IEEE802.15.3c Beamforming Overview

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Abstract

• Antenna configuration independent multi-level BST (Beam Switching/Steering & Tracking)
• Supports any antenna(s) system, i.e. supports single antenna element, switched antennas, sectored antennas, 1-D and 2-D beamforming antenna arrays, etc.
• Superframe structure with directional beaoning, association, CAP, and CTAP
TG3c Beamforming Protocols

• TG3c has specified two beamforming protocols:
  – BST (Beam Switching/Steering and Tracking) applicable to all antenna systems;
  – PET (Pattern Estimation and Tracking) applicable to 1-D and 2-D beamforming antenna arrays

• BST has itself two options
  – On demand beamforming between two DEVs or DEV and PNC;
  – Pro-active beamforming between PNC and DEVs

• This presentation gives an overview of the on-demand BST beamforming protocol
Beamforming Terminology

- **Quasi-omni patterns:**
  - 1\(^{st}\) level resolution pattern
  - Refers to an antenna pattern that covers a very broad area of the Region of Space of Interest (RSI)
  - A STA covers the RSI with a minimal set of, possibly overlapping, Q-omni patterns

- **Sectors**
  - 2\(^{nd}\) level resolution pattern
  - A pattern that covers a broad area of multiple beams that can be adjacent or not
  - Sectors can overlap
Beamforming Terminology

• **Beam**
  – 3\textsuperscript{rd} level resolution pattern
  – Beams are a subset of High Resolution Beams (HRBs) or patterns

• **HR Beams**
  – Highest resolution level
  – Adjustment from Beams to HRBs is done during Tracking

• **Cluster**
  – A group of beams around a center beam
  – Clustering is used to facilitate tracking
  – Only the number of beams within a cluster is required
Beamforming Terminology

Q-omni Patterns

Sectors

Beams

HR Beams
Superframe Structure

Provide omni coverage over the region of space of interest

Enables directional association

Directional random access after some beamforming

Beacon packet: direction $Q_{k-1}^{(1,t)}$

Beacon packet: direction $Q_{0}^{(1,t)}$

Dev1 ↔ Dev2 Data

Dev1 ↔ Dev2 Beamforming

Regular CAP $J(1,r)$ Association CAPs

$J(1,t)$ Q-omni beacon packets

CTAP

CTA

CTAP

CAP

Beacon
The Beacon

- PNC covers the region of space of interest by repeating /sweeping the beacon packet in $I^{(1,t)}$ Q-omni directions
- A STA may detect the beacon in one or multiple BIs (left to the implementer);
- The 1st beacon packet detected and demodulated by a DEV is not necessarily the best. DEV should measure the link quality from all other beacon packets to find the best PNC Tx direction and track it;
- After beacon detection, DEV has acquired knowledge of its best Rx Q-omni direction $q^{(2,r)}$ and PNC’s best Tx sector direction $q^{(1,t)}$;
Association

- The association period is divided into $I^{(1,r)}$ sections corresponding to the PNC $I^{(1,r)}$ q-omni Rx directions;
- Using a time allocation for association enables a more efficient usage of the regular CAP;
- A DEV sends an “Association Request command” by sweeping over its $I^{(2,t)}$ Q-omni transmit directions;
Association

• The “Association Request” includes the information about the PNC best Tx Q-omni direction index toward the source DEV, i.e. $q^{1,t}$;

• If the channel between STA and PNC is reciprocal, sweeping is not necessary;

• STA uses its best Q-omni Rx direction (found during beacon detection) $q^{2,r}$ to listen for an “Association Response”;

• Process is repeated in each association S-CAP until DEV successfully receives an “Association Response”;
Association

- A successful association does not however mean that the PNC has acquired STA’s best Tx direction. All we can say is that in the reverse link we have found a working DEV Tx direction;
- Fine tuning to find DEV’s best Q-omni direction and higher resolution best direction should not be completed in A-CAPs to avoid polluting it;
- PNC should poll a DEV to a CTA (from time to time: left to the implementer) to perform at least the 1\textsuperscript{st} level of beamforming which allows PNC and STA to track each other’s best sector pair of directions
Regular CAP

• Before two peer DEVs communicate in regular CAP, the two DEVs may perform beamforming;

