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

Submission Title: MedWiN MAC and Security Proposal – Part 1 of 2
Date Submitted: September 22, 2009


(1) GE Global Research, davenport@research.ge.com, 518-387-5041, 1 Research Circle, Niskayuna, NY, USA
(2) GE Healthcare, neal.seidl@med.ge.com, 414-362-3413, 8200 West Tower Avenue, Milwaukee, WI, USA
(3) Philips, j.moss@philips.com, +44 1223 427530, 101 Cambridge Science Park, Milton Road, Cambridge UK
(4) Philips, maulin.patel@philips.com, 914-945-6156, 345 Scarborough Road, Briarcliff Manor, NY, USA
(5) Texas Instruments, {batra@ti.com, 214-480-4220}, {jinmengho@ti.com, 214-480-1994}, {hosur@ti.com, 214-480-4432}, {jroh@ti.com, 214-567-4145}, {schmidl@ti.com, 214-480-4460}, 12500 TI Blvd, Dallas, TX, USA
(6) Toumaz Technology, {okundu.omeni@tomuaz.com, +44 1235 438950}, {alan.wong@toumaz.com, +44 1235 438961}, Building 3, 115 Milton Park, Abingdon, Oxfordshire, UK

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

Notice: This document has been prepared to assist the IEEE P802.15. It is offered as a basis for discussion and is not binding on the contributing individual(s) or organization(s). The material in this document is subject to change in form and content after further study. The contributor(s) reserve(s) the right to add, amend or withdraw material contained herein.

Release: The contributors acknowledge and accept that this contribution becomes the property of IEEE and may be made publicly available by P802.15
MedWiN MAC and Security Proposal

*Part 1 of 2 – MAC Sublayer*

GE Global Research: David Davenport

GE Healthcare: Neal Seidl

Philips: Jeremy Moss, Maulin Patel

Texas Instruments: Anuj Batra, Jin-Meng Ho, Srinath Hosur, June Chul Roh, Tim Schmidl

Toumaz Technology: Okundu Omeni, Alan Wong
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

H = hub
N = node

Interference mitigated between subnets
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
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)

(a) 1-periodic allocation of node 1

(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**

<table>
<thead>
<tr>
<th></th>
<th>Short distance</th>
<th>Long distance</th>
</tr>
</thead>
</table>
| **Poll**   | Poll, I-Ack+Poll, or B-Ack+Poll frame, with More Data = 0, Sequence Number = A, Fragment Number = Reserved :  
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 :  
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 Bth beacon period if B > 0. |
| **Post**   | Non-beacon management or data type frame, with More Data = 1 :  
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 :  
A post starts at the start of allocation slot A located in the current beacon period if B = 0 or in the next Bth 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

\[ B = \text{beacon} \quad BP = \text{beacon period} \quad L = \text{Minimum } B + \text{RAP1 Length} \]

Random access phases (RAPs)
Random Access (3)

- A node sets a back-off counter to a random integer in $[1, \text{CW}]$, with $\text{CW}_{\text{min}} \leq \text{CW} \leq \text{CW}_{\text{max}}$, 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 kbps 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 kbps 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

<table>
<thead>
<tr>
<th>Join Mode</th>
<th>Frames Required</th>
<th>MAC octets</th>
<th>Transfer Time Case 1</th>
<th>Transfer Time Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unsecured Connection</strong></td>
<td>Connection Request* + I-ACK</td>
<td>48 + 9</td>
<td>10.73 msec</td>
<td>2.07 msec</td>
</tr>
<tr>
<td></td>
<td>Connection Assignment* + I-ACK</td>
<td>40 + 9</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Secured Association &amp; Connection</strong></td>
<td>3 (Master Key Association + I-ACK)</td>
<td>3 (103 + 9)</td>
<td>62.67 msec</td>
<td>9.86 msec</td>
</tr>
<tr>
<td></td>
<td>3 (PTK Creation + I-ACK)</td>
<td>3 (47 + 9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Connection Request* + I-ACK</td>
<td>56 + 9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Connection Assignment* + I-ACK</td>
<td>48 + 9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*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

