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Re:	[Beamforming Draft]		
Abstract	[Proposed resolution for comments related to beamforming In memory of *Martin Morris*]		
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Notice			
Release			

1 Beamforming

This clause specifies the beamforming protocol for SC and HSI-OFDM. A multitude of antenna configurations such as single antenna element, sectored antennas, switched antennas, and 1-dimensional (1-D) and 2-dimensional (2-D) beamforming antenna arrays are supported.

Two types of beamforming protocols are specified: an on-demand beamforming and a pro-active beamforming.

On-demand beamforming can be used between two DEVs or between the PNC and a DEV and shall take place in the CTA allocated to the DEV for the purpose of beamforming.

Pro-active beamforming can be used when the PNC is the source of data to one or multiple DEVs. It allows multiple DEVs to train their receiver antennas for optimal reception from the PNC with lower overhead. The pro-active beamforming shall take place in the beacon and CTAP as described in 1.6.

Pro-active and on-demand beamforming are achieved using a two-level training mechanism, namely a coarse training level and a fine training level, followed by a tracking phase.

Two beamforming optimality criterions are specified: a beam switching (steering) and tracking (BST) criterion suitable for all antenna configurations, and pattern estimation and tracking (PET) option for 1-D linear antenna arrays and 2-D planar antenna arrays. The choice between these two options is left to the implementer. All devices shall support the BST criterion. PET criterion may be used only when the two devices support it. BST is based on selecting the best beam from a given set of beams whereas PET is based on finding the optimal beamformer and combiner vectors (i.e. antenna weights) that do not necessarily fall into the given set of beams.

The beamforming protocol shall be achieved using a two-level training mechanism, namely a sector (coarse) training level and a beam (fine) training level, and followed by an optional high resolution (HR) beam tracking phase.

Support for beamforming is optional. However, when beamforming is implemented, the two-level training mechanism shall be supported. The tracking phase is optional.

The beamforming terminology is detailed in subclause 1.1. The beam codebooks are specified in subclause 1.2. The beamforming reference system model is developed in subclause 1.3. The two-level training mechanism is detailed in 1.4.1 and the tracking is detailed in 1.4.2.

1.1 Beamforming terminology

This subclause introduces the concept of patterns with increasing resolution level, namely, quasi-omni (Q-omni) patterns, sectors, fine beams and high resolution (HR) beams (multi-resolution beams) as illustrated in Figure 1. In addition, the clustering concept is introduced and the convention used in beams numbering and cluster encoding are clarified.

When describing beamforming between two devices, the following notation will be used:

1. When two devices are communicating, they will be referred to as DEV1 and DEV2. DEV1 may also be the PNC. The device number, d, will be one for DEV1 (or the PNC) and 2 for DEV2;
2. The total number of transmit and receive antenna elements for device number d are denoted as $M^{(d,t)}$ and $M^{(d,r)}$ respectively. The corresponding transmit and receive antenna elements are denoted as $A_n^{(d,t)}$ where $n = 0: M^{(d,t)} - 1$ for the transmit antennas and $A_n^{(d,r)}$ where $n = 0: M^{(d,r)} - 1$ for the receive antennas;

3. The total number of Q-omni transmit and receive patterns of interest for device number d, is denoted as $I^{(d,t)}$ and $I^{(d,r)}$ respectively. The corresponding Q-omni transmit and receive patterns are denoted as $Q_n^{(d,t)}$ where $n = 0{:}I^{(d,t)} - 1$ for the transmit patterns and $Q_n^{(d,r)}$ where $n = 0{:}I^{(d,r)} - 1$ for the receive patterns;
4. The best pair of Q-omni transmit and receive patterns for device d when communicating with the other device are identified by indices $i^{(d,t)}$ and $i^{(d,r)}$ respectively. The corresponding Q-omni transmit and receive patterns are denoted as $Q_{i^{(d,t)}}^{(d,t)}$ and $Q_{i^{(d,r)}}^{(d,r)}$ respectively;
5. The total number of transmit and receive sectors of interest for device number d are denoted as $J^{(d,t)}$ and $J^{(d,r)}$ respectively. The corresponding transmit and receive sectors are denoted as $S_n^{(d,t)}$ where $n = 0{:}J^{(d,t)} - 1$ for the transmit sectors and $S_n^{(d,r)}$where $n = 0{:}J^{(d,r)} - 1$ for the receive sectors;
6. The best pair of transmit and receive sectors for device d when communicating with the other device are identified by indices $j^{(d,t)}$ and $j^{(d,r)}$ respectively. The corresponding transmit and receive sectors are denoted as $S_{j^{(d,t)}}^{(d,t)}$ and $S_{j^{(d,r)}}^{(d,r)}$ respectively;
7. The total number of transmit and receive fine-beams of interest for device number d are denoted as $K^{(d,t)}$ and $K^{(d,r)}$ respectively. The corresponding transmit and receive fine-beams are denoted as $B_n^{(d,t)}$ where $n = 0{:}K^{(d,t)} - 1$ for the transmit fine-beams and $B_n^{(d,r)}$where $n = 0{:}K^{(d,r)} - 1$ for the receive fine-beams;
8. The best pair of transmit and receive fine-beams for device d when communicating with the other device are identified by indices $k^{(d,t)}$ and $k^{(d,r)}$ respectively. The corresponding transmit and receive fine-beams are denoted as $B_{k^{(d,t)}}^{(d,t)}$ and $B_{k^{(d,r)}}^{(d,r)}$ respectively;
9. The total number of transmit and receive HR beams of interest for device number d, are denoted as $L^{(d,t)}$ and $L^{(d,r)}$ respectively. The corresponding transmit and receive HR-beams are denoted as $B_n^{(d,t)}$ where $n = 0{:}L^{(d,t)} - 1$ for the transmit HR-beams and $B_n^{(d,r)}$where $n = 0{:}L^{(d,r)} - 1$ for the receive HR-beams. The transmit (receive) HR beams are grouped into two clusters. The total number of HR beams in these two clusters are denoted as $L_1^{(d,t)}$ and $L_2^{(d,t)}$ ($L_1^{(d,r)}$ and $L_2^{(d,r)}$) respectively
10. The best pair of transmit and receive HR-beams for device d when communicating with the other device are identified by indices $l^{(d,t)}$ and $l^{(d,r)}$ respectively. The corresponding transmit and receive HR-beams are denoted as $H_{l^{(d,t)}}^{(d,t)}$ and $H_{l^{(d,r)}}^{(d,r)}$ respectively;
11. If both devices are SAS, the superscripts t and r can be dropped since they are the same.

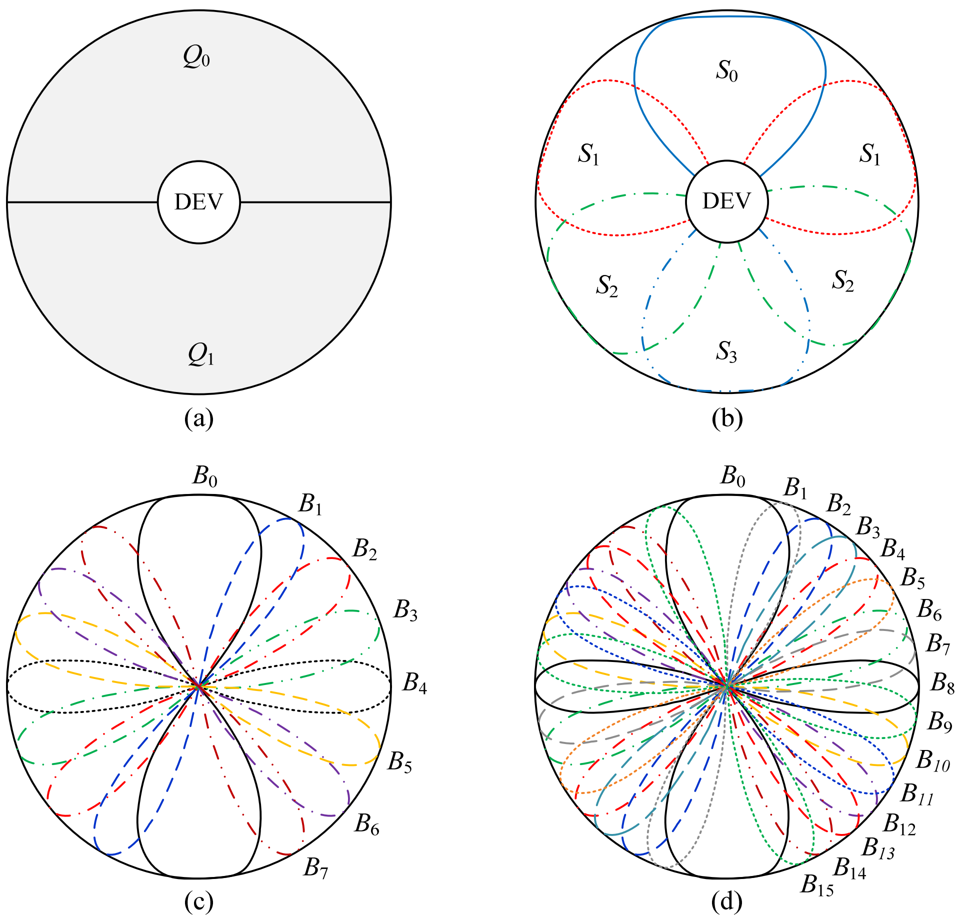


Figure 1 – Q-omni patterns, sectors, fine beams and HR-beams

1.1.1 Q-omni patterns

The term “Q-omni pattern” is the lowest resolution pattern and is used to refer to an antenna pattern that covers a very broad area of the region of space of interest around the device. A PNC covers the region of space of interest with a minimal set of, possibly overlapping, Q-omni patterns. A set size of one indicates that the PNC is omni capable.

1.1.2 Sectors

The term “sector” is the second level resolution pattern and is used to refer to an antenna direction or an array pattern that covers a relatively broad area of multiple beams. A sector can cover a set of consecutive or non-consecutive beams and different sectors can overlap.

1.1.3 Beams

For the pattern estimation and tracking option, beams shall be selected from the “beam codebooks” specified in subclause 1.2.1. A transmit or receive codebook is identified by the number of transmit or receive antennas, $M^{(t)}$ or $M^{(r)}$ respectively, and the desired number of transmit or receive beams, $K^{(t)}\ or\ K^{(r)}\ \ for\ fine\ beams, or\ L^{(t)}$ or $L^{(r)}$ for HR beams respectively. For a 2-D antenna array, separate codebooks are associated with each dimension as well as for transmit and receive.

Multi-resolution beams can be synthesized by specifying different numbers of beams. Figure 1c and 1d show an example of an 8-element linear antenna array with 8 fine beams and 16 HR-beams, respectively.

For a 1-D antenna array with K beams along the z-axis, beams shall be identified by indices zero through K -1 in the direction of increasing polar angle as shown in Figure 1. These beams shall correspond one to one with the beam vectors 0 to K-1 from the selected "beam codebook" detailed in subclause 1.2.1.

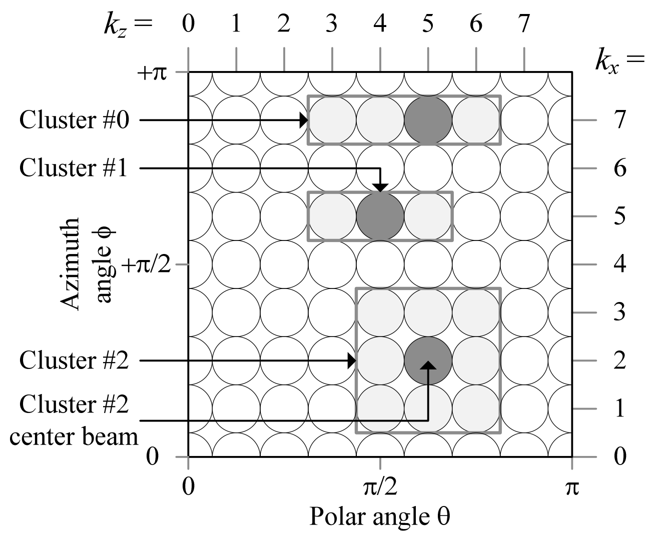


Figure 2 - Beam numbering and clusters

For a 2-D antenna array with K_x beams on the x-axis and K_z beams on the z-axis, the K_x beams along the x-axis shall be identified by indices zero through K_x -1 in the direction of increasing polar angle and shall correspond one to one with the beam vectors 0 to K_x -1 from the selected x-beam codebook. The K_z beams along the z-axis shall be identified by indices zero through K_z -1 in the direction of increasing polar angle and shall correspond one to one with the beam vectors 0 to K_z -1 from the selected z-beams codebook. This is further illustrated in Figure 2 for a 2-D antenna array with 8 beams in each direction.

1.1.4 Clusters

A cluster is a group of beams around a center beam. The clustering concept is introduced to facilitate tracking. The number of clusters per sector(s) is left to the implementer. Figure 2 gives examples of clusters of different sizes.

Cluster encoding shall be used for DEVs supporting the pattern estimation and tracking option. For DEVs implementing the beam switching and steering option, cluster encoding support is not required.

A cluster shall be encoded by an 8-bit field: $c_7c_6c_5c_4c_3c_2c_1c_0$. The first three LSB bits, i.e. $c_2c_1c_0$, encode the beams in the horizontal direction in reference to Figure 2, while the second set of three bits, i.e. $c_5c_4c_3$, encodes the beams in the vertical direction. The last set of two bits c_7c_6 specifies three different 2-D puncturing patterns, i.e. different cluster geometries.

Bits c_1c_0 shall encode the total number of beams in the horizontal direction (excluding the center beam). Bit c_3 shall be set to zero if the number of beams to the left of the center beam is smaller than or equal to the number of beams to the right of the center beam; otherwise, bit c_3 shall be set to one.

Bits c_4c_3 shall encode the total number of beams in the vertical direction (excluding the center beam). Bit c_5 shall be set to zero if the number of beams below the center beam is smaller than or equal to the number of beams above the center beam; otherwise, bit c_5 shall be set to one.

Bits c_1c_0 shall encode the 2-D puncturing patterns as follows. When bit c_0 is set to one, this shall indicate that the cluster is punctured; otherwise, all 2-D beams within a cluster shall be used. When $c_1c_0 = 11$, the cluster is fully punctured; i.e. only the beams along the *x*-axis and *z*-axis around the center beam are used. When $c_1c_0 = 01$, the beams along the *x*-axis and *z*-axis around the center beam as well as the adjacent beams to the center beam are used. Figure 3 shows some examples of cluster encoding.

Finally, beams in a cluster are ordered in increasing index k_z and decreasing index k_x in reference to Figure 2. When a cluster is transmitted, the first beam, i.e. the beam with lowest k_z index and highest k_x index, shall be transmitted first, and the last beam, i.e. the beam with highest k_z index and lowest k_x index, shall be transmitted last.

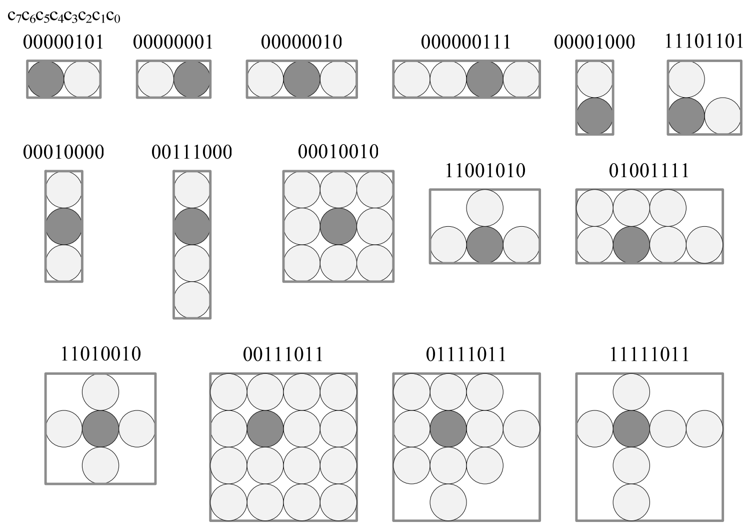


Figure 3 – Examples of cluster encoding

1.2 Beamforming codebooks

This subclause specifies codebooks for sectored and switched antennas, 1-D and 2-D arrays with uniform spacing of λ/2. For all other configurations, the sub-optimal beam-switching criterion shall be used, in which case, the knowledge of codebooks at the receiving side is no longer required.

A codebook is a matrix where each column specifies the beamformer vector or combiner vector (codeword) to be used. Each column specifies a specific pattern or direction. The set of columns span the entire space, which is 360 degrees. Columns shall be numbered in increasing order starting with zero.

