Fast and Low-Power Link Setup for IEEE 802.15.3c Multi-Gigabit/s Wireless Sensor Networks

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***Abstract*—In this paper, we propose a polynomial-time framework for fast and low-power link setup between two 60 GHz IEEE 802.15.3c wireless sensor devices. Due to the narrow beamwidth of 60 GHz radio beams, the beam training procedure needs to evaluate a lot of search spaces. Thus, the running time to establish an IEEE 802.15.3c radio link is relatively longer than the running time of other schemes. In addition, evaluating a large search space requires a lot of training packets transmission, which increases the communication power consumption. Therefore, our proposed framework reduces the number of training packet transmission (i.e., the number of search space evaluation) using multi-resolution beam training for fast and low-power link setup.**

***Index Terms*—IEEE 802.15.3c, fast link setup, low-power, wireless multimedia sensor networks.**

I. Introduction

AMONG the IEEE 802.15 wireless personal area networks (WPAN) standards, IEEE 802.15.3c is designed over 60 GHz wireless channels [1]. In 60 GHz wireless channels, about 7 Gigabit/s data rates are available due to their extremely high bandwidth [2]. Due to these high rates, uncompressed 1080p high-definition (HD) video streaming is made possible over such channels because approximately 3 gigabit/s data rate is needed to transmit 1080p HD video streams without any compression [2]. Another application that needs high data rates is wireless multimedia sensor network (WMSN) where research activities are increasing in importance, as discussed in [3]. The WMSN is one of the promising applications of wireless sensor networks (WSNs) because of its high-resolution monitoring functionalities [3]. Because IEEE 802.15 family of protocols is suitable for WSNs, the aforementioned IEEE 802.15.3c protocol is considered as an underlying building block for WMSNs with 60 GHz wireless channels.

In IEEE 802.15.3c, the weakness of 60 GHz wireless signals is one of the major operational challenges (cf. §II-A); thus *beamforming and training* are widely used to deal with this problem; which establishes the 60 GHz links by taking a lot of time because of the narrow beamwidth of 60 GHz wireless beams (1° in the worst case [2]). If the beamwidth is 1°, the beam training initiator and responder have to evaluate $\lceil 360^\circ/1^\circ \rceil$ spaces for each. Moreover, each beam training node has to send a training signal for each search space, i.e., the beam training requires high power expenditure. Thus, we have to design a *fast* and *low-power* beam training mechanism for 60 GHz WMSNs.

In IEEE 802.15.3c, the brief introduction of beamforming and training is done as follows [4]: There are two nodes named a beamforming initiator node (BIN) and a beamforming responder node (BRN). To find optimal beam directions for both BIN and BRN, each BIN and BRN initially finds coarse-grained optimal beam directions (a.k.a., low-resolution (L-Re) beam directions). Then, within the obtained coarse-grained directions, they again find the fine-grained optimal directions (a.k.a., high-resolution (H-Re) beam directions). This kind of hierarchical beam training is called *multi-resolution beam training*. With the given IEEE 802.15.3c beamforming and training, the proposed scheme determines the optimal number of L-Re coarse-grained directions. If the number of L-Re directions is large, evaluating each L-Re direction will take an excessive amount of time. Otherwise, if the number of L-Re directions is too small, the beamwidth of L-Re beam is relatively wide, i.e., the time for evaluating each H-Re beam direction within obtained one L-Re beam will take also lots of time. Thus, there exists the tradeoff between (i) the number of L-Re beam directions and (ii) the number of H-Re beam directions within one optimal L-Re direction. Our proposed scheme finds the optimal number of L-Re directions for minimizing the entire number of search spaces.

II. Preliminaries

A. 60 GHz Wireless Signals

For 60 GHz wireless signals, $p_{\text{rx}} = \frac{G_{\text{tx}} G_{\text{rx}} c^2}{(4\pi d)^2 f_c^2} p_{\text{tx}}$ holds according to the Friis path-loss model where p_{tx}, p_{rx}, G_{tx}, G_{rx}, c, d, f_c stand for the transmit power at a transmitter, receive power at a receiver, transmit antenna gain, receive antenna gain, the speed of light, distance, and carrier frequency, respectively. The signal strength of 60 GHz wireless signals is much weaker than the strength of conventional 2.4 GHz which is used in the IEEE 802.15 WPAN. To deal with the weakness of 60 GHz wireless signals, directional transmission or beamforming are generally used to focus the transmit power to one specific direction. Therefore, for example, the current 60 GHz commercial high-gain (more than 40 dBm) scalable horn or Cassegrain type antennas have extremely narrow beamwidths from 1° up to 10° [2]. Due to the fact that the beamwidth of 60 GHz wireless signals is extremely narrow, the beam training procedure takes more running time compared with other traditional techniques.