Table — Acknowledgment (Ack) Policy field encoding

<table>
<thead>
<tr>
<th>Field value b6 b7</th>
<th>Acknowledgment requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>No acknowledgment (N-Ack)</td>
</tr>
<tr>
<td>10</td>
<td>Immediate acknowledgment (I-Ack)</td>
</tr>
<tr>
<td>11</td>
<td>Block acknowledgment later (L-Ack)</td>
</tr>
<tr>
<td>01</td>
<td>Block acknowledgment (B-Ack)</td>
</tr>
</tbody>
</table>

Included in Frame Control field of MAC header

Transmissions in uplink and downlink allocation intervals
### Random Access – Prioritization

#### CWmin and CWmax values

<table>
<thead>
<tr>
<th>Priority</th>
<th>User Priority</th>
<th>Traffic designation</th>
<th>CWmin</th>
<th>CWmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowest</td>
<td>0</td>
<td>t.b.d.</td>
<td>16</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>t.b.d.</td>
<td>16</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>t.b.d.</td>
<td>8</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>t.b.d.</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>t.b.d.</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>t.b.d.</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>t.b.d.</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Highest</td>
<td>7</td>
<td>Emergency message</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>
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 $\text{PN}_m(n)$ to shift its beacon transmission time across beacon periods
  - A hub may choose $\text{PN}_0(n) = 0$ 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 $\text{PN}_5(n) = 0, 2, 1, 3$
Coexistence and Interference Mitigation (4)

Beacon shifting to mitigate interference between BANs

Submission
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

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

- 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 ($S_{I_n}$) determined by system parameters and beacon’s allocation slot length
    - Minimum allocation slot length (1msec), $S_{I_n} = 1.5$ seconds
    - Maximum allocation slot length (256 msec), $S_{I_n} = 639$ 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

- 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

<table>
<thead>
<tr>
<th>Device</th>
<th>@ 125 kbps</th>
<th>@ 1 Mbps</th>
<th>Standby</th>
<th>Hibernate (radio XTAL)</th>
<th>Hibernate (32 kHz watch XTAL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node</td>
<td>35 uW</td>
<td>280 uW</td>
<td>50 uW</td>
<td>50 uW</td>
<td>&lt; 5 uW</td>
</tr>
<tr>
<td>Hub</td>
<td>70 uW</td>
<td>320 uW</td>
<td>50 uW</td>
<td>50 uW</td>
<td>&lt; 5 uW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Gate Count (kgates)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hub minimum</td>
<td>80</td>
</tr>
<tr>
<td>Hub maximum</td>
<td>160</td>
</tr>
<tr>
<td>Node minimum</td>
<td>40</td>
</tr>
<tr>
<td>Node maximum</td>
<td>120</td>
</tr>
</tbody>
</table>
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:

\[
P_{\text{Avg Node}} = (T_{\text{sleep}}/T_{\text{beacon period}}) \times (P_{\text{MAC Standby}} + P_{\text{PHY Standby}}) + (T_{\text{transmit}}/T_{\text{beacon period}}) \times (P_{\text{MAC Active}} + P_{\text{PHY Tx}}) + (T_{\text{receive}}/T_{\text{beacon period}}) \times (P_{\text{MAC Active}} + P_{\text{PHY Rx}})
\]

\[
= (76 \text{ msec} / 80 \text{ msec}) \times (0.05 \text{ uW} + 0.05 \text{ uW}) + (2 \text{ msec} / 80 \text{ msec}) \times (280 \text{ uW} + 2.9 \text{ mW}) + (2 \text{ msec} / 80 \text{ msec}) \times (280 \text{ uW} + 3.1 \text{ mW})
\]

\[
= (0.95) \times (100 \text{ uW}) + (0.025) \times (3.18 \text{ mW}) + (0.025) \times (3.38 \text{ mW})
\]

\[
P_{\text{Avg Node}} = 259 \text{ uW}
\]