The codebook for a sectored antenna array and switched antenna array of M elements is given by the identity matrix:

$$\mathbf{W}_{M\times M} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix}$$

For the purpose of training, it is sufficient to provide codebooks in one dimension. The 2-dimensional antenna arrays can be trained by separable codebooks along the *x*-axis and *z*-axis. This is illustrated in Figure 4 where the 2-D antennas weights w_{m_x,m_z}, $m_x = 0{:}M_x - 1$ and $m_z = 0{:}M_z - 1$ can be computed from the antenna weights along the x-axis w_{m_x}, $m_x = 0{:}M_x - 1$ and the antenna weights along the z-axis w_{m_z}, $m_z = 0{:}M_z - 1$ as follows:

$$w_{m_x,m_z} = w_{m_x} w_{m_z} \text{ for } m_x = 0{:}M_x - 1 \text{ and } m_z = 0{:}M_z - 1$$

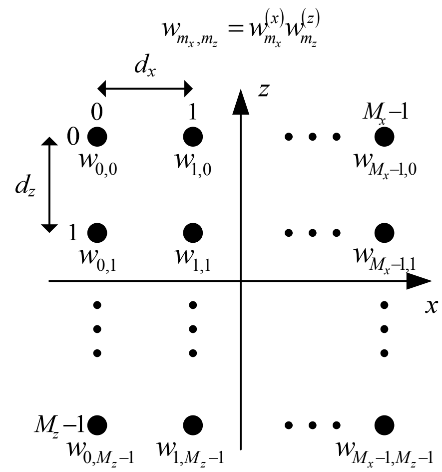


Figure 4 - Separable 2-dimensional antenna array

Consequently, if the *x*-axis codebook has M_x codewords and the *z*-axis codebook has M_z codewords, the 2-D codebook will have $M_x \times M_z$ codewords.

For a 1-D antenna array with uniform spacing of λ/2, the beam codebook for various number of antenna elements is given in 1.2.1.

The following convention shall be used for antenna numbering in reference to Figure 4: the antenna element on the m_x^{th} row ($m_x = 0{:}M_x\text{-}1$) and m_z^{th} column ($m_z = 0{:}M_z\text{-}1$) shall be numbered $(m_x\text{-}1)*M_x+M_z$.

1.2.1 Beam codebooks

This clause provides beam codebooks that should be used for 1-D and 2-D arrays with uniform spacing of λ/2. The codebooks specified here are one-dimensional. The 2-D codebooks can be obtained from the corresponding 1-D *x*-codebook and *z*-codebook as detailed in 1.2.

Each beam codebook is identified by the number of antenna elements, *M*, and the desired number of beams, *K*. For the case where $K \geq M$, the codebook beam vectors are given by the column vectors of the following matrix:

$$W(m,k) = j^{\text{fix}\left\{\frac{m \times mod[k+(K/2),K]}{K/4}\right\}} \text{ for } m = 0{:}M-1 \text{ and } k = 0{:}K-1$$

The function fix( ) returns the biggest integer smaller than or equal to its argument. It is also possible to substitute the function round( ) for the function fix( ) , where the function round( ) returns the closest integer to the input argument.
For the special case where $K = M/2$, the codebook beam vectors are given by the column vectors of the following matrix:

$$W(m,k) = \begin{cases} (-j)^{mod(n,2)} & m = 0:N-1 \text{ and } k = 0 \\ (-1)^{\text{fix}\left\{\frac{m \times mod[k+(K/2),K]}{K/4}\right\}} & m = 0:N-1 \text{ and } k = 1:K-1 \end{cases}$$

The function round( ) can be substituted for the function fix( ) as before.

The cases where $K < M$ and $K \neq M/2$ are not of interest.

The codebook ID is an 8 bits number where the 7 LSB bits indicate the number of desired beams and the MSB bit indicates whether the round (MSB bit = 0) or fix (MSB bit = 1) function is used.

1.3 Beamforming reference model

The beamforming reference model is illustrated in Figure 5. In this figure, DEV1 has $M^{(1,t)}$ transmit antennas and $M^{(1,r)}$receive antennas while DEV2 has $M^{(2,t)}$transmit antennas and $M^{(2,r)}$ receive antennas. Depending on the implementation, the transmit and receive antenna weight vectors **w** and **c** belong to specific alphabets. For example, for sectored antennas where one antenna is active at a time, the weights belong to the alphabet {0, 1}. For a phased antenna array implementing specific phase shifts, the weights are restricted to those specific phase shifts. For a complex beamforming antenna array, the weights can be adjusted in both phase and amplitude.

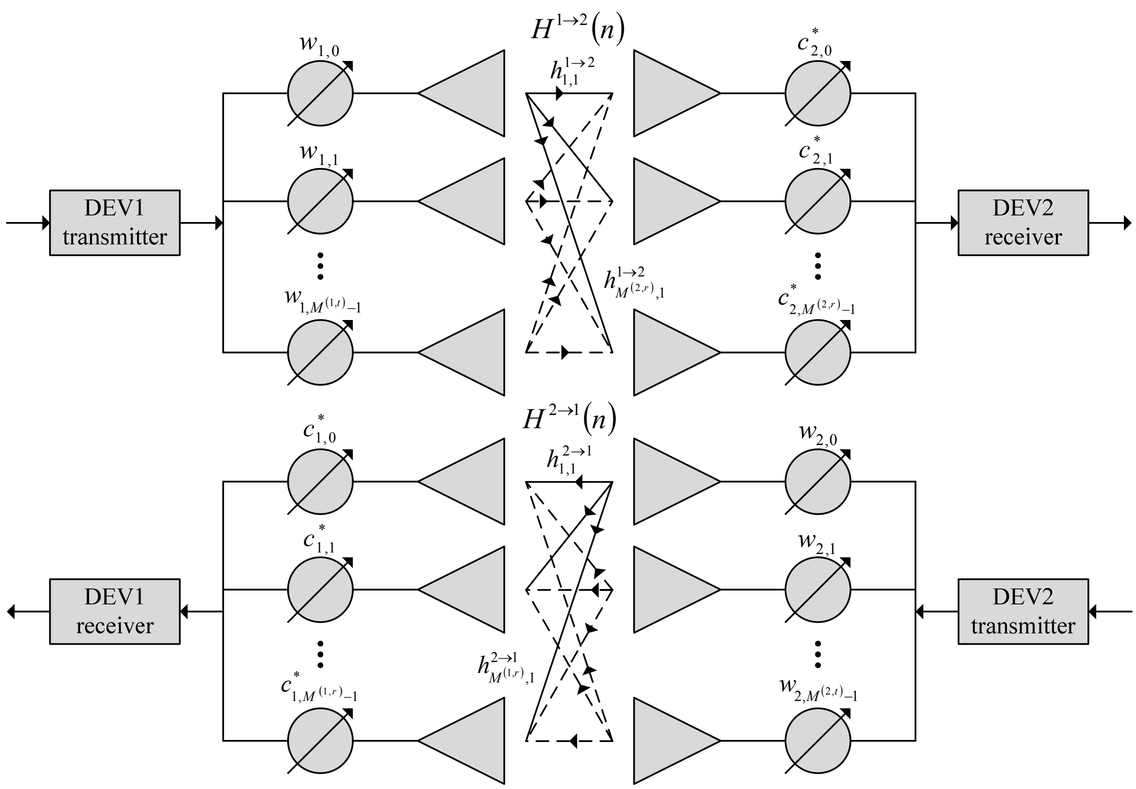


Figure 5 - Beamforming reference model

The system model is developed in reference to Figure 5. At DEV1's transmitter, the SC or HSI-OFDM bit stream is modulated by the beamformer vector (BV):

$$\mathbf{w}_1^T = [w_{1,0} \quad w_{1,1} \quad \cdots \quad w_{1,M^{(1,t)}-1}]$$

and then transmitted through a multipath MIMO channel with frequency domain channel state information (CSI) matrix $\mathbf{H}^{1\to 2}(n) \in \mathbb{C}^{M^{(1,t)}\times M^{(2,r)}}$ at frequency bin number n (n = 0, 1, …, K-1):

$$\mathbf{H}^{1\to 2}(n) = \begin{bmatrix} h_{1,1}^{1\to 2}(n) & h_{1,2}^{1\to 2}(n) & \dots & h_{1,M^{(2,r)}}^{1\to 2}(n) \\ h_{2,1}^{1\to 2}(n) & h_{2,2}^{1\to 2}(n) & \dots & h_{2,M^{(2,r)}}^{1\to 2}(n) \\ \vdots & \vdots & \ddots & \vdots \\ h_{M^{(1,t)},1}^{1\to 2}(n) & h_{M^{(1,t)},2}^{1\to 2}(n) & \cdots & h_{M^{(1,t)},M^{(2,r)}}^{1\to 2}(n) \end{bmatrix}$$

where $h_{i,j}^{1\to 2}(n)$ represents the channel response between DEV1 j^{th} transmit antenna and DEV2's i^{th} receive antenna. The number of frequency bins K corresponds to the burst size in SC (i.e. K = 256) or to the number of used carriers in HSI-OFDM (i.e. K = 352).

At DEV2's receiver, the received signals are processed through the combiner vector (CV):

$$\mathbf{c}_2^T = [c_{2,0} \quad c_{2,1} \quad \cdots \quad c_{2,M^{(2,r)}-1}]$$

The equivalent channel between DEV1's transmitter and DEV2's receiver is a single input single output (SISO) channel with frequency response at bin n given by:

$$G^{1\to 2}(n) = \mathbf{c}_2^H \mathbf{H}^{1\to 2}(n)\mathbf{w}_1 \; for \; n = 0, 1, \dots, K-1$$

In a similar way, the equivalent channel between DEV2's transmitter and DEV1's receiver is a single input single output (SISO) channel with frequency response at bin n given by:

$$G^{2\to 1}(n) = \mathbf{c}_1^H \mathbf{H}^{2\to 1}(n)\mathbf{w}_2 \; for \; n = 0, 1, \dots, K-1$$

The objective of the pattern estimation beamforming is to select the beamformer vectors $\mathbf{w}_1$ and $\mathbf{w}_2$ and the combiner vectors $\mathbf{c}_1$ and $\mathbf{c}_2$ that optimize a cost function which measures the link quality according to a selected criterion. If for example an effective SNR criterion is selected, than DEV2 has to be able to acquire and track the CSI matrices $\mathbf{H}^{1\to 2}(n) \; for \; n = 0\colon K-1$ in the region of space of interest. Furthermore, if the channel is asymmetric, then DEV1 has to be able to acquire and track the CSI matrices $\mathbf{H}^{2\to 1}(n) \; for \; n = 0\colon K-1$. If a beam-switching option is selected, than a DEV needs only to measure the link quality per beam pair. The exact optimization criterion is left to the implementer.

For the special case of a symmetric antenna system (SAS), i.e. the same antenna elements are used for transmission and reception and for a symmetric channel, the optimal beamformer and combiner vectors are related as follows:

$$\mathbf{c}_1 = \mathbf{w}_1^* \; and \; \mathbf{c}_2 = \mathbf{w}_2^*$$

For this special case, it is sufficient to determine one of the two vectors for each device.

The general case where at least one of the devices uses a different antenna system for transmission and reception shall be referred to as asymmetric antenna system (AAS).

Measuring the link quality between all beam pairs, or acquisition of the entire set of CSI matrices, is time costly and incurs high overhead. In order to reduce the amount of time and overhead required for training, a two-level beamforming mechanism shall be used as detailed in clause 1.4.1.

1.4 Beamforming protocol

The beamforming protocol consists of a mandatory two-level training mechanism and an optional tracking phase. The two-level training mechanism is used to find the best pair of beams (patterns) between two devices with a given beam resolution. Tracking is used to achieve higher resolution and to track the best set of beams (patterns) between the two devices.

1.4.1 Two-level training mechanism

The two-level training mechanism shall consist of a sector (coarse) level, and a beam (fine) level training.

The sector level is used to limit the region of space that is of interest and to find the best pair of sectors. These sectors are then sliced into beams in preparation for beam level training. Beam level training is used to select the optimal BV and CV as outlined in 1.3. In the simple case of beam switching, this reduces to selecting the best transmit-receive pair of beams. Beam level training is achieved using a set of beamformer and combiner vectors (BCVs) (from selected beam codebooks) covering the sector(s) selected during sector level training. The beamformer (combiner) codebooks are specified in 1.2.1.

1.4.1.1 Sector level training

If the two devices are both SAS, the sector level training is described in 1.4.1.1.1. If either or both devices are AAS, the sector level training is described in 1.4.1.1.2.

1.4.1.1.1 AAS sector level training

The sector level consists of four stages: training, feedback, mapping, and acknowledgment, as illustrated in Figure 10.
The first stage, sector training, shall be divided into two parts: sector training from DEV1 to DEV2 and sector training from DEV2 to DEV1.

The sector training from DEV1 to DEV2 consists of $J^{(1,t)}$ cycles. During each cycle, DEV1 shall send $J^{(2,r)}$ repetitions of a sector training (ST) sequence in the same direction, i.e. the direction specified by the corresponding sector codeword. Each cycle except the last one shall end with a guard time of 62.5 ns. The $J^{(1,t)}$ cycles shall be sent in $J^{(1,t)}$ different directions, $\left[S_0^{(1,t)}, S_1^{(1,t)}, \cdots, S_{J^{(1,t)}-1}^{(1,t)}\right]$ corresponding to the chosen $J^{(1,t)}$ transmit sector codewords. The ST sequence shall be identical to the long preamble, which consists of a long SYNC followed by a long CES.

During a cycle, DEV2 shall attempt to receive each of the $J^{(2,r)}$ sector training sequences using a different listening (receive) direction. The $J^{(2,r)}$ different listening directions, $\left[S_0^{(2,r)}, S_1^{(2,r)}, \cdots, S_{J^{(2,r)}-1}^{(2,r)}\right]$, during a cycle shall correspond to DEV2's $J^{(2,r)}$ chosen sector codewords.

At the completion of the full $J^{(1,t)}$ cycles, DEV2 will have had an opportunity to receive an ST sequence using each combination of DEV1 transmit sector direction (0 to $J^{(1,t)}$ - 1) and DEV2 receive sector direction (0 to $J^{(2,r)}$ - 1). Based on this information, DEV2 selects the best sector pair, i.e. DEV1's optimal transmit sector, $S_{j^{(1,t)}}^{(1,t)}$, and DEV2's optimal receive sector, $S_{j^{(2,r)}}^{(2,r)}$.

Following the sector training from DEV1 to DEV2, a similar sector training from DEV2 to DEV1 takes place where DEV2 transmits ST sequences over $J^{(2,t)}$ cycles as shown in Figure 10. At the completion of the $J^{(2,t)}$ cycles, DEV1 selects the best sector pair, i.e. DEV2's optimal transmit sector, $S_{j^{(2,t)}}^{(2,t)}$, and DEV1's optimal transmit sector, $S_{j^{(1,r)}}^{(1,r)}$.

In the second stage of sector level training, DEV1 shall transmit its sector feedback in a Feedback IE (Figure 6) by sending an Announce command with Imp-ACK requested. The Announce command shall be sent $J^{(1,t)}$ times in the $J^{(1,t)}$ different transmit directions, $\left[S_0^{(1,t)}, S_1^{(1,t)}, \cdots, S_{J^{(1,t)}-1}^{(1,t)}\right]$. This is required since

DEV1 does not yet know its optimal transmit sector. DEV2 switches to its optimal receive sector, $J_{j(2,r)}^{(2,r)}$, and attempts to receive at least the transmission sent on DEV1's optimal transmit sector, $J_{j(1,t)}^{(1,t)}$. The Feedback IE informs DEV2 of its optimal transmit sector, $S_{j(2,t)}^{(2,t)}$, second best transmit sector, and the corresponding LQIs (Link Quality Indicators). The LQI is a measure that indicates the channel link quality (e.g. RSSI, SNIR, and SNR). The exact definition of LQI metric is implementation dependent.