• Configurable:
  – Slotted Aloha
    • Enables spatial reuse
    • DEV↔DEV or DEV↔PNC
  – CSMA/CA for AV PHY
  – PNC based:
    • Directional RTS/CTS
Beamforming BST Protocol

- **The BST protocol is a very low complexity protocol:**
  - It is independent of antenna configuration, i.e. supports single antenna element, sectored antennas, switched antennas, beamforming antenna arrays of any nature;
  - Does not require any codebook exchange;
  - Requires a very little amount of information to be exchanged between STAs to operate properly, i.e. number of Tx & Rx directions;

- **The BST protocol is a bidirectional multi-level beamforming protocol, the outcome of which is:**
  - The best pair of directions in forward and reverse links and;
  - The start MCS to be used in each direction
Beamforming Protocol Summary

• **Sector level objective:**
  – Find fwd link (DEV1→DEV2) and reverse link (DEV2→DEV1) best pair of sector directions (in terms of LQI)
  – Optionally second best pair of sector directions
  – Mapping of best pair of sector directions into a set of beam level directions in preparation for level-2;

• **Beam level objective:**
  – Find fwd link (DEV1→DEV2) and reverse link (DEV2→DEV1) best pair of beam directions
  – Mapping of best pair of beam directions into a set of higher resolution beam directions in preparation for nest level or tracking;

• **Tracking objective:**
  – Track the best pair of HR (high resolution beams) by monitoring the adjacent HR beams in the cluster centered around the best beam;
  – Switch to new better high resolution beam if found and re-cluster around the newly found HR beam
Beamforming

- Beamforming between two DEVs or a DEV and PNC takes place in a CTA;
- DEV1 reserve a CTA from the PNC for the special purpose of beamforming with STA2
- The BST beamforming protocol consists of a two-level beamforming, followed by a tracking phase:
  - Two-level beamforming:
    - Sector level
    - Beam level
  - High resolution beam level (tracking)
Beamforming CTA Reservation

- Beamforming between two DEVs or a DEV and PNC takes place in a CTA;
- DEV1 reserve a CTA from the PNC for the special purpose of beamforming with STA2;
- PNC allocates a CTA & broadcasts the CTA allocation, DEV1’s and DEV2’s “Beamforming capabilities”
- DEV1 and DEV2 start the beamforming process in the allocated CTA;
- DEV beamforming capabilities:
  - #Tx sectors = 1 ⇔ DEV is Tx omni-capable in (RoSoI)
  - #Rx sectors = 1 ⇔ DEV is Rx omni-capable in (RoSoI)
  - #Antenna Type (0 ⇔ no beamforming, etc.)
Sector & Beam Level Format

- **Unified sector and beam level format (n=1, 2, 3)**
  - *Level-n training*: forward and reverse link sweeping
  - *Level-n feedback*: feedback of best and 2\textsuperscript{nd} best directions and associated LQIs;
  - *Level-n mapping*: mapping of best direction results of current level into a set of directions to be used in level n+1 (3 being tracking);
  - *Acknowledgment*: closes the loop
Sector Training

Non-reciprocal sector training: (Sector-Level: Training Stage)

DEV-1 ($f^{1,t}$ transmit directions, $f^{1,r}$ receive directions) and DEV-2 ($f^{2,t}$ transmit directions, $f^{2,r}$ receive directions)
### Sector Feedback

**Fwd Link (DEV1→DEV2) Sector Feedback IE**

<table>
<thead>
<tr>
<th>LQI 2\textsuperscript{nd} best</th>
<th>DEV1 2\textsuperscript{nd} best Tx sector index</th>
<th>LQI best</th>
<th>DEV1 best Tx sector, $S_{\text{Tx}}^{(2)<em>{j</em>{T}}} \text{, index}</th>
<th>Length</th>
<th>Element ID</th>
</tr>
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<tbody>
<tr>
<td>4b</td>
<td>4b</td>
<td>4b</td>
<td>4b</td>
<td>8b</td>
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**Rev Link (DEV2→DEV1) Sector Feedback IE**

<table>
<thead>
<tr>
<th>LQI 2\textsuperscript{nd} best</th>
<th>DEV2 2\textsuperscript{nd} best Tx sector index</th>
<th>LQI best</th>
<th>DEV2 best Tx sector, $S_{\text{Tx}}^{(2)<em>{j</em>{T}}} \text{, index}</th>
<th>Length</th>
<th>Element ID</th>
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**Feedback packets**