• 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 mAh)
  – Estimated > 170 hours operation at 1V with Power Paper STD-2 battery (1.5 V, 30 mAh),

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

<table>
<thead>
<tr>
<th>Application Area - Use Case</th>
<th>PHY Frequency Bands and Data Rates</th>
<th>Scheduled Access Mechanism</th>
<th>Improvised Access Mechanism</th>
<th>Random Access Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medical Applications – Continuous Patient Monitoring</td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
</tr>
<tr>
<td>physiological waveforms, vital signs, location, body motion and posture, etc.</td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
</tr>
<tr>
<td>Medical Application – Episodic Home Monitoring</td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
</tr>
<tr>
<td>weight scale, blood pressure, fall and impact, environment and context sensing, etc.</td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
</tr>
<tr>
<td>Consumer Application – Entertainment &amp; Gaming</td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
</tr>
<tr>
<td>Streaming audio, visual with controller response input</td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
</tr>
<tr>
<td>Consumer Application – Social Interaction &amp; Networking</td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
</tr>
<tr>
<td>Friend finder, business card exchange, etc.</td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
<td><img src="#" alt="High" /> <img src="#" alt="Medium" /> <img src="#" alt="Low" /></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Proposed Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Regulatory</td>
<td>Compliant with TG6 regulatory document in multiple frequency bands</td>
</tr>
<tr>
<td>2. Raw PHY data rate</td>
<td>100 kbps to 1 Mbps supported between node and hub</td>
</tr>
<tr>
<td>3. Transmission distance</td>
<td>PER and link budget shown to support 10% PER for 255 octet PSDU at 3 meters within all operating frequency bands proposed.</td>
</tr>
<tr>
<td>4. Packet error rate</td>
<td>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</td>
</tr>
<tr>
<td>5. Link budget</td>
<td>MAC provides 3 levels of security (none, authentication, authentication + encryption) based on AES-128. Association protocols provided for master key setup.</td>
</tr>
<tr>
<td>6. Power emission level</td>
<td>-10 dBm / -16 dBm maximum EIRP</td>
</tr>
<tr>
<td>7. Interference and coexistence</td>
<td>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.</td>
</tr>
<tr>
<td>9. Reliability</td>
<td>MAC transparent across multiple frequency bands proposed</td>
</tr>
<tr>
<td>10. Quality of Service</td>
<td>MAC: Sleep and Hibernate modes. PHY: ≤ 3.1 mW (active), 50 uW (standby), 250/125 nW (deep sleep)</td>
</tr>
<tr>
<td>11. Scalability</td>
<td>MAC: Time to join a network ~ 63 msec for message exchange. Fast (&lt;1sec) channel access available via prioritized CSMA/CA random access as well as scheduled or improvised access mechanisms.</td>
</tr>
<tr>
<td>12. MAC transparency</td>
<td>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</td>
</tr>
<tr>
<td>13. Power Efficiency</td>
<td>Star topology, broadcast beacon supported. Maximum number of nodes supported via multiple access mechanisms.</td>
</tr>
<tr>
<td>14. Topology</td>
<td>Merged proposal focused on satisfying needs of medical BAN applications as defined by TG6 PAR.</td>
</tr>
<tr>
<td>15. Bonus Point</td>
<td>Merged proposal focused on satisfying needs of medical BAN applications as defined by TG6 PAR.</td>
</tr>
</tbody>
</table>
Bonus Material
Beacon Transmission

Hub transmits beacon message each beacon period

<table>
<thead>
<tr>
<th>Octets:</th>
<th>6</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Octet order:</td>
<td>0-5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