SAS sector DEV2→DEV1: Feedback IE

SNIR 2nd best	DEV1 2nd best sector index	SNIR best	DEV1 best sector, $S_{j(1,t)}^{(1,t)}$, index	Length	Element ID
4b	4b	4b	4b	8b	8b

AAS sector DEV2→DEV1: Feedback IE

SNIR 2nd best	DEV1 2nd best Tx sector index	SNIR best	DEV1 best Tx sector, $S_{j(1,t)}^{(1,t)}$, index	Length	Element ID
4b	4b	4b	4b	8b	8b

AAS sector DEV1→DEV2: Feedback IE

SNIR 2nd best	DEV2 2nd best Tx sector index	SNIR best	DEV2 best Tx sector, $S_{j(2,t)}^{(2,t)}$, index	Length	Element ID
4b	4b	4b	4b	8b	8b

Figure 6 – Sector level Feedback IEs

In return, DEV2 shall transmit its sector feedback in a Feedback IE by sending an Announce command with Imp-ACK requested. The Announce command shall be sent on DEV2's optimal transmit sector, $S_{j(2,t)}^{(2,t)}$ and DEV1 shall listen on its optimal receive sector, $S_{j(1,r)}^{(1,r)}$. The Feedback IE informs DEV1 of its optimal transmit sector, $S_{j(1,t)}^{(1,t)}$, second best transmit sector, and the corresponding LQIs.

Upon completion of the feedback stage, both DEV1 and DEV2 know their optimal transmit and receive sectors. These shall be used for any further frame exchanges in this level.

Following the feedback stage, DEV1 shall transmit its sector to beam mapping in an Announce command with Imp-ACK requested. This command contains up to three IEs which inform DEV2 of the following:

1. Mapping IE (Figure 7): number of DEV1 transmit and receive beams and the SYNC mode (short or long SYNC) to be used in the beam level training. This IE is always present.
2. BST or PET Clustering IE (Figure 8): number of DEV1 transmit and receive clusters and the number of beams in each cluster, and the cluster encoding (when both devices use PET.) The BST clustering IE shall be exchanged only when both devices support tracking and not PET.
3. Beam PET IE (Figure 9): number of transmit and receive antennas on the *z*-axis and *x*-axis, the corresponding codebook IDs, and the amplitude and phase resolution capabilities. The PET IE shall be exchanged only when both devices use PET.

SAS beam DEV2→DEV1: Mapping IE

Beam SYNC Mode	Number of DEV2 beams - 1	Length	Element ID
2b	6b	8b	8b

SAS beam DEV1→DEV2: Mapping IE

Beam SYNC Mode	Number of DEV1 beams - 1	Length	Element ID
2b	6b	8b	8b

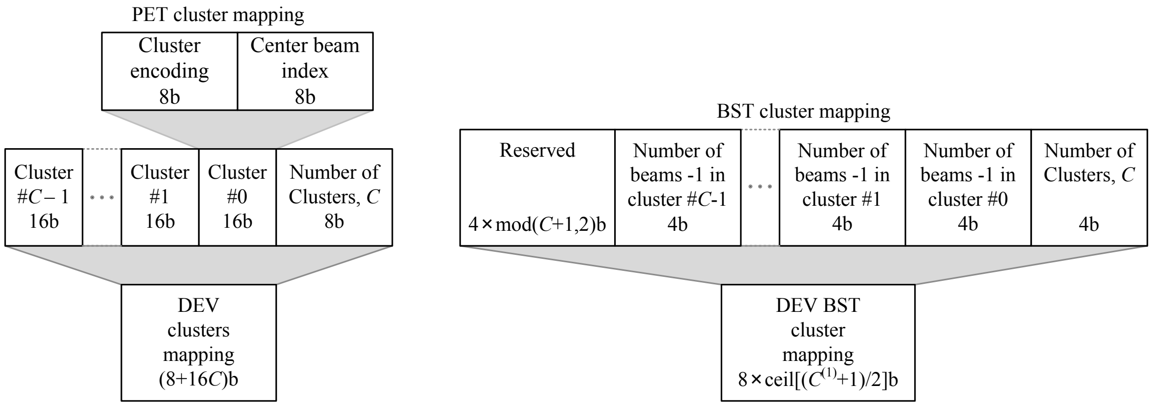
AAS beam DEV2→DEV1: Mapping IE

Reserved	Number of DEV2 Rx beams – 1	Beam SYNC Mode	Number of DEV2 Tx beams - 1	Length	Element ID
2b	6b	2b	6b	8b	8b

AAS beam DEV1→DEV2: Mapping IE

Reserved	Number of DEV1 Rx beams – 1	Beam SYNC Mode	Number of DEV1 Tx beams - 1	Length	Element ID
2b	6b	2b	6b	8b	8b

Figure 7 – Sector level Mapping IEs



SAS PET sector-beam DEV1→DEV2: Clustering IE

DEV2 PET cluster mapping	Length	Element ID
$(8+16C^{(2)})$b	8b	8b

SAS PET sector-beam DEV1→DEV2: Clustering IE

DEV1 PET cluster mapping	Length	Element ID
$(8+16C^{(1)})$b	8b	8b

AAS PET sector-beam DEV2→DEV1: Clustering IE

DEV2 Rx PET cluster mapping	DEV2 Tx PET cluster mapping	Length	Element ID
$(8+16C^{(2,r)})$b	$(8+16C^{(2,t)})$b	8b	8b

AAS PET sector-beam DEV1→DEV2: Clustering IE

DEV1 Rx PET cluster mapping	DEV1 Tx PET cluster mapping	Length	Element ID
$(8+16C^{(1,r)})$b	$(8+16C^{(1,t)})$b	8b	8b

SAS BST sector-beam DEV2→DEV1: Clustering IE

DEV2 BST cluster mapping	Length	Element ID
$8\times$ceil$[(C^{(2,t)}+1)/2]$b	8b	8b

SAS BST sector-beam DEV1→DEV2: Clustering IE

DEV1 BST cluster mapping	Length	Element ID
$8\times$ceil$[(C^{(1)}+1)/2]$b	8b	8b

AAS BST sector-beam DEV2→DEV1: Clustering IE

DEV2 Rx BST cluster mapping	DEV2 Tx BST cluster mapping	Length	Element ID
$8\times$ceil$[(C^{(2,r)}+1)/2]$b	$8\times$ceil$[(C^{(2,t)}+1)/2]$b	8b	8b

AAS BST sector-beam DEV1→DEV2: Clustering IE

DEV1 Rx BST cluster mapping	DEV1 Tx BST cluster mapping	Length	Element ID
$8\times$ceil$[(C^{(1,r)}+1)/2]$b	$8\times$ceil$[(C^{(1,t)}+1)/2]$b	8b	8b

Figure 8 – Sector level Clustering IEs

Reserved	Amplitude resolution	Phase resolution	*x*-axis beam codebook ID	*z*-axis beam codebook ID	Number of x-axis antennas-1	Number of z-axis antennas-1
2b	3b	3b	8b	8b	4b	4b

DEV Tx, Rx or Trx PET info.
32b

SAS DEV2→DEV1: Beam PET IE

DEV2 Trx PET info.	Length	Element ID
32b	8b	8b

SAS DEV1→DEV2: Beam PET IE

DEV1 Trx PET info.	Length	Element ID
32b	8b	8b

AAS DEV2→DEV1: Beam PET IE

DEV2 Rx PET info.	DEV2 Tx PET info.	Length	Element ID
32b	32b	8b	8b

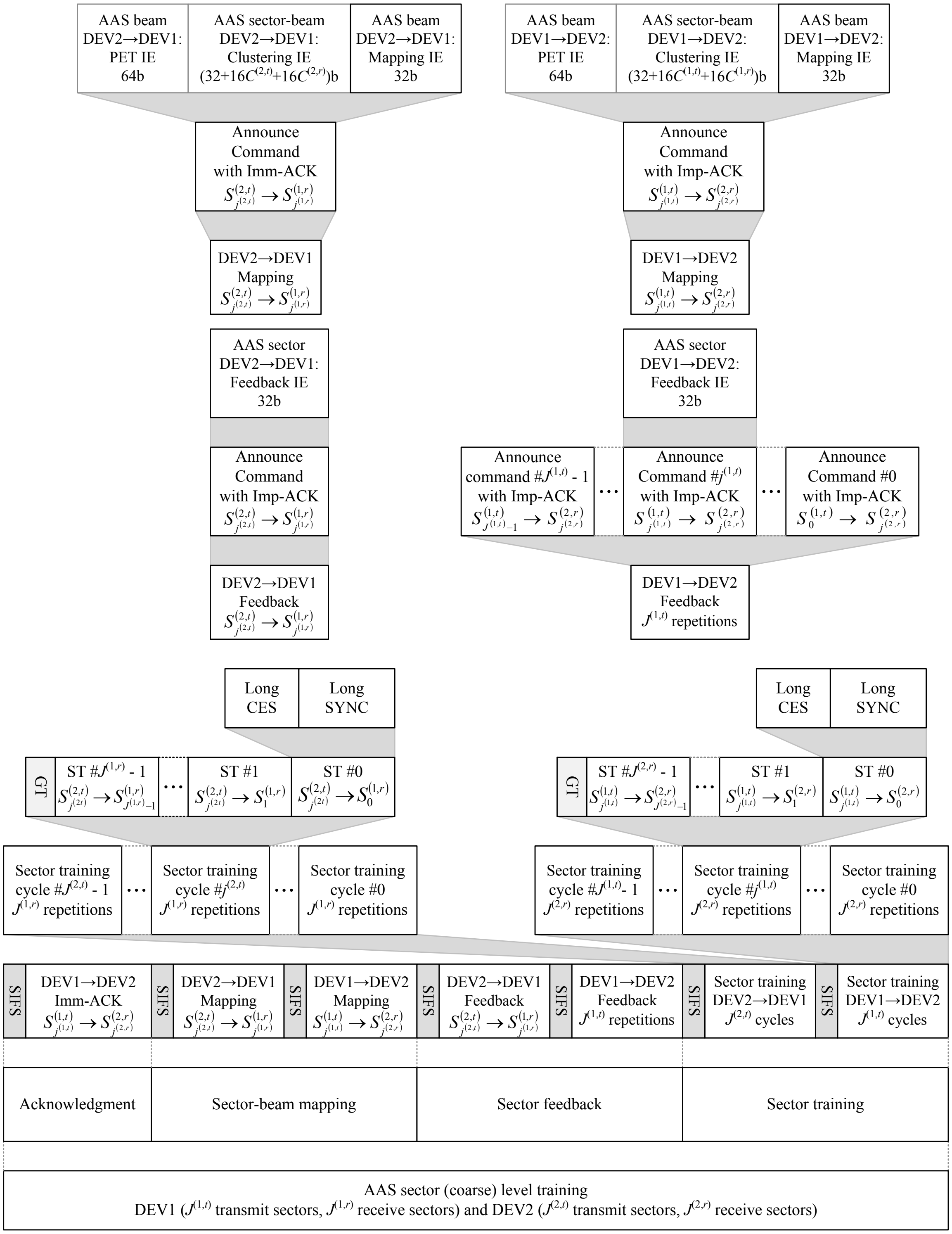
AAS DEV1→DEV2: Beam PET IE

DEV1 Rx PET info.	DEV1 Tx PET info.	Length	Element ID
32b	32b	8b	8b

Figure 9 – Sector level Beam PET IEs

DEV2 shall reply by sending back its own sector to beam mapping in an Announce command with Imm-ACK requested. DEV1 shall reply with an Imm-ACK which completes the sector level training as illustrated in Figure 10.

Figure 11 illustrates the message flow for a successful AAS sector level training process.

1


2 **Figure 10 – AAS sector level training**

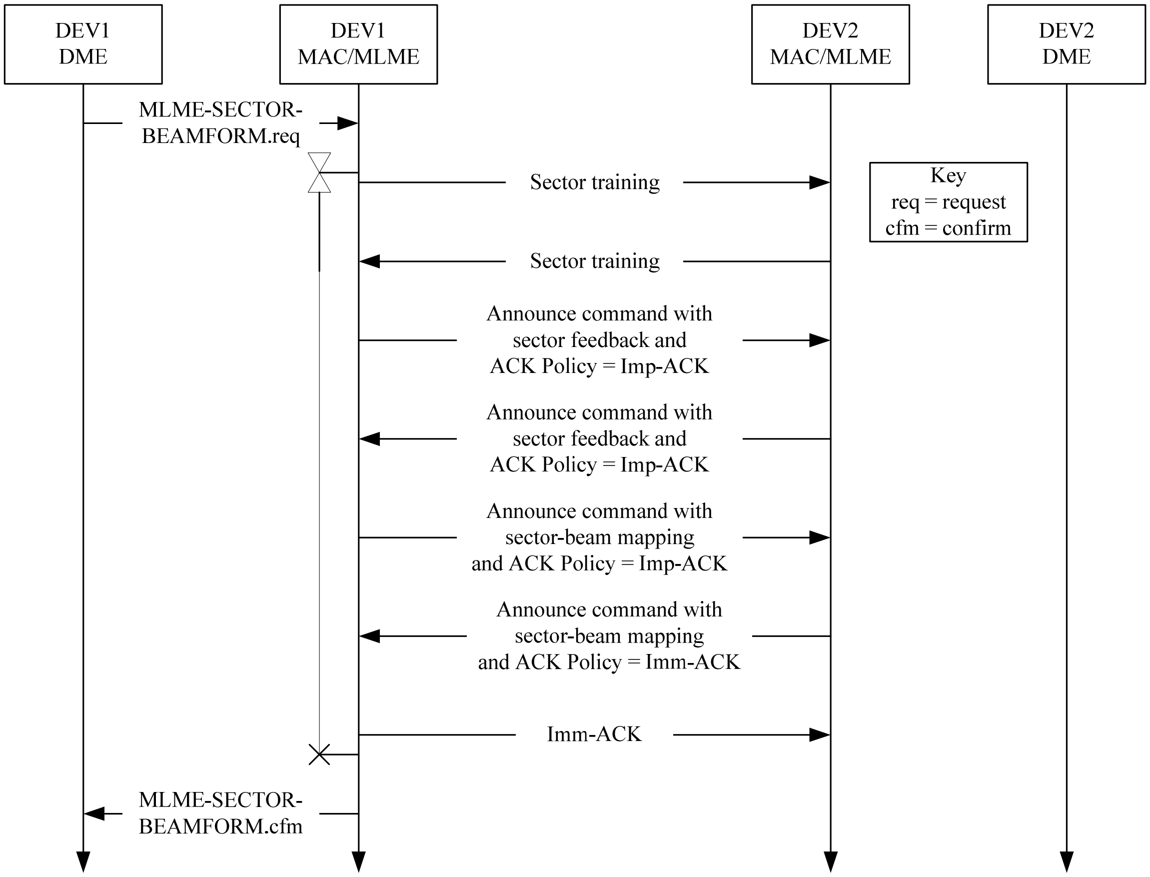


Figure 11 –Sector level training process

1.4.1.1.2 SAS sector level training

The sector level for a SAS is illustrated in Figure 12.

The sector training consists of $J^{(1)}$ cycles. During each cycle, DEV1 shall send $J^{(2)}$ repetitions of a sector training (ST) sequence in the same direction. Each cycle except the last one shall end with a guard time of 62.5 ns. The $J^{(1)}$ cycles shall be sent in $J^{(1)}$ different directions, $\left[S_0^{(1)}, S_1^{(1)}, \cdots, S_{J^{(1)}-1}^{(1)}\right]$ corresponding to the chosen $J^{(1)}$ sector codewords. The ST sequence shall be identical to the long preamble.

During a cycle, DEV2 shall attempt to receive each of the $J^{(2)}$ sector training sequences using a different direction. The $J^{(2)}$ different directions, $\left[S_0^{(2)}, S_1^{(2)}, \cdots, S_{J^{(2)}-1}^{(2)}\right]$, during a cycle shall correspond to DEV2's $J^{(2)}$ chosen sector codewords.

At the completion of the full $J^{(1)}$ cycles, DEV2 will have had an opportunity to receive an ST sequence using each combination of DEV1 transmit sector (0 to $J^{(1)}$-1) and DEV2 receive sector (0 to $J^{(2)}$-1). Based on this information, DEV2 selects the best sector pair, i.e. DEV1's optimal transmit and receive sector, $J_{i^{(1)}}^{(1)}$, and DEV2's optimal transmit and receive sector, $J_{i^{(2)}}^{(2)}$.

Following the sector training, DEV2 shall transmit its sector feedback in a Feedback IE (Figure 6) by sending an Announce command with Imp-ACK requested. The Announce command shall be sent in the optimal transmit sector, $S_{j^{(2)}}^{(2)}$, and shall be repeated $J^{(1)}$ times as shown in Figure 12. This is required since DEV1 does not yet know which sector to use to receive packets from DEV2, and therefore shall listen on each of the $J^{(1)}$ sectors until it hears the Announce command packet from DEV2. The feedback IE informs DEV1 of its optimal sector, $S_{j^{(1)}}^{(1)}$, second best sector, and the corresponding LQIs.