- **Feedback packet #0** with **sector feedback IE & Imp-ACK**
  
  $S_{0}^{(1)_{j_{T}}} \rightarrow S_{j_{T}}^{(2)_{j_{T}}}$

- **Feedback packet #j** with **sector feedback IE & Imp-ACK**
  
  $S_{j_{T}}^{(1)_{j_{T}}} \rightarrow S_{j_{T}}^{(2)_{j_{T}}}$

- **Feedback packet #j - 1** with **sector feedback IE & Imp-ACK**
  
  $S_{j_{T}}^{(1)_{j_{T}}} \rightarrow S_{j_{T}}^{(2)_{j_{T}}}$

**Fwd link feedback (DEV-1→DEV-2)**

- $j^{(1)_{j}}$ repetitions
  
  (No sweeping if DEV-1 is Tx-omni capable)

**Non-reciprocal sector feedback:** **(Sector-level: Feedback Stage)**

- DEV-1 ($j^{(1)_{j}}$ transmit directions, $j^{(1)_{r}}$ receive directions) and DEV-2 ($j^{(2)_{j}}$ transmit directions, $j^{(2)_{r}}$ receive directions)
Sector-Level Mapping

- **Sector → Beam mapping IE**
  - Number of DEV Tx beams
  - Number of DEV Rx beams

![Sector Mapping IE Diagram](image-url)
Sector-Level Process Summary

Diagram:

- STS1 DME
- STA1 MAC/MLME
- MLME-SECTOR-BEAMFORM.req
- Sector training
- STA2 MAC/MLME
- STA2 DME
- Key: req = request, cfm = confirm
- MLME-SECTOR-BEAMFORM.cfm
- Announcement command with sector feedback and ACK Policy = Imp-ACK
- Announcement command with sector-beam mapping and ACK Policy = Imp-ACK
- Announcement command with sector-beam mapping and ACK Policy = Imp-ACK
- IMM-ACK
Beam-Level Training

Fwd link beam training (DEV-1→DEV-2)
K₁ cycles

Reverse link beam training (DEV-2→DEV-1)
K₂ cycles

Non-reciprocal beam training: (Beam-Level: Training DEVge)
DEV-1 (K₁ transmit directions, K₁ receive directions) and DEV-2 (K₂ transmit directions, K₂ receive directions)
Beam-Level Feedback

- **Feedback Stage:**
  - Fwd link DEV1→DEV2: uses best pair of sectors from 1st level
  - Fwd link DEV2→DEV1 uses best pair of sectors from 1st level
Beam-Level Mapping

- **Beam → HR-Beam mapping IE**
  - Number of DEV Tx HR (High Resolution) beams
  - Number of DEV Rx HR (High Resolution) beams

![Beam Mapping IE Diagram](image-url)
Beam-Level Process Summary

MLME-BEAM-BEAMFORM.req

Beam training

Announce command with beam feedback and ACK Policy = Imp-ACK

Announce command with beam feedback and ACK Policy = Imp-ACK

Announce command with beam-HIR beam mapping and ACK Policy = Imp-ACK

Announce command with beam-HIR beam mapping and ACK Policy = Imm-ACK

Imm-ACK

MLME-BEAM-BEAMFORM.cfm

Key
req = request

cfm = confirm
Tracking

• **Clustering Rules:**
  – Definition: a set of adjacent beams identified by a center beam
  – Clusters are paired, i.e. a cluster-1 from DEV1 is associated to a cluster-1 from DEV2 & cluster-2 from DEV1 is paired with cluster-2 from DEV2

• **Tracking mechanism:**
  – Track center beam in each cluster (re-clustering)
  – Tracking packets are used to enable distributed tracking
  – A tracking packet is a regular packet with “Tracking Bit Field” set to 1 in the PHY header, and followed by beam training sequence (short preamble)
Tracking

• A Packet with “Tracking Bit” set to one is followed by a short training sequence transmitted in one of the HR beam directions within the cluster;
Summary

• BST is one of two beamforming protocols adopted in IEEE802.15.3c;
• BST is simple and require only exchange of number of directions within a given stage;
• BST is independent of the used antenna system;
• BST is based on a two-level beamforming: a sector level and a beam level
• Tracking moving DEVs is enables by the distributed cluster of HR beams tracking
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