- Sender Address
- Beacon Shifting Sequence
- Beacon Period Length
- Allocation Slot Length
- B+RAP1 Length
- RAP2 Length

<table>
<thead>
<tr>
<th>Octets:</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Octet order:</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0-1</td>
</tr>
</tbody>
</table>

- Security Requirement
- Security Capability
- MAC Capability
- PHY Capability
- Channel Hopping State

Beacon PN Sequence format

Bits:

- 4 b0-b3
- 4 b4-b7

Beacon PN Sequence Index
Beacon PN Sequence Phase
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 header format

<table>
<thead>
<tr>
<th>Octets:</th>
<th>2</th>
<th>1</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Octet order:</td>
<td>L-R</td>
<td>L-R</td>
<td>L-R</td>
</tr>
<tr>
<td>Fields:</td>
<td>HID</td>
<td>NID</td>
<td>Frame Control</td>
</tr>
</tbody>
</table>

#### MAC frame format

<table>
<thead>
<tr>
<th>Octets:</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Octet order:</td>
<td>L-R</td>
</tr>
<tr>
<td>Fields:</td>
<td>MAC Header</td>
</tr>
</tbody>
</table>

#### MAC frame body format

<table>
<thead>
<tr>
<th>Octets:</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Octet order:</td>
<td>L_FB</td>
</tr>
<tr>
<td>Security Sequence Number</td>
<td>Frame Payload</td>
</tr>
</tbody>
</table>

#### NID selection

<table>
<thead>
<tr>
<th>NID value in hex</th>
<th>NID notation</th>
<th>NID usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x00</td>
<td>Unconnected_Broadcast_NID</td>
<td>For broadcast to unconnected nodes</td>
</tr>
<tr>
<td>0x01-0F</td>
<td>Unconnected_NID</td>
<td>For unicast to unconnected nodes</td>
</tr>
<tr>
<td>0x10-EF</td>
<td>Connected_NID</td>
<td>For unicast to/from connected nodes</td>
</tr>
<tr>
<td>0xF0-FE</td>
<td>Multicast_NID</td>
<td>For multicast to connected nodes</td>
</tr>
<tr>
<td>0xFF</td>
<td>Broadcast_NID</td>
<td>For broadcast to all nodes</td>
</tr>
</tbody>
</table>

#### Frame control format

<table>
<thead>
<tr>
<th>Bits:</th>
<th>2</th>
<th>2</th>
<th>1</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit order:</td>
<td>b0-b1</td>
<td>b2-b3</td>
<td>b4</td>
<td>b5</td>
<td>b6-b7</td>
</tr>
<tr>
<td>Fields:</td>
<td>Protocol Version</td>
<td>Security Level</td>
<td>TK Index</td>
<td>Retry</td>
<td>Ack Policy</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bits:</th>
<th>2</th>
<th>4</th>
<th>1</th>
<th>1</th>
<th>8</th>
<th>3</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit order:</td>
<td>b0-b1</td>
<td>b2-b5</td>
<td>b6</td>
<td>b7</td>
<td>b0-b7</td>
<td>b0-b2</td>
<td>b3-b7</td>
</tr>
<tr>
<td>Fields:</td>
<td>Frame Type</td>
<td>Frame Subtype</td>
<td>More Data</td>
<td>First Frame</td>
<td>Sequence Number</td>
<td>Fragment Number</td>
<td>Reserved</td>
</tr>
</tbody>
</table>
## Frame Types and Subtypes

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

\[ t = \text{(beacon period or superframe \#, allocation slot \#, offset from current allocation slot start)} \]
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

Allocation interval – assigned to a specific node

![Diagram showing periodic allocation intervals](image-url)
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

<table>
<thead>
<tr>
<th></th>
<th>Short distance (immediate)</th>
<th>Long distance (future)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Poll</strong></td>
<td>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.</td>
<td>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 Bth beacon period if B &gt; 0.</td>
</tr>
<tr>
<td><strong>Post</strong></td>
<td>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.</td>
<td>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 Bth beacon period if B &gt; 0.</td>
</tr>
</tbody>
</table>