Upon completion of the feedback stage, both DEV1 and DEV2 know their optimal transmit and receive sectors. These shall be used for any further frame exchanges in this level.

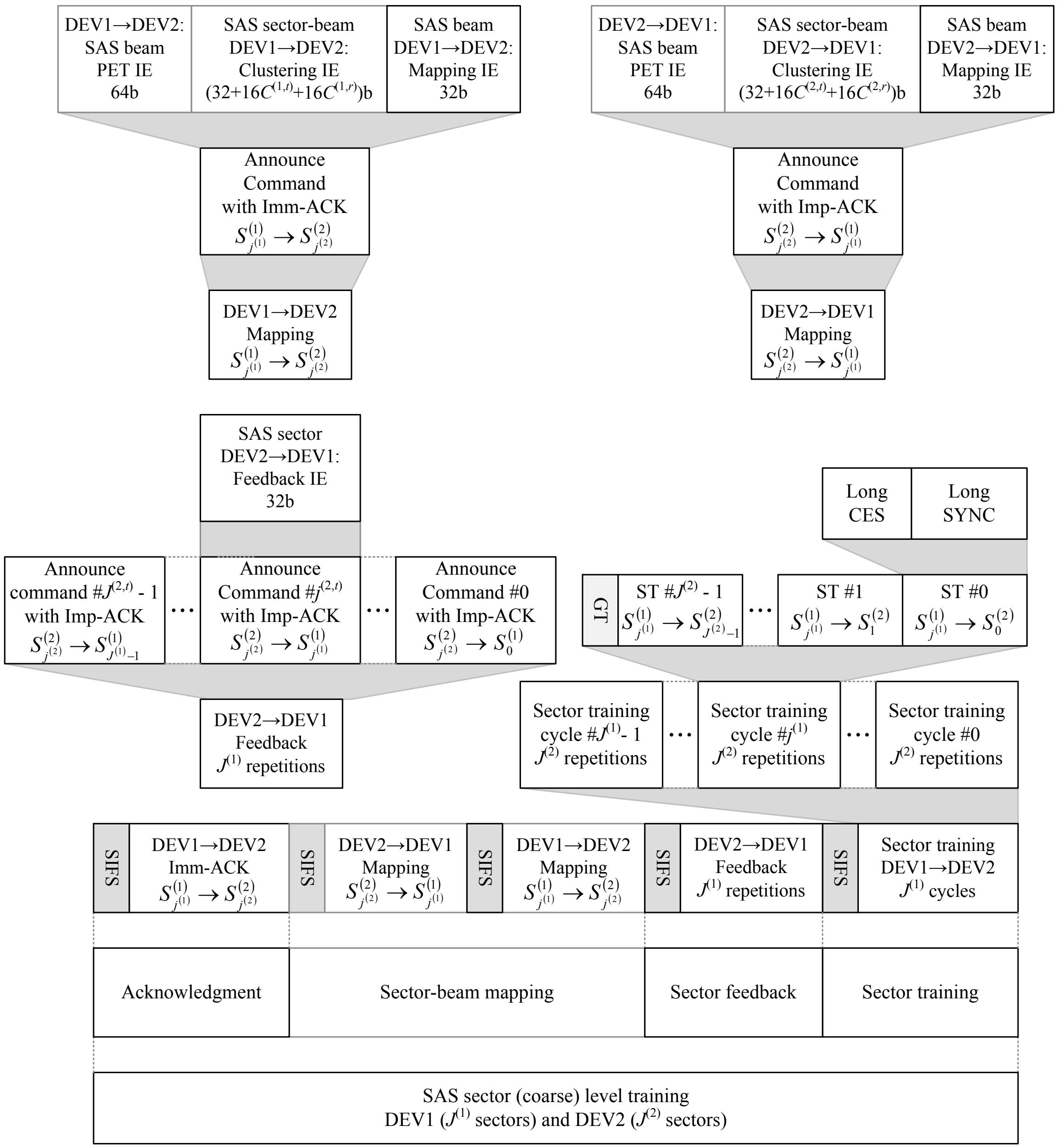
Following the feedback stage, DEV1 shall transmit its sector to beam mapping in an Announce command with Imp-ACK requested. This command contains up to three IEs which inform DEV2 of the following:

1. Mapping IE (Figure 7): number of DEV1 beams and the SYNC mode to be used in the beam level training. This IE is always present.
2. BST or PET Clustering IE (Figure 8): number of DEV1 clusters and the number of beams in each cluster, and the cluster encoding (when both devices use PET.) The BST clustering IE shall be exchanged only when both devices support tracking.
3. PET IE (Figure 9): number of transmit and receive antennas on the *z*-axis and *x*-axis, the corresponding codebooks IDs, and the amplitude and phase resolution capabilities. The PET IE shall be exchanged only when both devices use PET.

DEV2 shall reply by sending back its own sector to beam mapping in an Announce command with Imm-ACK requested. DEV1 shall reply with an Imm-ACK which completes the sector level training as illustrated in Figure 12.

Figure 13 illustrates the message flow for a successful AAS sector level training process.

1



2 **Figure 12 - SAS Sector level training**

3

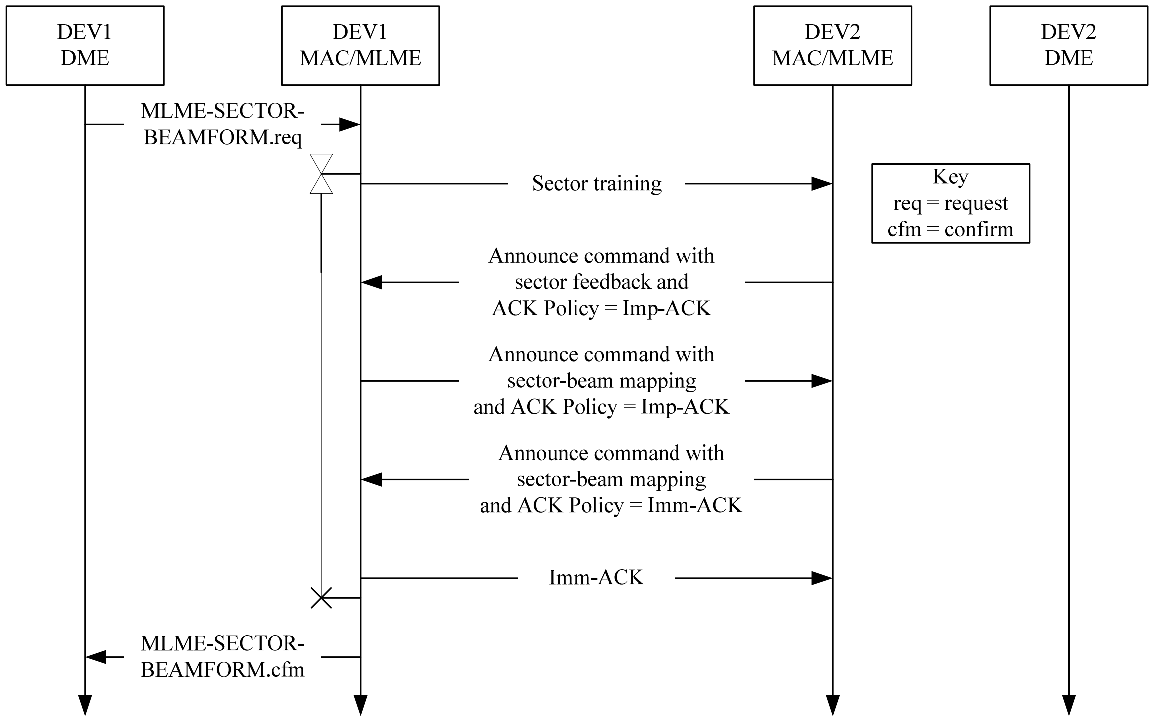


Figure 13 – SAS sector training process

1.4.1.1.3 Sector level training failure remedy

Announce commands may be retransmitted according to 8.8. Should the Announce command in either direction fail to be acknowledged after a number of retransmissions that is implementation dependent, or if there is not enough time remaining in the CTA for the entire frame exchange, the device that is attempting the retransmissions shall terminate the stream. DEV1 shall then request a CTA again from the PNC and restart the beamforming process from the beginning.

1.4.1.2 Beam level training

Once sector level training is completed, DEV1 and DEV2 shall start beam level training. The beam level training explores beams within the best sectors to find the best beam pair (best transmit and receive patterns) for DEV1 and DEV2. The AAS case is described first, followed by the SAS case.

If the two devices use PET or if tracking is enabled, than when referring to beams transmission, than clusters shall be transmitted in increasing index number, i.e. cluster number 0 shall be transmitted first. Furthermore, beams within a cluster shall be transmitted first in the order specified in 1.1.4.

The AAS beam level training is described first, followed by the SAS case.

1.4.1.2.1 AAS beam level training

The beam level consists of four stages: training, feedback, mapping, and acknowledgment, as illustrated in Figure 19.

The beam training from DEV1 to DEV2 consists of $K^{(1,t)}$ cycles. During each cycle, DEV1 shall send $K^{(2,r)}$ repetitions of a beam training (BT) sequence in the same direction, i.e. the direction specified by the corresponding beam codeword. Each cycle except the last one shall end with a guard time of 62.5 ns. The

$K^{(1,t)}$ cycles shall be sent in the $K^{(1,t)}$ different directions, $\left[B_0^{(1,t)},\ B_1^{(1,t)}, \cdots, B_{K^{(1,t)}-1}^{(1,t)}\right]$ corresponding to the chosen $K^{(1,t)}$ transmit beam codewords. The BT sequence shall be transmitted in the mode (preamble type) agreed upon during the sector mapping stage of the sector level training.

During a cycle, DEV2 shall attempt to receive each of the $K^{(2,r)}$ beam training sequence repetitions using a different listening (receive) direction. The $K^{(2,r)}$ different listening directions, $\left[B_0^{(2,r)},\ B_1^{(2,r)}, \cdots, B_{K^{(2,r)}-1}^{(2,r)}\right]$, during a cycle shall correspond to DEV2's $K^{(2,r)}$ chosen beam codewords.

At the completion of the full $K^{(1,t)}$ cycles, DEV2 will have had an opportunity to receive a BT sequence using each combination of DEV1 transmit beam (0 to $K^{(1,t)}$ - 1) and DEV2 receive beam (0 to $K^{(2,r)}$ - 1). Based on this information, DEV2 selects the best beam pair, i.e. DEV1's optimal transmit beam, $B_{k^{(1,t)}}^{(1,t)}$, and DEV2's optimal receive beam, $B_{k^{(2,r)}}^{(2,r)}$.

Following the beam training from DEV1 to DEV2, a similar beam training from DEV2 to DEV1 takes place where DEV2 transmits BT sequences over $K^{(2,t)}$ cycles as shown in Figure 20. At the completion of the $K^{(2,t)}$ cycles, DEV1 selects the best beam pair, i.e. DEV2's optimal transmit beam, $B_{k^{(2,t)}}^{(2,t)}$, and DEV1's optimal receive beam, $B_{k^{(1,r)}}^{(1,r)}$.

In the second stage of beam level training, DEV1 shall transmit its beam feedback in an Announce command with Imp-ACK requested. The Announce command shall be sent on DEV1's optimal transmit sector, $S_{j^{(1,t)}}^{(1,t)}$ and DEV2 shall listen on its optimal receive sector, $S_{j^{(2,t)}}^{(2,t)}$. The Announce command contains up to three IEs which inform DEV2 of the following:

1. Feedback IE (Figure 14): DEV2's optimal transmit beam, $B_{k^{(2,t)}}^{(2,t)}$, second best transmit beam, and the corresponding LQIs. This IE is always present.
2. PET Phase IE (Figure 15): DEV2's phase vector, i.e. the phase for each of the $M^{(2,t)}$ transmit antenna elements. This IE shall be exchanged only when both devices use PET and DEV2's transmit phase resolution is greater than one.
3. PET Amplitude IE (Figure 15): DEV2's amplitude vector, i.e. the amplitude for each of the $M^{(2,t)}$ transmit antenna elements. This IE shall be exchanged only when both devices use PET and DEV2's transmit amplitude resolution is greater than one.

SAS beam DEV1→DEV2: Feedback IE

SNR 2nd best	DEV2 2nd best beam index	SNR best	DEV2 best beam, $B^{(2)}_{k^{(2)}}$, index	Length	Element ID
4b	4b	4b	4b	8b	8b

SAS beam DEV2→DEV1: Feedback IE

SNR 2nd best	DEV1 2nd best beam index	SNR best	DEV1 best beam, $B^{(1)}_{k^{(1)}}$, index	Length	Element ID
4b	4b	4b	4b	8b	8b

AAS beam DEV1→DEV2: Feedback IE

SNR 2nd best	DEV2 2nd best Tx beam index	SNR best	DEV2 best Tx beam, $B^{(2,t)}_{k^{(2,t)}}$, index	Length	Element ID
4b	4b	4b	4b	8b	8b

AAS beam DEV2→DEV1: Feedback IE

SNR 2nd best	DEV1 2nd best Tx beam index	SNR best	DEV1 best Tx beam, $B^{(1,t)}_{k^{(1,t)}}$, index	Length	Element ID
4b	4b	4b	4b	8b	8b

Figure 14 - Beam level Feedback IEs

SAS beam DEV2→DEV1: Beam Amplitude PET IE

Reserved	DEV1 element# $M^{(1)}$-1 amplitude	…	DEV1 element# 1 amplitude	DEV1 element# 0 amplitude	Length = ceil($M^{(1)}$/2)	Element ID
(0 or 4)b	4b		4b	4b	8b	8b

AAS beam DEV1→DEV2: Beam Amplitude PET IE

Reserved	DEV2 element# $M^{(2,t)}$-1 amplitude	…	DEV2 element# 1 amplitude	DEV2 element# 0 amplitude	Length = ceil($M^{(2,t)}$/2)	Element ID
(0 or 4)b	4b		4b	4b	8b	8b

AAS beam DEV2→DEV1: Beam Amplitude PET IE

Reserved	DEV1 element# $M^{(1,t)}$-1 amplitude	…	DEV1 element# 1 amplitude	DEV1 element# 0 amplitude	Length = ceil($M^{(1,t)}$/2)	Element ID
(0 or 4)b	4b		4b	4b	8b	8b

SAS beam DEV2→DEV1: Beam Phase PET IE

Reserved	DEV1 element# $M^{(1)}$-1 phase	…	DEV1 element# 1 phase	DEV1 element# 0 phase	Length = ceil($M^{(1)}$/2)	Element ID
(0 or 4)b	4b		4b	4b	8b	8b

AAS beam DEV1→DEV2: Beam Phase PET IE

Reserved	DEV2 element# $M^{(2,t)}$-1 phase	…	DEV2 element# 1 phase	DEV2 element# 0 phase	Length = ceil($M^{(2,t)}$/2)	Element ID
(0 or 4)b	4b		4b	4b	8b	8b

AAS beam DEV2→DEV1: Beam Phase PET IE

Reserved	DEV1 element# $M^{(1,t)}$-1 phase	…	DEV1 element# 1 phase	DEV1 element# 0 phase	Length = ceil($M^{(1,t)}$/2)	Element ID
(0 or 4)b	4b		4b	4b	8b	8b

Figure 15 - Beam level PET results IEs

In return, DEV2 shall transmit its beam feedback by sending an Announce command with Imp-ACK requested. The Announce command shall be sent on DEV2's optimal transmit sector, $S_{j^{(2,t)}}^{(2,t)}$ and DEV1 shall listen on its optimal receive sector, $S_{j^{(1,r)}}^{(1,r)}$.

Upon completion of the feedback stage, both DEV1 and DEV2 know their optimal transmit and receive beams (patterns). These shall be used for any further frame exchanges in this level.

If either or both of the devices do not support tracking, the beam to HR beam mapping exchange shall be skipped and the last Announce command from DEV2 to DEV1 in the feedback stage shall be sent with Imm-ACK instead.

If tracking is supported, then following the feedback stage, DEV1 shall transmit its beam to HR beams mapping in an Announce command with Imp-ACK requested. This command contains up to three IEs which inform DEV2 of the following:

1. Mapping IE (Figure 16): number of DEV1 transmit and receive HR beams and the SYNC mode to be used in the HR beam tracking phase. This IE is present if both devices support tracking.
2. BST or PET Clustering IE (Figure 17): number of DEV1 transmit and receive clusters and the number of HR beams in each cluster, and the cluster encoding (when both devices use PET.) The BST clustering IE shall be exchanged only when both devices support tracking and not PET.
3. HR PET IE (Figure 18): the z-axis and x-axis HR codebook IDs. The HR PET IE shall be exchanged only when both devices use PET.

