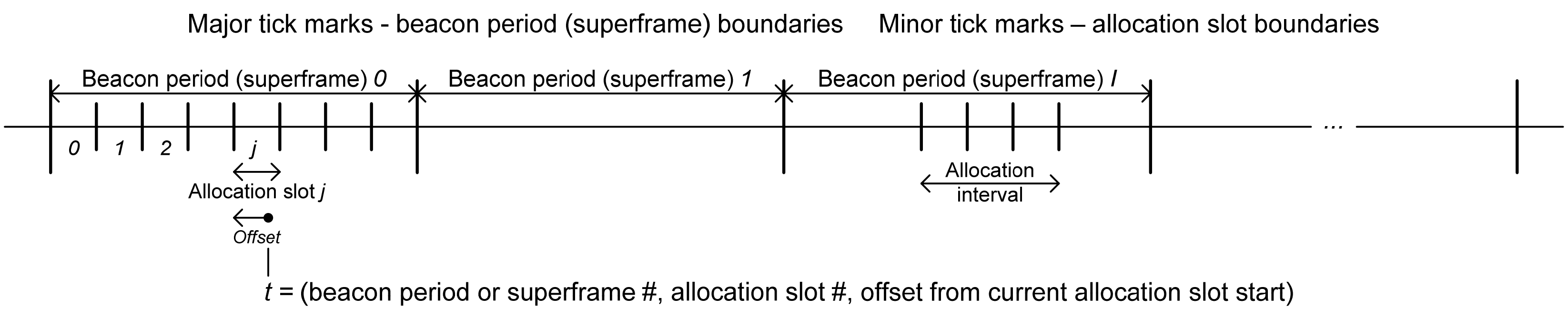
# T-Poll Frames

| Octets: | 1 | 1 | 2 |
|---|---|---|---|
| Octet order: | 0 | 0 | 0-1 |
| | Current Beacon Period | Current Allocation Slot | Current Slot Offset |

(a) NID ≠ Unconnected_Broadcast_NID

| Octets: | 1 | 1 | 2 | 1 | 1 |
|---|---|---|---|---|---|
| Octet order: | 0 | 0 | 0-1 | 0 | 0 |
| | Current Beacon Period | Current Allocation Slot | Current Slot Offset | Beacon Period Length | Allocation Slot Length |

(b) NID = Unconnected_Broadcast_NID



# Beacon Frames

| Octets: | 6 | 1 | 1 | 1 | 1 | 1 |
|---|---|---|---|---|---|---|
| Octet order: | 0-5 | 0 | 0 | 0 | 0 | 0 |
| | Sender Address | Beacon Shifting Sequence | Beacon Period Length | Allocation Slot Length | B+RAP1 Length | RAP2 Length |

| Octets: | 1 | 1 | 1 | 1 | 2 |
|---|---|---|---|---|---|
| Octet order: | 0 | 0 | 0 | 0 | 0-1 |
| | Security Requirement | Security Capability | MAC Capability | PHY Capability | Channel Hopping State |

| Bits: | 2 | 1 | 5 |
|---|---|---|---|
| Bit order: | b0-b1 | b2 | b3-b7 |
| | Lowest Security Level Required | Control Frame Authentication | Reserved |

Security Requirement format

| Bits: | 2 | 1 | 1 | 1 | 1 | 1 | 1 |
|---|---|---|---|---|---|---|---|
| Bit order: | b0-b1 | b2 | b3 | b4 | b5 | b6 | b7 |
| | Security Support | Master Key Pre-shared Association | Unauthen-ticated Association | Public Key Hidden Association | Password Authenticated Association | Display Authenticated Association | Reserved |

Security Capability format

| Bits: | 1 | 1 | 1 | 5 |
|---|---|---|---|---|
| Bit order: | b0 | b1 | b2 | b3-b7 |
| | B-Ack Support | Poll Support | Random Access Support | Reserved |

MAC Capability format

| Bits: | 1 | | 1 |
|---|---|---|---|
| Bit order: | b0 | | b7 |
| | Data Rate 1 | … | Data Rate 8 |