**Diagram:**
- Hub transmits
  - Data (0-Ack)
  - Scheduled uplink allocation interval
  - Poll
- Node 1 transmits
  - Data (0-Ack)
  - Poll
  - Polled allocation
- Hub transmits
  - Data (1-Ack)
  - Immediate
- Node 1 transmits
  - Data (0-Ack)
  - Scheduled downlink allocation interval
  - Data (0-Ack)
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

\[ p_{\text{MICSUnconnectedPollPeriod}} \]
\[ p_{\text{MICSUnconnectedPolls}} \]
\[ (\text{group } p) \]
\[ p_{\text{MICSUnconnectedPollSeparation}} \]
\[ \leq p_{\text{MICSUnconnectedPolls}} \]
\[ (\text{group } p+1) \]

\[ \text{Tx}_{\text{Hub}} \text{ transmitson channel } c \]
\[ \text{Rx} \text{ node first receives and then transmits} \]

\[ \text{Channel } c \]
\[ \text{Channel } d \]
\[ \text{Channel } a \]
\[ \text{Channel } j \]

\[ p_{\text{MICSChannelSwitchTime}} \]
\[ p_{\text{MICSUnconnectedPollRxTime}} \]

\[ \text{M-frame = management frame prior to connection} \]
\[ \text{Ack = I-Ack} \]
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 too 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

<table>
<thead>
<tr>
<th>Priority</th>
<th>User Priority</th>
<th>Traffic designation</th>
<th>CWmin</th>
<th>CWmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowest</td>
<td>0</td>
<td>Background (BK)</td>
<td>16</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Best effort (BE)</td>
<td>16</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Excellent effort (EE)</td>
<td>8</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Controlled load (CL)</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Video (VI)</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Voice (VO)</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Network control</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Highest</td>
<td>7</td>
<td>Emergency or medical event report</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>
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

[Diagram showing the scheduling and acknowledgment of data packets between a hub and multiple nodes, highlighting the concept of TIFS and sleep intervals.]
Coexistence – Beacon Shifting

- Beacon shifting of each BAN in time domain
  - Hub selects a PN sequence $\text{PN}_m(n)$ 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 $\text{PN}_0(n) = 0$ 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 $\text{PN}_5(n) = 0, 2, 1, 3$
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

(a) Subnet of node 1: PN1(n) = 0, 0, 0, 0, …; subnet of node 2: PN2(n) = 0, 0, 0, 0, …

(b) Subnet of node 1: PN1(n) = 0, 2, 1, 3, …; subnet of node 2: PN2(n-1) = 3, 0, 2, 1, …

(c) Subnet of node 1: PN1(n) = 0, 2, 1, 3, …; subnet of node 2: PN2(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

Table — Acknowledgment (Ack) Policy field encoding

<table>
<thead>
<tr>
<th>Field value b6 b7</th>
<th>Acknowledgment requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>No acknowledgment (N-Ack)</td>
</tr>
<tr>
<td>10</td>
<td>Immediate acknowledgment (I-Ack)</td>
</tr>
<tr>
<td>11</td>
<td>Block acknowledgment later (L-Ack)</td>
</tr>
<tr>
<td>01</td>
<td>Block acknowledgment (B-Ack)</td>
</tr>
</tbody>
</table>