DEV2 shall reply by sending back its own beam to HR beam mapping in an Announce command with Imm-ACK requested. DEV1 shall reply with an Imm-ACK which completes the beam level training as illustrated in Figure 19.

Figure 20 illustrates the message flow for a successful AAS beam level training process.

SAS HR beam DEV1→DEV2 : Mapping IE

HR Beam SYNC Mode	Number of DEV1 HR beams - 1	Length	Element ID
2b	6b	8b	8b

SAS HR beam DEV2→DEV1 : Mapping IE

HR Beam SYNC Mode	Number of DEV2 HR beams - 1	Length	Element ID
2b	6b	8b	8b

AAS HR beam DEV1→DEV2 : Mapping IE

RES	Number of DEV1 Rx HR beams – 1	HR Beam SYNC Mode	Number of DEV1 Tx HR beams - 1	Length	Element ID
2b	6b	2b	6b	8b	8b

AAS HR beam DEV2→DEV1 : Mapping IE

RES	Number of DEV2 Rx HR beams - 1	HR Beam SYNC Mode	Number of DEV2 Tx HR beams - 1	Length	Element ID
2b	6b	2b	6b	8b	8b

Figure 16 - Beam level Mapping IEs

SAS HR beam DEV1→DEV2 : Clustering IE

DEV1 HR clusters mapping	Length	Element ID
$(8+16C^{(1)})$b	8b	8b

SAS HR beam DEV2→DEV1 : Clustering IE

DEV2 HR clusters mapping	Length	Element ID
$(8+16C^{(2)})$b	8b	8b

AAS HR beam DEV1→DEV2 : Clustering IE

DEV1 Rx HR clusters mapping	DEV1 Tx HR clusters mapping	Length	Element ID
$(8+16C^{(1,r)})$b	$(8+16C^{(1,t)})$b	8b	8b

AAS HR beam DEV2→DEV1 : Clustering IE

DEV2 Rx HR clusters mapping	DEV2 Tx HR clusters mapping	Length	Element ID
$(8+16C^{(2,r)})$b	$(8+16C^{(2,t)})$b	8b	8b

Figure 17 - Beam level Clustering IEs

HR PET info.

x-axis HR beam codebook ID	*z*-axis HR beam codebook ID
8b	8b

DEV Tx, Rx, or Trx HR PET info.
24b

SAS beam DEV1→DEV2: HR PET IE

DEV1 Trx HR PET info.	Length	Element ID
16b	8b	8b

SAS beam DEV2→DEV1: HR PET IE

DEV2 Trx HR PET info.	Length	Element ID
16b	8b	8b

AAS beam DEV1→DEV2: HR PET IE

DEV1 Rx PET info.	DEV1 Tx PET info.	Length	Element ID
16b	16b	8b	8b

AAS beam DEV2→DEV1: HR PET IE

DEV2 Rx HR PET info.	DEV2 Tx HR PET info.	Length	Element ID
16b	16b	8b	8b

Figure 18 - Beam level PET IEs

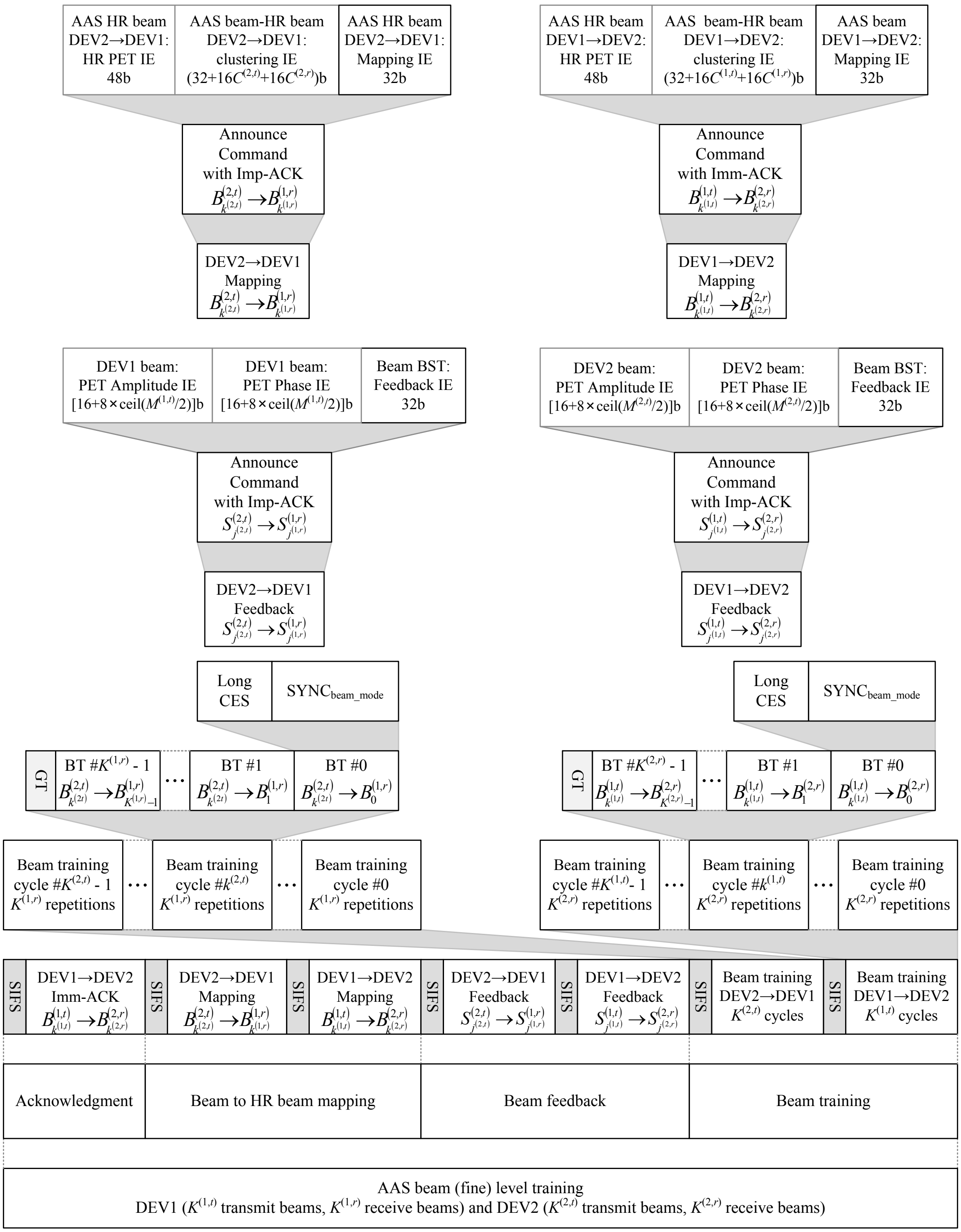


Figure 19 – AAS beam level training

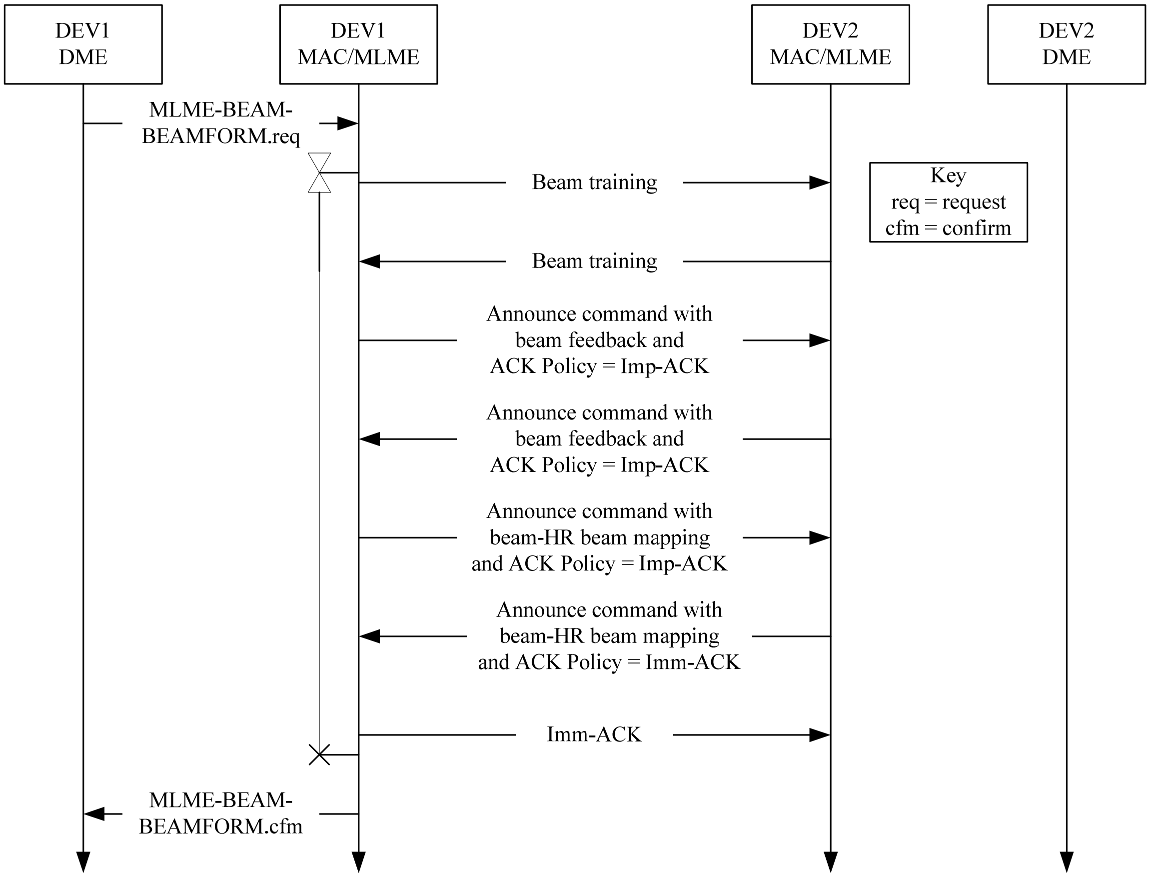


Figure 20 – AAS beam level training process

1.4.1.2.2 SAS beam level training

The SAS beam level training is illustrated in Figure 21.

The beam training from DEV1 to DEV2 consists of $K^{(1)}$ cycles. During each cycle, DEV1 shall send $K^{(2)}$ repetitions of a beam training (BT) sequence in the same direction, i.e. the direction specified by the corresponding beam codeword. Each cycle except the last one shall end with a guard time of 62.5 ns. The $K^{(1)}$ cycles shall be sent in the $K^{(1)}$ different directions, $\left[B_0^{(1)},\ B_1^{(1)}, \cdots, B_{K^{(1)}-1}^{(1)}\right]$ corresponding to the chosen $K^{(1)}$ transmit beam codewords. The BT sequence shall be transmitted in the mode agreed upon during the sector mapping stage of the sector level training.

During a cycle, DEV2 shall attempt to receive each of the $K^{(2)}$ beam training sequence repetitions using a different listening (receive) direction. The $K^{(2)}$ different listening directions, $\left[B_0^{(2)},\ B_1^{(2)}, \cdots, B_{K^{(2)}-1}^{(2)}\right]$, during a cycle shall correspond to DEV2's $K^{(2)}$ chosen beam codewords.

At the completion of the full $K^{(1)}$ cycles, DEV2 will have had an opportunity to receive a BT sequence using each combination of DEV1 transmit beam (0 to $K^{(1)}$ - 1) and DEV2 receive beam (0 to $K^{(2)}$ - 1). Based on this information, DEV2 selects the best beam pair, i.e. DEV1's optimal transmit and receive beam, $B_{k^{(1)}}^{(1)}$, and DEV2's optimal receive beam, $B_{k^{(2)}}^{(2)}$.

Following the beam training, DEV2 shall transmit its beam feedback in an Announce command with Imp-ACK requested. The Announce command shall be sent on DEV2's optimal transmit sector, $S_{j^{(2)}}^{(2)}$ and DEV1 shall listen on its optimal receive sector, $S_{j^{(1)}}^{(1)}$. The Announce command contains up to three IEs which inform DEV1 of the following:

4. Feedback IE (Figure 14): DEV1's optimal transmit and receive beam, $B_{k^{(1)}}^{(1)}$, second best transmit and receive beam, and the corresponding LQIs. This IE is always present.
5. PET Phase IE (Figure 15): DEV1's phase vector, i.e. the phase for each of the $M^{(1)}$ antenna elements. This IE shall be exchanged only when both devices use PET and DEV1's phase resolution is greater than one.
6. PET Amplitude IE (Figure 15): DEV1's amplitude vector, i.e. the amplitude for each of the $M^{(1)}$ antenna elements. This IE shall be exchanged only when both devices use PET and DEV1's amplitude resolution is greater than one.

Upon completion of the feedback stage, both DEV1 and DEV2 know their optimal transmit and receive beams (patterns). These shall be used for any further frame exchanges in this level.

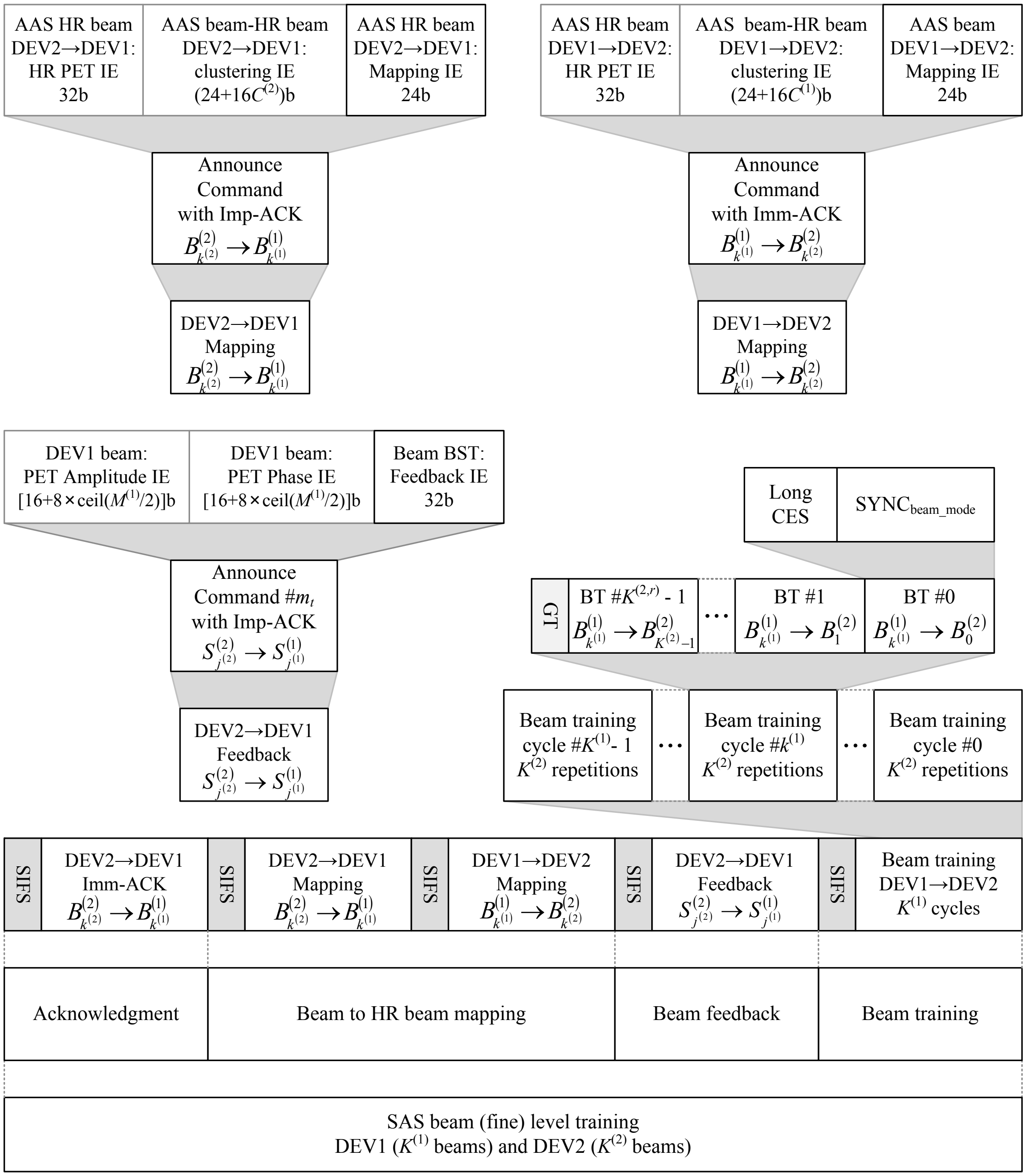
If either or both of the devices do not support tracking, the beam to HR beam mapping exchange shall be skipped and the Announce command from DEV2 to DEV1 in the feedback stage shall be sent with Imm-ACK instead.