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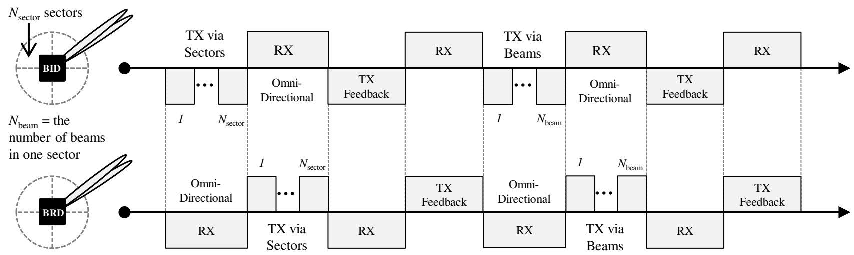


Fig. 1. Two-Stage Multi-Resolution Beam Training in IEEE 802.15.3c WPAN, $\mathcal{N}_{\text{sector}} = \mathcal{N}_{\text{L-Re}}$ and $\mathcal{N}_{\text{beam}} = \mathcal{N}_{\text{H-Re}}$.

TABLE I
COMPARISON ON THE NUMBER OF TRAINING AND FEEDBACK PACKET TRANSMISSION

H-Re Beamwidth ($\theta_{\text{H-Re}}$)	1°	2°	3°	4°	5°	6°	7°	8°	9°	10°
Brute-Force Beam Training	722	362	242	182	146	122	106	92	82	74
Multi-Resolution Beam Training with $\theta_{\text{L-Re}} = \lceil \frac{360}{2} \rceil^\circ$	368	188	128	98	80	68	60	54	48	44
Multi-Resolution Beam Training with $\theta_{\text{L-Re}} = \lceil \frac{360}{4} \rceil^\circ$	192	102	72	58	48	42	38	36	32	30
Multi-Resolution Beam Training with $\theta_{\text{L-Re}} = \lceil \frac{360}{8} \rceil^\circ$	110	66	50	44	38	36	34	32	30	30
Multi-Resolution Beam Training with $\theta_{\text{L-Re}} = \lceil \frac{360}{16} \rceil^\circ$	82	60	52	48	46	44	44	42	42	42
Multi-Resolution Beam Training with $\theta_{\text{L-Re}} = \lceil \frac{360}{32} \rceil^\circ$	92	80	76	74	74	72	72	72	72	72

B. Related Work

1) Brute-Force Search: As explained in [5], the general beamforming and training procedure using brute-force search operates as follows. First of all, note that the omni-directional data transmission ranges of BIN and BRN are divided into $\mathcal{N}$ directions. To initiate the beam training procedure, BIN transmits training packets over all given directions by sweeping the beams sequentially. While BIN transmits the training packets for every single direction, BRN tries to receive the training packet with an omni-directional antenna pattern. Then, when BIN finally transmits the last training packet over to the last direction, BRN can recognize which direction of BIN has the highest signal-to-noise ratio (SNR) from BIN. After obtaining the optimal direction of BIN at BRN, BIN and BRN change their roles and do the same operation. Then, BIN can eventually recognize which beam direction of BRN has the highest SNR. Accordingly, both sides know the optimal beam directions of their opposite sides, and by exchanging the feedback training packet signals, both sides can eventually know their own optimal beam directions.