Frame Control format

Bits: Bit order: 2 b6-b7

Acknowledgment Policy

Frame Payload format for B-Ack frames
### Table — NID selection

<table>
<thead>
<tr>
<th>NID value in hex</th>
<th>NID notation</th>
<th>NID usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>x00</td>
<td>Broadcast_Unconnected_NID</td>
<td>For broadcast to unconnected nodes</td>
</tr>
<tr>
<td>x01-0F</td>
<td>Unconnected_NID</td>
<td>For unicast to unconnected nodes</td>
</tr>
<tr>
<td>x10-EF</td>
<td>Connected_NID</td>
<td>For unicast to/from connected nodes</td>
</tr>
<tr>
<td>xF0-FE</td>
<td>Multicast_NID</td>
<td>For multicast to connected nodes</td>
</tr>
<tr>
<td>xFF</td>
<td>Broadcast_NID</td>
<td>For broadcast to all nodes</td>
</tr>
</tbody>
</table>

**MAC frame format**

**MAC Header format**

**MAC Frame Body format**

**Frame Format**

**MAC Header format**

**MAC Frame Body format**

<table>
<thead>
<tr>
<th>Octets:</th>
<th>7</th>
<th>L_F8</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-R</td>
<td></td>
<td>L-R</td>
<td>L-R</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Octets:</th>
<th>2</th>
<th>1</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>O-C</td>
<td>0-1</td>
<td>0</td>
<td>L-R</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Octets:</th>
<th>4</th>
<th>0-3</th>
<th>L_FP</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0, 1, ...</td>
<td>0-3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Frame Control format**

**Bits: Bit order:**

<table>
<thead>
<tr>
<th>2</th>
<th>b0-b7</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Protocol Version</th>
<th>Security Level</th>
<th>TK Index</th>
<th>Retry</th>
<th>Ack Policy</th>
</tr>
</thead>
</table>

**Bits: Bit order:**

<table>
<thead>
<tr>
<th>2</th>
<th>b0-b1</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Frame Type</th>
<th>Frame Subtype</th>
<th>More Data</th>
<th>First Frame</th>
<th>Sequence Number</th>
<th>Fragment Number</th>
<th>Reserved</th>
</tr>
</thead>
</table>
## Frame Types and Subtypes

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

(a) NID ≠ Unconnected_Broadcast_NID

(b) NID = Unconnected_Broadcast_NID

Major tick marks – beacon period (superframe) boundaries
Minor tick marks – allocation slot boundaries

\( t = (\text{beacon period or superframe } #, \text{ allocation slot } #, \text{ offset from current allocation slot start}) \)
# Beacon Frames

### Octets: Octet order:

<table>
<thead>
<tr>
<th>Octet</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Sender Address</td>
</tr>
<tr>
<td>0-5</td>
<td>Beacon Shifting</td>
</tr>
<tr>
<td></td>
<td>Sequence</td>
</tr>
<tr>
<td>1</td>
<td>Beacon Period Length</td>
</tr>
<tr>
<td>1</td>
<td>Allocation Slot</td>
</tr>
<tr>
<td>1</td>
<td>Length</td>
</tr>
<tr>
<td>1</td>
<td>B+RAP1 Length</td>
</tr>
<tr>
<td>1</td>
<td>RAP2 Length</td>
</tr>
</tbody>
</table>

### Octets: Octet order:

<table>
<thead>
<tr>
<th>Octet</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Security Requirement</td>
</tr>
<tr>
<td>1</td>
<td>Security Capability</td>
</tr>
<tr>
<td>1</td>
<td>MAC Capability</td>
</tr>
<tr>
<td>1</td>
<td>PHY Capability</td>
</tr>
<tr>
<td>2</td>
<td>Channel Hopping State</td>
</tr>
</tbody>
</table>

### Bits: Bit order:

<table>
<thead>
<tr>
<th>Bit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>b0</td>
<td>Lowest Security Level</td>
</tr>
<tr>
<td>b1</td>
<td>Required</td>
</tr>
<tr>
<td>b2</td>
<td>Control Frame</td>
</tr>
<tr>
<td>b3-b7</td>
<td>Authentication</td>
</tr>
<tr>
<td>b2</td>
<td>Reserved</td>
</tr>
</tbody>
</table>