PHY Capability format

# Connection Request Frames

| Octets: | 6 | 6 | 6 | 1 | 1 | 1 |
|---|---|---|---|---|---|---|
| Octet order: | 0-5 | 0-5 | 0-5 | 0 | 0 | 0 |
| | Recipient Address | Sender Address | Former Hub Address | Security Requirement | Security Capability | MAC Capability |

| Octets: | 1 | 1 | 1 | 1 | ≥ 7 | ≥ 7 | ≥ 7 |
|---|---|---|---|---|---|---|---|
| Octet order: | 0 | 0 | 0 | 0 | L-R | L-R | L-R |
| | PHY Capability | Change Indication | Next Wakeup | Wakeup Interval | Uplink Request IE | Downlink Request IE | Bilink Request IE |

| Octets: | 1 | 1 | 5 | | 5 |
|---|---|---|---|---|---|
| Octet order: | 0 | 0 | L-R | | L-R |
| | Element ID | Length (= 5N) | Allocation Request 1 | … | Allocation Request N |

Uplink/Downlink/Bilink Request IE format

| Bits: | 4 | 4 | 8 | 8 | 8 | 8 |
|---|---|---|---|---|---|---|
| Bit order: | b0-b3 | b4-b7 | b0-b7 | b0-b7 | b0-b7 | b0-b7 |
| | Frame Subtype | User Priority | Maximum Gap | Minimum Gap | Minimum Length | Allocation Length |
| | Allocation ID | | | | | |

Allocation Request format

# Connection Assignment Frames

| Octets: | 6 | 6 | 1 | 1 | 1 | 1 |
|---|---|---|---|---|---|---|
| Octet order: | 0-5 | 0-5 | 0 | 0 | 0 | 0 |
| | Recipient Address | Sender Address | Channel Dwell Length | Channel Dwell Phase | Minimum B+RAP1 Length | Status Code |

| Octets: | 1 | 1 | 1 | 1 | 1 | 1 |
|---|---|---|---|---|---|---|
| Octet order: | 0 | 0 | 0 | 0 | 0 | 0 |
| | Security Requirement | Security Capability | MAC Capability | PHY Capability | NID | Change Indication |

| Octets: | 1 | 1 | ≥ 5 | ≥ 5 | ≥ 5 | ≥ 1 |
|---|---|---|---|---|---|---|
| Octet order: | 0 | 0 | L-R | L-R | L-R | L-R |
| | Next Wakeup | Wakeup Interval | Uplink Assignment IE | Downlink Assignment IE | Bilink Assignment IE | Channel Order IE |

| Bits: | 1 | 1 | 1 | 1 | 1 | 1 | 2 |
|---|---|---|---|---|---|---|---|
| Bit order: | b0 | b1 | b2 | b3 | b4 | b5 | b6-b7 |
| | Next Wakeup | Wakeup Interval | Uplink Request/ Assignment IE | Downlink Request/ Assignment IE | Bilink Request/ Assignment IE | Channel Order IE | Reserved |

Change Indication format

| Octets: | 1 | 1 | 3 | | 3 |
|---|---|---|---|---|---|
| Octet order: | 0 | 0 | L-R | | L-R |
| | Element ID | Length (= 3J) | Allocation Assignment 1 | … | Allocation Assignment J |

Uplink/Downlink/Bilink Assignment IE format

| Bits: | 4 | 4 | 8 | 8 |
|---|---|---|---|---|
| Bit order: | b0-b3 | b4-b7 | b0-b7 | b0-b7 |
| | Frame Subtype | User Priority | Interval Start | Interval End |
| | Allocation ID | | | |

Allocation Assignment format

# Summary

- Star topology – suitable to medical applications
- Time partitioning – simple but configurable time slot structure
- Access methods – scalable reservation & contention accesses
  - Scheduled access (one-periodic & multi-periodic allocations)
  - Improvised access (polls & posts)
  - Random access (CSMA/CA contention)
  - MICS band communication (no beacon transmission)
- Synchronization & guardtime provisioning – effective, simple
- Power management – for both long-run and short-run
- Coexistence – time randomization and frequency diversity
- Acknowledgment policy – versatile but simple
- MAC frame structure – simple, effective
  - MAC header & MAC frame body
- Frame types & subtypes – orthogonal, effective