2) Multi-Resolution Beam Training: This section introduces multi-resolution beam training that is used for current beamforming and training techniques in the IEEE 802.15.3c WPAN. The IEEE 802.15.3c standard uses coarse-grained beam training first and then performs fine-grained beam training. The beam direction search mechanism starts from L-Re beams which cover larger space per beam. After that, H-Re beams covered by the selected L-Re beam in previous stage are searched as follows. The omni-directional beam spaces of BIN and BRN are divided into several areas which are covered by L-Re beams. For that, the following two steps are performed. First, BIN transmits training packets over all possible L-Re beams. While BIN is transmitting the packets, BRN tries to listen to the training packets. Then, BRN is able to identify which L-Re beam of BIN has the highest SNR. After this procedure, BIN and BRN change their roles, BRN transmits training packets over all possible L-Re beams. While BRN transmits the packets, BIN tries to listen to the packets from BRN. Then, BIN is able to identify which L-Re beam of BRN has the highest SNR; thus both BIN and BRN exchange feedback packets to let their opposite sides know their optimal L-Re beams. Second, BIN transmits training packets over all possible H-Re beam directions within the obtained optimal L-Re beam direction. The opposite side (BRN) is then made able to identify which H-Re beam direction of BIN is the optimal in terms of the highest SNR. Then BIN and BRN change their roles: BRN transmits training packets over all possible H-Re beam directions within the obtained optimal L-Re beam direction. After that, the opposite side, i.e., BIN, can identify which H-Re beam direction of BRN is the optimal, thus both BIN and BRN exchange feedback packets to make both nodes know their optimal H-Re beam directions. The flowing diagram for this procedure is illustrated in Fig. 1.

3) Comparison: This section compares the number of training and feedback packets transmission between the brute-force beam training and multi-resolution beam training. In brute-force beam training, the number of packet transmission is:

$$n_{\text{brute-force}} = (\mathcal{N}+1) + (\mathcal{N}+1) = 2(\mathcal{N}+1). \qquad (1)$$

As presented in (1), BIN beam training operation transmits $(\mathcal{N}+1)$ training and feedback packets where $\mathcal{N}$ is for the beam training packet transmission and 1 is for feedback packet transmission. In multi-resolution beam training, the number of packet transmission is described as follows:

$$\begin{aligned} n_{\text{multi-resolution}} &= 2\{(\mathcal{N}_{\text{L-Re}}+1) + (\mathcal{N}_{\text{H-Re}}+1)\} \\ &= 2(\mathcal{N}_{\text{L-Re}} + \mathcal{N}_{\text{H-Re}} + 2), \end{aligned} \qquad (2)$$

where $\mathcal{N}_{\text{L-Re}}$ and $\mathcal{N}_{\text{H-Re}}$ stand for the number of L-Re beams in an omni-direction and the number of H-Re beams within an L-Re beam, respectively. As presented in (2), $\mathcal{N}_{\text{L-Re}}$ training packets transmission is required for both BIN and BRN to find the optimal L-Re beam directions. After that, one additional feedback packet transmission is required for each BIN and BRN. Then, $\mathcal{N}_{\text{H-Re}}$ training packets should be transmitted for finding the optimal beam directions. Finally, one additional

Data:
1) Beamwidth $\theta_{\text{H-Re}}$ where $1 \leq \theta_{\text{H-Re}} \leq 10$

Result:
1) Optimal number of L-Re beams: $\mathcal{N}^*_{\text{L-Re}}$

Initialization;
1) $\mathcal{N}^*_{\text{L-Re}} \leftarrow \alpha$ where $\alpha > 360$
2) $n^*_{\text{multi-resolution}} \leftarrow \beta$ where $\beta = 10^{10}$

For the given beamwidth $\theta_{\text{H-Re}}$ where $1 \leq \theta_{\text{H-Re}} \leq 10$,

```
while N_L-Re ∈ {1, 2, ···, 360} do
    n_multi-resolution ← 2 (N_L-Re + ⌈⌈360/N_L-Re⌉ / θ_H-Re⌉ + 2)
    if n*_multi-resolution > n_multi-resolution then
        n*_multi-resolution ← n_multi-resolution;
        N*_L-Re ← N_L-Re;
    end
end
```

Algorithm 1: Dynamic Multi-Resolution Beam Training

feedback packet transmission is done again.