### Security Requirement format

<table>
<thead>
<tr>
<th>Bit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>b0-b1</td>
<td>Security Support</td>
</tr>
<tr>
<td>b2</td>
<td>Master Key</td>
</tr>
<tr>
<td>b3</td>
<td>Pre-shared</td>
</tr>
<tr>
<td>b4</td>
<td>Association</td>
</tr>
<tr>
<td>b5</td>
<td>Unauthenticated</td>
</tr>
<tr>
<td>b6</td>
<td>Association</td>
</tr>
<tr>
<td>b7</td>
<td>Reserved</td>
</tr>
</tbody>
</table>

### Security Capability format

<table>
<thead>
<tr>
<th>Bit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>b0</td>
<td>B-Ack Support</td>
</tr>
<tr>
<td>b1</td>
<td>Poll Support</td>
</tr>
<tr>
<td>b2</td>
<td>Random Access</td>
</tr>
<tr>
<td>b5-b7</td>
<td>Support</td>
</tr>
<tr>
<td>b5-b7</td>
<td>Reserved</td>
</tr>
</tbody>
</table>

### MAC Capability format

<table>
<thead>
<tr>
<th>Bit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>b0</td>
<td>Data Rate 1</td>
</tr>
<tr>
<td>b1</td>
<td>...</td>
</tr>
<tr>
<td>b7</td>
<td>Data Rate 8</td>
</tr>
</tbody>
</table>
Connection Request Frames

- **Octets:** 6 6 6 1 1 1
  - **Octet order:** 0-5 0-5 0-5 0 0 0
  - **Fields:**
    - 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 1 1 1 7 7 7
  - **Fields:**
    - 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 1 1 5 5
  - **Fields:**
    - Element ID
    - Length (=5N)
    - Allocation Request 1...
    - Allocation Request N

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

Uplink/Downlink/Bilink Request IE format

Allocation Request format
Connection Assignment Frames

Octets: 6 6 1 1 1 1 1
Octet order: 0-5 0-5 0 0 0 0 0

<table>
<thead>
<tr>
<th>Recipient Address</th>
<th>Sender Address</th>
<th>Channel Dwell Length</th>
<th>Channel Dwell Phase</th>
<th>Minimum B+RAP1 Length</th>
<th>Status Code</th>
</tr>
</thead>
</table>

Octets: 1 1 1 1 1 1 1
Octet order: 0 0 0 0 0 0 0

<table>
<thead>
<tr>
<th>Security Requirement</th>
<th>Security Capability</th>
<th>MAC Capability</th>
<th>PHY Capability</th>
<th>NID</th>
<th>Change Indication</th>
</tr>
</thead>
</table>

Octets: 1 1 ≥ 5 ≥ 5 ≥ 5 ≥ 1
Octet order: 0 0 L-R L-R L-R L-R

<table>
<thead>
<tr>
<th>Next Wakeup</th>
<th>Wakeup Interval</th>
<th>Uplink Assignment IE</th>
<th>Downlink Assignment IE</th>
<th>Bilink Assignment IE</th>
<th>Channel Order IE</th>
</tr>
</thead>
</table>

Bits: 1 1 1 1 1 1 1 2
Bit order: b0 b1 b2 b3 b4 b5 b6-b7

Change Indication format

Octets: 1 0 1 3 L-R 3 L-R
Octet order: 0 0 3 L-R 3 L-R

<table>
<thead>
<tr>
<th>Element ID</th>
<th>Length (= 3b)</th>
<th>Allocation Assignment 1</th>
<th>...</th>
<th>Allocation Assignment J</th>
</tr>
</thead>
</table>

Uplink/Downlink/Bilink Assignment IE format

Octets: 4 4 8 8
Octet order: 0 0 0 0

<table>
<thead>
<tr>
<th>Frame Subtype</th>
<th>User Priority</th>
<th>Interval Start</th>
<th>Interval End</th>
</tr>
</thead>
</table>

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