If tracking is supported, then following the feedback stage, DEV1 shall transmit its beam to HR beams mapping in an Announce command with Imp-ACK requested. This command contains up to three IEs which inform DEV2 of the following:

4. Mapping IE (Figure 16): number of DEV1 HR beams and the SYNC mode to be used in the HR beam tracking phase. This IE is present if both devices support tracking.
5. BST or PET Clustering IE (Figure 17): number of DEV1 clusters and the number of HR beams in each cluster, and the cluster encoding (when both devices use PET.) The BST clustering IE shall be exchanged only when both devices support tracking and not PET.
6. HR PET IE (Figure 18): the *z*-axis and *x*-axis HR codebook IDs. The HR PET IE shall be exchanged only when both devices use PET.

DEV2 shall reply by sending back its own beam to HR beam mapping in an Announce command with Imm-ACK requested. DEV1 shall reply with an Imm-ACK which completes the beam level training as illustrated in Figure 21.

Figure 22 illustrates the message flow for a successful SAS beam level training process.

1 

2 **Figure 21 – SAS beam level training**

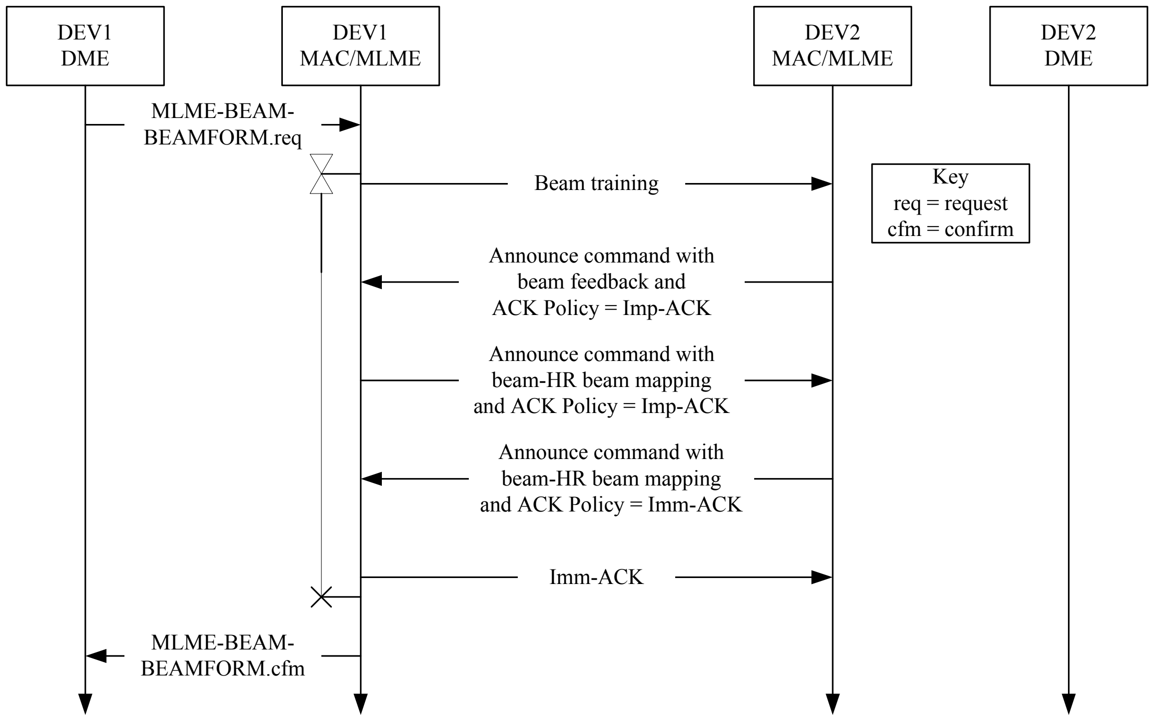


Figure 22 – SAS beam level training process

1.4.2 Beam tracking

When tracking is enabled, beams within a sector are further grouped into HR clusters and tracked as described below. Transmission of clusters and beams within a cluster shall follow the order outlined in subclause 1.4.1.2. During tracking, each device tracks the best and second best HR beams.

The tracking phase is used to achieve higher beam resolution and to track the changes in the beamformer and combiner vectors due to channel characteristics variability over time. When beam switching optimality criterion is used, pattern tracking reduces to beam tracking. In the more general case, the beamformer and combiner directions (patterns) need to be adjusted dynamically to achieve optimal link quality. Tracking is enabled by clustering which is a beam grouping method as explained later in this clause.

Tracking the best beam, best cluster and second best cluster is performed quasi-periodically as defined by the tracking frequency in the mapping IE. The tracking frequency of the best cluster of HR beams is higher than the tracking frequency of the second best cluster of HR beams.

Tracking takes place in the CTA allocated to data transfer from DEV1 to DEV2 in a distributed manner. Each data packet sent from DEV1 to DEV2 with the "direction tracking bit" in the PHY header set to 1, shall be followed by a guard time of 62.5ns followed by a one or more high resolution beam training (HT) sequences sent in the HR beams (directions) identified during the beam level phase. In the following, such a packet shall be referred to as a tracking packet. Not every packet sent by DEV1 is a tracking packet and the frequency at which tracking packets are sent is left to the implementer.

Normally, the m^{th} (m = 0, 1, …) tracking packet shall contain $L_{1+mod(m,2)}^{(t,1)}$ cycles. During each cycle, DEV1 shall send $L_{1+mod(m,2)}^{(r,2)}$ repetitions of an HT sequence in the same direction, i.e. the direction specified by the corresponding HR beam codeword. Each cycle except the last one shall end with a guard time of 62.5 ns as shown in Figure 23.

For devices operating in the low latency mode, however, only a single HT sequence shall be transmitted in each of the tracking packets as shown Figure 24. The orders in which the HR beams are interrogated remain the same as above. It is worth noting that the low latency tracking from DEV1 to DEV2 is distributed over $L(1,t)\times L(1,r) + L(2,t)\times L(2,r)$ tracking packets.

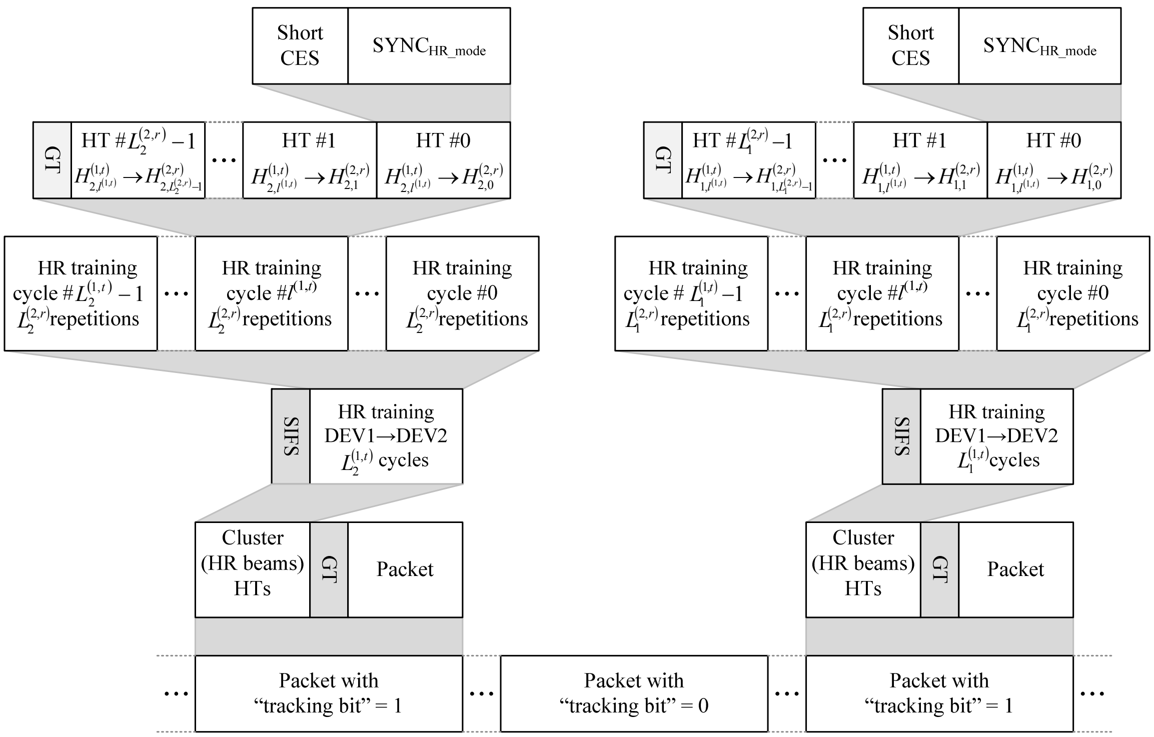


Figure 23 – Data packets with "beam tracking" bit set to one (normal case)

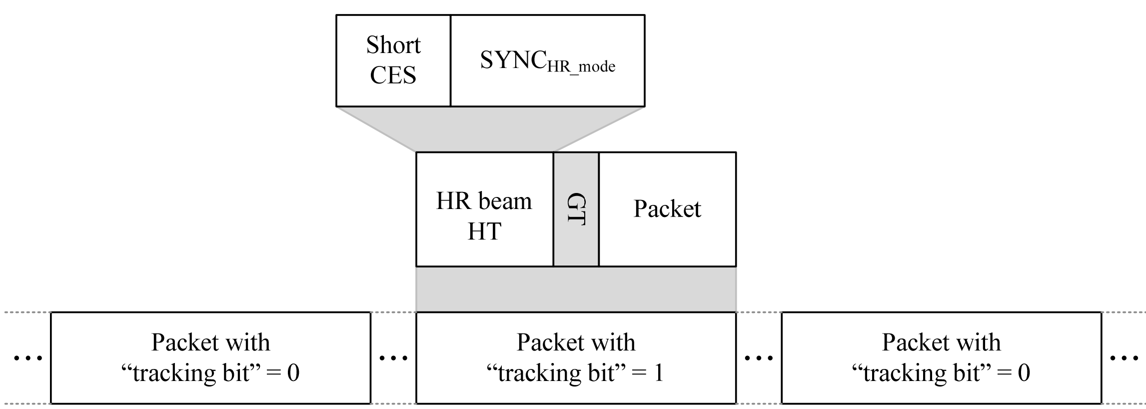


Figure 24 – Packet with "beam tracking" bit set to one for the low latency case

The tracking packet that interrogates the last beam in either cluster index may be sent with ACK policy set to Imp-ACK and the “last HR beam” bit in the PHY header set to one. The frequency with which this is done is implementation dependent. If DEV2 does not have results indicating that a change in transmit beam is desirable, DEV2 shall respond with an Imm-ACK and tracking continues. If, however, DEV2 has results indicating that DEV1 has a better choice of transmit beam (pattern), DEV2 shall respond with a feedback of the results in an empty data packet with ACK policy set to Imm-ACK. Upon receiving any results, DEV1 shall acknowledge the results with an Imm-ACK still using the old transmit beam. It shall then continue the data exchange using the new transmit beam.

DEV2 shall wait for the Imm-ACK on the old receive beam prior to switching to the new receive beam. Of course, if the results indicate that DEV2 should use a new receive beam but DEV1 should still use the same transmit beam, DEV2 shall switch as soon as possible. The switching beams sequence is shown in Figure 25.

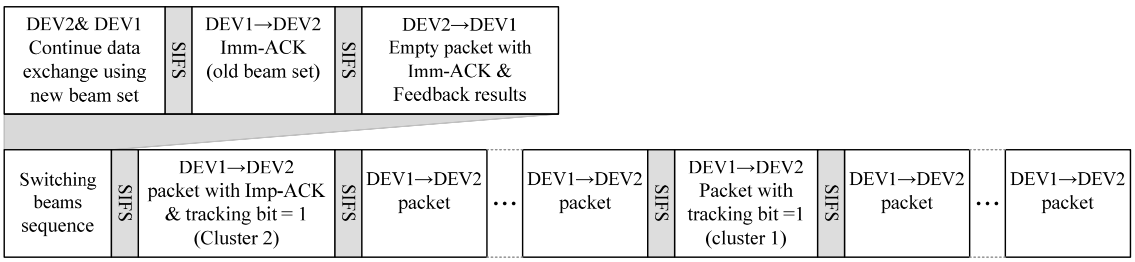


Figure 25 – Switching beams (patterns) during tracking

If the switching beams takes place, than it should be understood to the two devices that the old cluster is automatically replaced by the new cluster of the same size and identified by the new beam center.

Tracking from DEV2 to DEV1 is implemented in a similar way and can be run independently of tracking from DEV1 to DEV2.

Add as tracking IE.

Tracking IE

cluster size 3b	Beam number 3b	Cluster number 1b	Beam Tracking 1b

1.5 On-demand beamforming

On-demand beamforming takes place in the CTA allocated to the DEV. DEV1 shall reserve a CTA for the special purpose of beamforming acquisition. The sector level training as described in 1.4.1.1 shall occur first followed by the beam level training as described in 1.7.8.

[Note: Some indication information should be added to 7.4.1, 7.5.6.1, or 7.2.5 to indicate that the reserved Channel time allocation block is for antenna training purpose, i.e. introcude the concept of BF CTA].

1.6 Pro-active beamforming

In the pro-active beamforming, the sector training shall be performed according to sector level training in clause 1.4.1.1 and shall take place in the sector training section of the beacon part of the superframe as illustrated in Figure 26. The PNC number of sectors $J^{(1,t)}$ is specified in the PNC beamforming IE.

The message exchange following the sector training as specified in clause 1.4.1.1 and the beam level phase as specified in clause 1.7.8 shall take place in the beamforming CTAP allocated to the PNC and DEV.

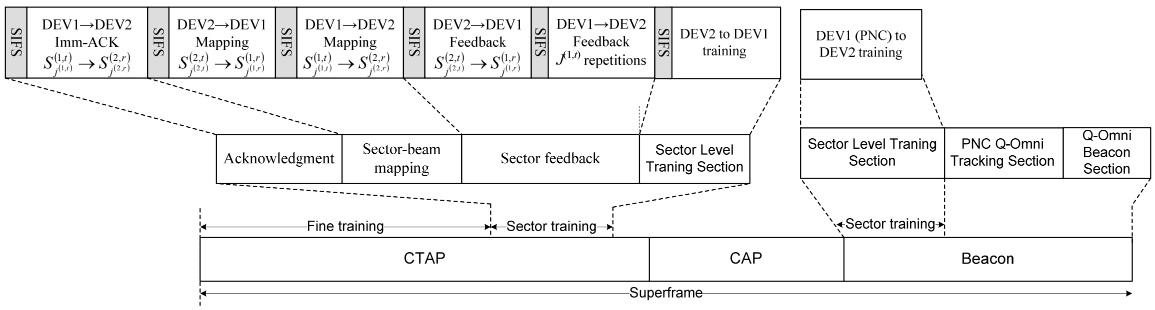


Figure 26 – AAS Two-level pro-active beamforming

1.7 Beamforming information elements

1.7.1 Feedback IE

The Feedback IE shall provide a device with the results of the training sequences previously sent by that device. It shall be formatted as illustrated in Figure 27.

bits: 4	4	4	4	8	8
SNIR for 2^{nd} best sector	2^{nd} best sector	SNIR for best sector	Best sector	Length (=2)	Element ID

Figure 27 - Beamforming Feedback IE

The sector fields shall be the indexes of the best transmit sector and second best transmit sectors for the device which transmitted training sequences to the device which is sending this IE (that is, the destination device for this IE.) In the SAS case, since the channel is symmetrical, these also represent the indexes of the best and second best receive sectors for that device.

In either case, associated with each sector shall be the effective SNIR seen by the receiving device.

1.7.2 Mapping IE

The Mapping IE is illustrated in Figure 28. This IE shall be used by a device to inform the other device with which it is beamforming of the sync mode and number of beams it will be using for the next level of training. These numbers are used to identify which codebook to use if a codebook is needed.

bits: 2	4	4	6	2	6	8	8
Tracking frequency resolution	Tracking frequency of second beam cluster	Tracking frequency of best beam cluster	Number of Rx beams - 1	Sync mode	Number of Tx beams - 1	Length (=3 or 2)	Element ID

Figure 28 - Beamforming Mapping IE

When sent at the end of sector level training, the (number of Tx beams – 1) and (number of Rx beams – 1) fields shall be set to the number of beams which the sending device will be using during the beam level training. When sent at the end of the beam level training, these fields shall be set to the number of HR beams to be used during tracking.

If the system is SAS, the number of Tx beams is the same as the number of Rx beams, so the (number of Rx beams – 1) shall not be included, in which case the length of the IE shall be 2 octets instead of 3.

The sync mode field shall encode the length of the sync sequence to be used for subsequent training sequences. The value of the field shall be the same as that used in the PHY header, as described in 12.2 and 12.3.

Tracking frequency includes the tracking frequency of the best cluster and the second best cluster. The tracking frequency is defined according to Table 1. The tracking frequency shall be encoded as shown in Table 2.

Table 1 – Tracking frequency

Tracking frequency	1/Tracking frequency value
0000	unused
0001	4 μs
0010 - 1101	Tracking frequency
1110	16ms
1111	Reserved

Table 2 – Tracking frequency resolution encoding

Tracking frequency resolution bits	1/Tracking frequency resolution
00	1 μs
01	10 μs
10	100 μs
11	1000 μs

1.7.3 BST Clustering IE

For the case where pattern estimation is not used (i.e., the beamforming does not use PET), the BST Clustering IE shall be sent during the mapping phases of sector and beam level training. The BST Clustering IE contains the number of beams or HR beams in each cluster which the sending device will be using during the beam level training (if sent during sector level training) or HR beam tracking (if sent during beam level training) stages of beamforming. The BST Clustering IE is illustrated in Figure 29.

8×ceil[(C_T+1)/2]	**8×ceil[(C_T+1)/2]**	**8**	**8**
C_R cluster mapping fields for Rx	C_T cluster mapping fields for Tx	Length (= ceil[(C_T + C_R +2)/2] or ceil[(C_T + 1)/2])	Element ID

Figure 29 - Beamforming BST Clustering IE

Each device selects groups of beams (for beam level training) or HR beams (for tracking) to be formed into C_R clusters (for receive) and C_T clusters (for transmit.) The transmit and receive clusters shall each be described by a cluster mapping field as shown in Figure 30. In the case of a SAS system, the transmit and receive clusters are identical, and only one cluster mapping field shall be included in the IE.

bits: 4	4	…	4	4	4
Reserved (If number of clusters is even)	Number of beams in cluster #C_R - 1 or #C_T - 1	…	Number of beams - 1 in cluster #1	Number of beams - 1 in cluster #0	Number of Clusters (C_R or C_T)

Figure 30 - Cluster mapping field of BST Clustering IE

The cluster mapping field shall consist of the count of clusters included, followed by a count of beams contained in each of the clusters. If the number of clusters is even, the last octet shall be padded with 4 reserved bits.

1.7.4 PET Clustering

For the case where beamforming uses PET, the PET Clustering IE shall be sent during the mapping phases of sector and beam level training. The PET Clustering IE contains the geometry of the clusters of beams or HR beams which the sending device will be using during the beam level training or HR beam tracking stages of beamforming. The Clustering IE is illustrated in Figure 31.

bits: (16 C_R + 8)	(16 C_T + 8)	8	8
C_R cluster mapping fields for Rx	C_T cluster mapping fields for Tx	Length (= 2(C_T + C_R + 1) or (2C_T + 1))	Element ID

Figure 31 - Beamforming PET Clustering IE

Each device selects groups of beams (for beam level training) or HR beams (for tracking) to be formed into C_R clusters (for receive) and C_T clusters (for transmit.) The transmit and receive clusters shall each be described by a cluster mapping field as shown in Figure 32. In the case of a SAS system, the transmit and receive clusters are identical, and only one cluster mapping field shall be included in the IE.

bits: 16	…	16	16	8
Cluster #C_R - 1 or #C_T – 1 descriptor	…	Cluster #1 descriptor	Cluster #0 descriptor	Number of Clusters (C_R or C_T)

Figure 32 - Cluster mapping field of PET Clustering IE

The cluster mapping field shall consist of the count of clusters included, followed by a cluster descriptor field for each of the clusters. The number of clusters and their descriptors shall describe the transmit and/or receive cluster mapping as determined by the position of the cluster mapping field in the PET Clustering IE.

Each cluster descriptor contains two fields, as shown in Figure 33.

bits: 8	8
Cluster encoding	Center beam index

Figure 33 - Cluster descriptor field of PET Clustering IE

The cluster encoding describes the geometry of the cluster and shall be as described in ***clause x.x.x***. The center beam index shall be the index of the beam or HR beam around which the cluster is formed.

1.7.5 Beam PET Information

For those beamforming cases where both devices use pattern estimation and tracking (PET), each device needs to know the antenna configuration of the other. This information shall be exchanged in PET Information IEs. The contents of the PET Information IE shall be as shown in Figure 34.

bits: 24	24	8	8
Rx PET configuration	Tx PET configuration	Length (=3 or 6)	Element ID

Figure 34 - PET Information IE

For the SAS case, the transmit and receive PET configurations are the same, so the Rx PET configuration field shall be omitted, and the length of the IE shortened to 3 octets of data.

Each PET configuration field shall be formatted as shown in Figure 35.

bits: 8	8	4	4
x-axis beam codebook ID	*z*-axis beam codebook ID	Number of *x*-axis antennas - 1	Number of *z*-axis antennas - 1

Figure 35 - PET configuration field of PET Information IE

The amplitude resolution field shall indicate the number of discrete values for amplitude that can result from pattern estimation. The field shall be coded as N, where there are 2^N possible resulting amplitude values. The value of this field shall be limited to the range 0 to 4.

Similarly, the phase resolution field shall indicate the number of discrete phase values that can result from pattern estimation. This field shall also be coded as N, where there are 2^N possible resulting phase values. The value of this field shall be limited to the range 0 to 4.

The beam codebook ID fields shall identify the codebooks to be used for the respective axes, while the number of antennas fields shall provide the size of the rectangular antenna array along the *x*- and *z*-axes. These values shall be for the transmit and/or receive arrays as identified by the position of the field in the PET Information IE.

1.7.6 HR Beam PET Information

For those beamforming cases where both devices use pattern estimation and tracking (PET), each device needs to know the antenna configuration of the other. This information shall be exchanged in PET Information IEs. The contents of the PET Information IE shall be as shown in Figure 34.

bits: 16	16	8	8

Rx PET HR configuration	Tx PET HR configuration	Length (=2 or 4)	Element ID

Figure 36 – HR PET Information IE

For the SAS case, the transmit and receive PET HR configurations are the same, so the Rx PET configuration field shall be omitted, and the length of the IE will be shorter.

Each PET HR configuration field shall be formatted as shown in Figure 37.

8	8
x-axis HR beam codebook ID	*z*-axis HR beam codebook ID

Figure 37 - PET HR configuration field of HR PET Information IE

The HR beam codebook ID fields shall identify the codebooks to be used for the respective axes. These values shall be for the transmit and/or receive arrays as identified by the position of the field in the HR PET Information IE.

1.7.7 PET Amplitude IE

In the case where both DEVs are using PET, the calculated phase and amplitude values are returned during the feedback stage. If the PET configuration field of the PET Information IE indicates that more than one possible value exists for amplitude results, the PET Amplitude IE shall contain the calculated amplitude values and shall be added to the Announce command which contains the Feedback IE.

The PET Amplitude IE shall contain one value of amplitude for each antenna element, and the values are sent in the predefined antenna element order (specified in clause REFERENCE???). If F represents the amplitude relative to the element with the highest amplitude, the field value shall be the numerator N of a fraction N/D = F, where D is the number of possible values as specified by the amplitude resolution subfield of the PET Information IE. For example, if the amplitude resolution field value is 3, then there are 2^3 = 8 possible values and D = 8. In this case, one of the antenna element amplitudes shall be set to N = 8, and the others shall have values in the range of N = 1 to N = 8.

Each value shall be transmitted in the IE as field value = (N – 1), as shown in Figure 38.

bits: 4 or 0	4	…	4	4	8	8
Reserved (If needed to pad)	Element #M-1 amplitude - 1	…	Element #1 amplitude - 1	Element #0 amplitude - 1	Length (=ceil(M/2))	Element ID

Figure 38 - PET Amplitude IE

1.7.8 PET Phase IE

If the PET configuration field of the PET Information IE indicates that more than one possible value exists for phase results, the PET Phase IE shall contain the calculated amplitude values and shall be added to the Announce command which contains the Feedback IE.

The PET Phase IE shall contain one value of phase for each antenna element and the values are sent in the predefined antenna element order (specified in clause REFERENCE???). If F represents the phase as a fraction of a full circle, the field value shall be the numerator N of a fraction $N/D = F$, where D is the number of possible values as specified by the phase resolution subfield of the PET Information IE. For example, if the phase resolution field value is 4, then there are $2^4 = 16$ possible values and D = 16. In this case, each LSb of the phase value is equal to 22.5°, and the values shall be in the range of $N = 0$ to $N = 15$ or 0° to 342.5°.

Each phase value shall be transmitted in the IE as field value = N, as shown in Figure 39, where M is the number of antenna elements in the array.

bits: 4 or 0	**4**	**…**	**4**	**4**	**8**	**8**
Reserved (If needed to pad)	Element #M – 1 phase	…	Element #1 phase	Element #0 phase	Length (=ceil(M/2))	Element ID

Figure 39 - PET Phase IE

[7.5.1.1 Association request]

The DEV Utility field shall be formatted as illustrated in Figure 50.
{Replace figure 50 with the new one below which adds the Response Tx sector field}

bits: b7–b5	b4-b2	b1	b0
Reserved	Response Tx sector	Neighbor PNC	Piconet services inquiry

Figure 50—DEV utility field format

{Insert the following paragraph following the table}
If the PNC utilizes an AAS (as determined from the received beacon), the Response Tx sector field shall be set to the index of the beacon that was initially heard by the DEV. This corresponds to the best transmit sector for the PNC to use for its response and any further communication. In all other cases, the Response Tx sector field shall be set to zero.

The Piconet Services Inquiry bit shall be set to one if the associating DEV is requesting that the PNC send the Piconet Services command, as described in 7.5.5.1, and shall be set to zero otherwise.

The Neighbor PNC bit shall be set to one if the DEV intends to be a neighbor PNC, as described in 8.2.6, in the current piconet and shall be set to zero otherwise.

8.4.2 Contention based channel access

To minimize collisions, a transmitting DEV is required to first sense that the medium is idle for a random length of time. The medium shall be considered idle when it is sensed idle in all of the DEV's Q-omni receive directions. P.170

when the BSS criterion is used. For the case where the two devices are PET, DEV2 shall compute the best DEV1's beamformer vector, $\mathbf{w}_1$, and DEV2's best combiner vector, $\mathbf{c}_2$

ADD mapping :00 = long preamble, 01 = medium preamble, 10 = short preamble, 11 = extra short preamble.

When tracking is enabled, beams within a sector are further grouped into clusters and tracked as detailed in 1.4.2.

2 Superframe structure

One or more devices in the piconet may not be omni capable on transmission or on reception. Therefore, adaptations to the beacon, CAP, and association process are required as shown in the example superframe structure in Figure 40. The different fields are detailed below.

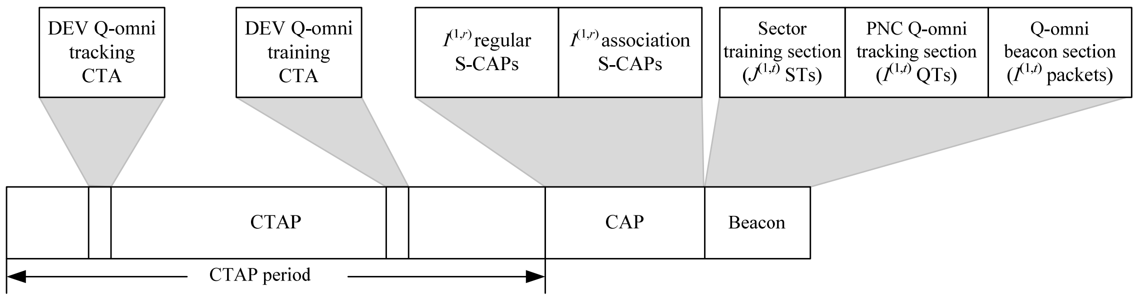


Figure 40 – Superframe structure

2.1 The beacon

The beacon structure is illustrated in Figure 41.

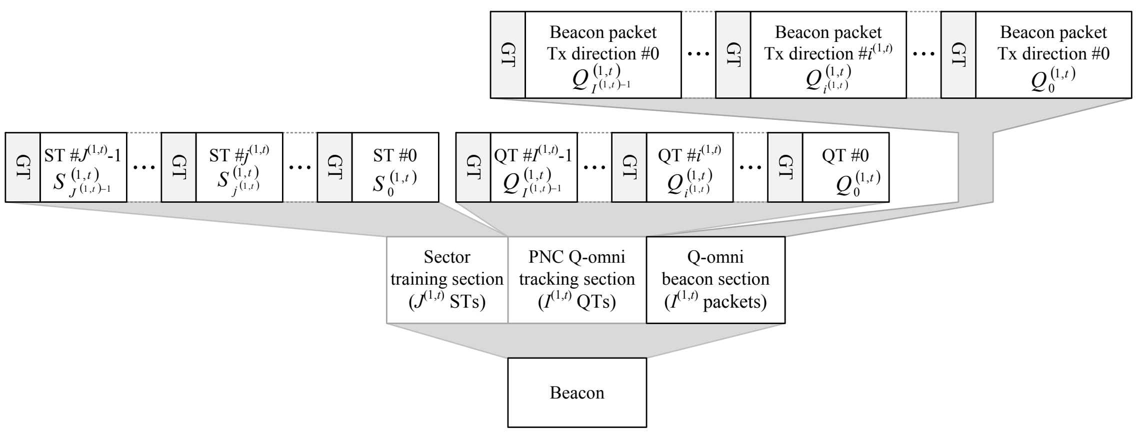


Figure 41 - Beacon structure

Quasi-omni coverage during beaconing shall be supported by repeating the beacon packet $I^{(1,t)}$ times and sending each repetition with a different TX antenna, Q-omni (Quasi-omni) direction, or array pattern. Each repetition is followed by a guard time of 62.5 ns. The $I^{(1,t)}$ antenna directions or array patterns shall be identified by indices zero through $I^{(1,t)}$-1. The number of beacon packet repetitions $I^{(1,t)}$ and the index of the current beacon transmit direction are parameters in the piconet synchronization parameters field in 7.3.1.1. In the following the term "direction" shall be used to refer to an antenna direction or an array pattern, and the guard time duration shall be 62.5 ns.

When the PNC Q-omni tracking bit in the Synchronization IE is set to one, then a PNC Q-omni tracking section shall follow the Q-omni beacon section to allow devices in the piconet to track the PNC Q-omni directions. The PNC Q-omni tracking section consists of $I^{(1,t)}$ Q-omni training (QT) sequences transmitted in the $I^{(1,t)}$ PNC Q-omni directions. The $I^{(1,t)}$ training sequences may be transmitted at once in a superframe or distributed over multiple superframes. The QT sequence shall be identical to the long preamble.

When the sector training bit in the Synchronization IE is set to one, then a sector training section shall follow the PNC Q-omni tracking section to enable pro-active beamforming. The sector training section consists of $J^{(1,t)}$ sector training (ST) sequences transmitted in the $J^{(1,t)}$ PNC sector directions. The $J^{(1,t)}$ ST sequences may be transmitted at once in a superframe or distributed over multiple superframes. The ST sequence shall be identical to the long preamble.

2.2 The CAP

The CAP period may be divided into two sections, an association section and a regular CAP section as shown in Figure 42. If PNC allows new association request, an association section exists at the CAP period. The association section may be further divided into a set of $I^{(1,r1)}$ equal size association sub CAPs (S-CAPs) corresponding to some of the $I^{(1,r)}$ PNC different Q-omni receive directions within one superframe or distributed over multiple superframes ($r1 \leq r$). The regular CAP section is equally divided in into the $I^{(1,r1)}$ equal size sub CAPs (S-CAPs) corresponding to some of the $I^{(1,r)}$ PNC different Q-omni receive directions within one superframe or distributed over multiple superframes.. Each S-CAP is received by the PNC using a different antenna receive direction.

The association section CAP shall be used solely for devices to send association request commands to the PNC. The regular CAP may be used for all command and data exchanges.

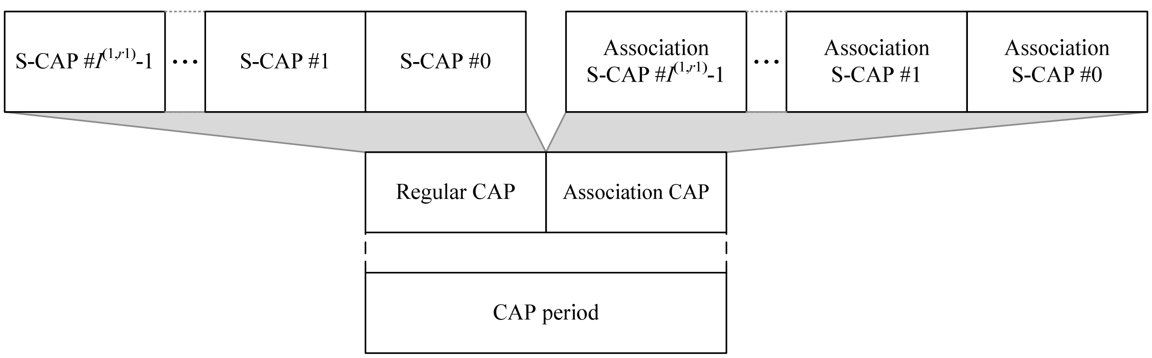


Figure 42 – CAP structure

If the AAS bit in the piconet synchronization parameters field is set to zero, indicating that the PNC is SAS, the number of S-CAPs shall be one-to-one with the number of beacons ($I^{(1,t)} = I^{(1,r)}$). That is, the PNC transmit direction used for the i^{th} ($i = 0, ..., I^{(1,t)}-1$) beacon packet transmission shall be used for the i^{th} S-CAP respectively.

If the AAS bit in the piconet synchronization parameters field is set to one, indicating that the PNC is AAS, the number of S-CAPs shall be equal to $I^{(1,r)}$ which is specified in the piconet synchronization parameters field. The special case where $I^{(1,t)} = 1$ indicates that the PNC is omni capable on reception.

2.3 Device Discovery and Association

Let $I^{(1,t)}$ and $I^{(1,r)}$ be the number of PNC Q-omni transmit and receive directions respectively, and let $I^{(2,t)}$ and $I^{(2,r)}$ be the number of DEV Q-omni transmit and receive directions of a DEV who wants to find a PNC and associate with that PNC respectively.

While searching for a PNC, a DEV shall listen to Q-omni beacons at all $I^{(2,r)}$ Q-omni receive directions to find the best and second best pairs of (PNC Q-omni transmit direction, DEV Q-omni receive direction) based on LQI measurement. The DEV shall use the best DEV Q-omni receive direction to receive further transmissions from the PNC when Q-omni transmisison is used. The DEV shall include the information of the best PNC Q-omni transmit direction in its Association Request commands to inform the PNC the best PNC Q-omni transmit direction for further Q-omni transmissions to the DEV.

The DEV shall track the best and second best pairs of (PNC Q-omni transmit direction, DEV Q-omni receive direction) during the Q-omni beacon section and PNC Q-omni tracking section of beacons based on LQI measurement. If the beacon quality in the second best pair is better than the best pair, the PNC and the DEV shall switch to the second best pair which becomes the newly best pair of (PNC Q-omni transmit direction, DEV Q-omni receive direction).

The association procedure of a DEV depends on the antenna types at both the PNC and the DEV. The DEV shall transmit one or multiple Association Request commands formatted as described in 7.5.1.1. If both the DEV itself and the PNC utilize SAS antennas, this command shall be transmitted on DEV antenna Q-omni direction $i^{(2,t)} = i^{(2,r)}$, during the S-CAP with index, $i^{(1,t)}$. The transmission shall obey the rules for contention access as described in 8.4.2.

If either the DEV or the PNC is AAS, the DEV does not know which Q-omni transmit direction to use, nor which S-CAP is the best. In this case, the DEV shall transmit the Association Request command at different pairs of (DEV Q-omni transmit direction, PNC Q-omni receive direction) during association S-CAPs in one or multiple superframes until it receives an Association Response command successfully or association timeout. The Association Response command shall include the information of the pair of (DEV Q-omni transmit direction, PNC Q-omni receive direction) from which it receives the Association Request command.

Once an Association response command is received successfully, the DEV shall cease the transmission of Association Request command in association S-CAPs and ignore other copies of the same Association Response command from PNC. The DEV shall use the regular S-CAP of the PNC Q-omni receive direction carried in the Association Response command for all further CAP transactions with the PNC before the completion of the best pair of (DEV Q-omni transmit direction, PNC Q-omni receive direction) searching. In addition, the DEV shall use the DEV transmit Q-omni direction carried in the Association Response command before the completion of the best pair of (DEV Q-omni transmit direction, PNC Q-omni receive direction) searching.

2.4 DEV Q-omni transmit direction training and tracking

Since the pair of (DEV Q-omni transmit direction, PNC Q-omni receive direction) found at the association stage may not be the best pair due to possible collisions in CAP, the PNC shall reserve a CTA to search for the best and the second best pairs of (DEV Q-omni transmit direction, PNC Q-omni receive direction) when channel has free time. The CTA structure for DEV Q-omni transmit direction training is illustrated in Figure 43.

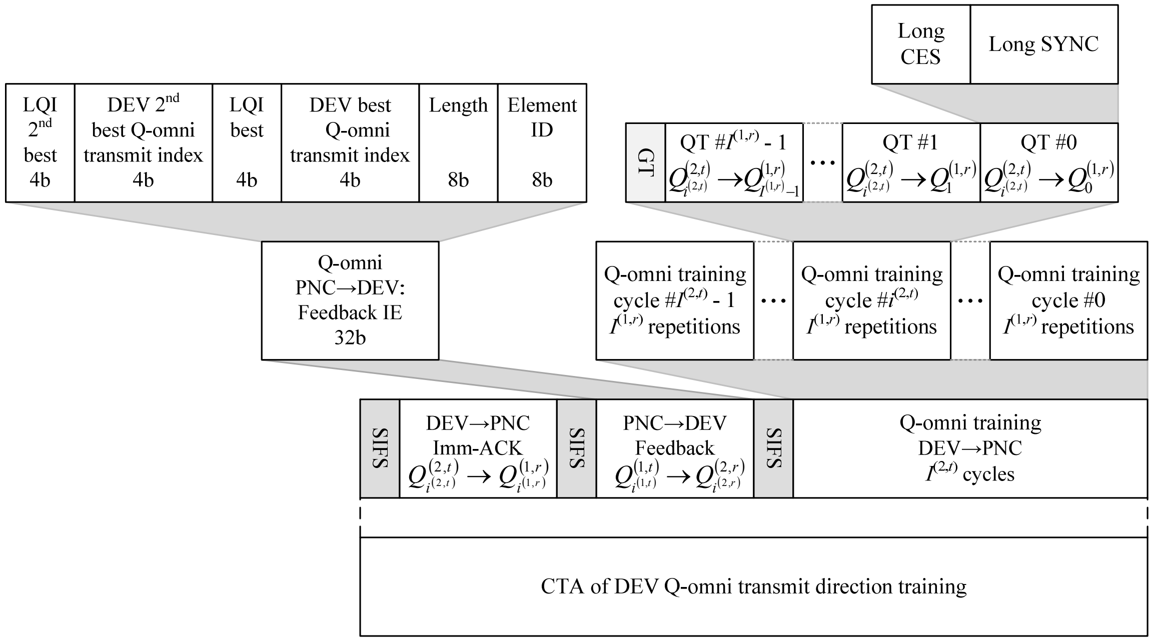


Figure 43 – CTA structure for DEV Q-omni transmit direction training

The Q-omni training consists of $I^{(2,t)}$ cycles. During each cycle, the DEV shall send $I^{(1,r)}$ repetitions of a Q-omni training (QT) sequence in the same direction. Each cycle except the last one shall end with a guard time of 62.5 ns. The $I^{(2,t)}$ cycles shall be sent in $I^{(2,t)}$ different directions, namely $\left[Q_0^{(2,t)},\ Q_1^{(2,t)}, \cdots, Q_{I^{(2,t)}-1}^{(2,t)}\right]$. The QT sequence shall be identical to the long preamble.

During a cycle, the PNC shall attempt to receive each of the $I^{(1,r)}$ Q-omni training sequences using a different direction. The $I^{(1,r)}$ different directions, $\left[Q_0^{(1,r)},\ Q_1^{(1,r)}, \cdots, Q_{I^{(1,r)}-1}^{(1,r)}\right]$, during a cycle shall correspond to the PNC's Q-omni receive directions.

At the completion of the full $I^{(2,t)}$ cycles, the PNC will have had an opportunity to receive a QT sequence using each combination of DEV2 transmit Q-omni direction (0 to $I^{(2,t)}$ -1) and PNC receive Q-omni direction (0 to $I^{(1,r)}$ -1). Based on this information, the PNC selects the best Q-omni pair, i.e. DEV2's optimal transmit Q-omni direction, $I_{i(2,t)}^{(2,t)}$, and the PNC optimal transmit and receive sector, $I_{i(1,r)}^{(1,r)}$.

Following the Q-omni training, the PNC shall transmit its Q-omni feedback in a Feedback IE by sending an Announce command with Imm-ACK requested. The Announce command shall be sent in the optimal transmit Q-omni direction, $Q_{i(2)}^{(1,t)}$, and DEV shall listen on its optimal receive direction, $Q_{i(2,r)}^{(1,r)}$. The feedback IE informs DEV of its optimal transmit Q-omni direction, $Q_{i(2,t)}^{(2,t)}$, second best Q-omni direction, and the corresponding LQIs.

DEV shall reply with an Imm-ACK which completes the device Q-omni tracking transmit direction training.

The PNC shall track the best and second best pairs of (DEV Q-omni transmit direction, PNC Q-omni receive direction) based on LQI measurement by allocating a tracking CTA periodically when channel has free time. The CTA structure for DEV Q-omni transmit direction tracking is illustrated in Figure 44. If the signal quality in the second best pair is better than the best pair, the PNC and the DEV shall switch to the second best pair which becomes the newly best pair of (DEV Q-omni transmit direction, PNC Q-omni receive direction) thereafter.

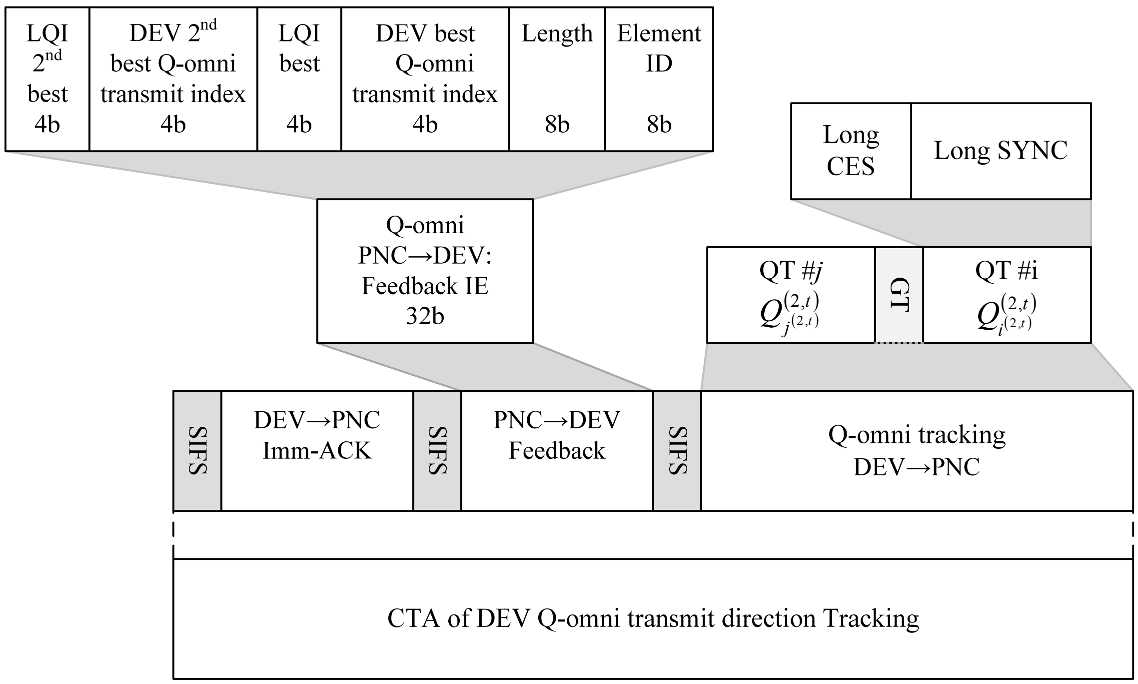


Figure 44 – CTA structure for DEV Q-omni transmit direction tracking

2.5 Superframe structure IE

Page 108: Change 7.3.1.1 Figures 11 and 12 (Piconet synchronization parameters is now 24 octets instead of 21); Add 3 octets,

1. 13 bits for the offset from start of superframe,
2. 3 bits for current index of beacon
3. 3 bits for total number of beacon packets
4. 3 bits for total number of S-CAPs
5. 1 bit to state whether the PNC is SAS or AAS
6. 1 bit to state whether PNC is beamforming capable or not.

Page 109: Change Figure 13

1. 1 bit for low-latency (b5)
2. 1 bit for sectors only (b6)
3. 1 bit to indicate if beamforming (BST) is supported or not (b7)

The following should be added to the current 15.3 IEs

The following field indicates BF properties of DEVs, which will be put in DEV capability IE.

- *Antenna types (3bits)*
  - 000 : Omni antenna capable only (no beamforming capable)
  - 001: BF antenna capable
  - 010-111: Reserved
- *Number of RX Quasi-Omni (2bits)*
- *Number of TX Quasi-Omni (2bits)*
- *Number of RX sector (4bits)*
- *Number of Tx sector (4bits)*

- *PET (1bit)*: enable/disable pattern estimation and tracking
  - 0: not support

1: support pattern estimation and tracking

Table 3 – Beamforming capabilities in DEV Capability IE

1b	4b	4b	2b	2b	3b
PET	Number of Rx sectors	Number of Tx sectors	Number of Rx Quasi-omni directions	Number of Tx Quasi-omni directions	Antenna types

Table 4 – Superframe structure IE

Bits: 40	40	1	1	1	1	8	8
Regular CAP section info	Association CAP section info	Regular CAP section indication	Association CAP section indication	Sector training section indication	PNC Q-omni tracking indication	Length	Element ID

Table 5 Association CAP section info

Bits: 2	**2**	**2**	**2**	**16**	**16**
Reserved	First PNC RX Q-omni index in the current superframe	Number of association S-CAPs in current Superframe	Total number of Association S-CAPs	S-CAP duration	Association CAP Start Time

Table 6 – Regular CAP section info

Bits: 2	**2**	**2**	**2**	**16**	**16**
Reserved	First PNC RX Q-omni index in the current superframe	Number of regular S-CAPs in current Superframe	Total number of Association S-CAPs	S-CAP duration	Regular CAP Start Time

PNC Q-omni tracking indication bit shall set to 1 if PNC Q-omni tracking section exists in the beacon.

Sector training section indication bit shall set to 1 if Sector training section exists in the beacon

Association CAP section indication bit shall set to 1 if Association CAP section exist in the CAP.

Regular CAP section indication bit shall set to 1 if Regular CAP section exist in the CAP.

Association CAP section info specifies the Association CAP section structure.

Regular CAP section info specifies the Regular CAP section structure.

Association CAP Start Time specifies the start time offset of the Association CAP from the start of the superframe.

Regular CAP Start Time specifies the start time offset of the Regular CAP from the start of the superframe.

S-CAP duration specifies the duration of the S-CAP.

First PNC RX Q-omni index in the current superframe specifies the First PNC RX Q-omni index # k in the current superframe.

Total number of Association S-CAPs is specified as the same total number of PNC Q-omni receive directions.

Total number of Regular S-CAPs is specified as the same total number of PNC Q-omni receive directions.

Number of association S-CAPs in current Superframe specifies the number of association S-CAPs in current Superframe.

Number of regular S-CAPs in current Superframe specifies the number of regular S-CAPs in current Superframe.

Total number of Association S-CAPs is specified as the same total number of PNC Q-omni receive directions.

Total number of Regular S-CAPs is specified as the same total number of PNC Q-omni receive directions.