Table I presents the computation results for the number of the training and feedback packet transmissions (i.e., $n_{\text{brute-force}}$ and $n_{\text{multi-resolution}}$) where the beamwidth is from 1° up to 10°. As presented in Table I, multi-resolution beam training generally provides better performance than brute-force beam training, i.e., $n_{\text{multi-resolution}} < n_{\text{brute-force}}$. Moreover, fixing $\mathcal{N}_{\text{L-Re}}$ does not guarantee the optimal solution for fast and low-power IEEE 802.15.3c link setup. For example, among the multi-resolution beam training with various L-Re beamwidth ($\theta_{\text{L-Re}}$), the algorithm with $\theta_{\text{L-Re}} = \lceil \frac{360}{16} \rceil^\circ$ presents the best performance when the H-Re beamwidth is 1°, i.e., $\theta_{\text{H-Re}} = 1^\circ$ as shown in Table I. However, the algorithm with $\theta_{\text{L-Re}} = \lceil \frac{360}{8} \rceil^\circ$ represents the best performance when $\theta_{\text{H-Re}} = 9^\circ$.

III. Dynamic Multi-Resolution Beam Training

A. Concepts and Algorithm Description

In IEEE 802.15.3c beam training, it holds that the number of optimal H-Re beam search within the L-Re is small if both BIN and BRN have a lot of L-Re beams because the L-Re has the narrower sector angle. Otherwise, if both BIN and BRN have the small number of L-Re beams and the central angle is large, the number of the beam search space within the sector becomes large. Thus a tradeoff exists between *the number of L-Re beams* and *the number of beams within one L-Re*.

Our proposed framework aims at a dynamic $\mathcal{N}_{\text{L-Re}}$ selection based on $\theta_{\text{H-Re}}$ to minimize $n_{\text{multi-resolution}}$ for low-power and fast link configuration. As presented in (2), i.e., $n_{\text{multi-resolution}} = 2(\mathcal{N}_{\text{L-Re}} + \mathcal{N}_{\text{H-Re}} + 2)$, if we want to minimize $n_{\text{multi-resolution}}$, $2(\mathcal{N}_{\text{L-Re}} + \mathcal{N}_{\text{H-Re}} + 2)$ should be minimized where $\mathcal{N}_{\text{H-Re}}$ can be computed as follows:

$$\mathcal{N}_{\text{H-Re}} = \lceil \lceil 360/\mathcal{N}_{\text{L-Re}} \rceil / \theta_{\text{H-Re}} \rceil \tag{3}$$

where $1^\circ \leq \theta_{\text{H-Re}} \leq 10^\circ$. Finally, (2) can be represented as:

$$n_{\text{multi-resolution}} = 2(\mathcal{N}_{\text{L-Re}} + \lceil \lceil 360/\mathcal{N}_{\text{L-Re}} \rceil / \theta_{\text{H-Re}} \rceil + 2). \tag{4}$$

Thus, for a given $\mathcal{N}_{\text{L-Re}}$ which is the integer value between 1° and 10°, the minimum $n_{\text{multi-resolution}}$ can be obtained.

Based on the described algorithm concept, the procedure to compute $\mathcal{N}_{\text{L-Re}}$ with the given parameter $\theta_{\text{H-Re}}$ is as described in Algorithm 1. Thus, $\theta_{\text{H-Re}}$ in (4) is given as a real number between 1° and 10°. Then our objective is to find $\mathcal{N}_{\text{L-Re}}$ which can minimize $n_{\text{multi-resolution}}$ where $1 \leq \mathcal{N}_{\text{L-Re}} \leq 360$ where $\mathcal{N}_{\text{L-Re}} \in \mathbb{Z}^+$ and $\mathbb{Z}^+$ stands for the set of all positive integers.

After obtaining the optimal $\mathcal{N}_{\text{L-Re}}$ for each BIN and BRN, BIN transmits training signals for $\mathcal{N}_{\text{L-Re}}$ L-Re beams and then BRN transmits training signals for $\mathcal{N}_{\text{L-Re}}$ L-Re beams. Then, they exchange feedback signals. After that, BIN transmits training signals for $\mathcal{N}_{\text{H-Re}}$ beams within the optimal L-Re, which can be computed as $\left\lceil \frac{\lceil 360/\mathcal{N}_{\text{L-Re}} \rceil}{\theta_{\text{H-Re}}} \right\rceil$. Then, BRN transmits training signals for $\mathcal{N}_{\text{H-Re}}$ beams within its optimal L-Re. Finally, feedback signals are exchanged to determine optimal beam directions for each BIN and BRN. Note that the proposed operation cannot be formulated as closed-form equation due to the fact that it has duplicated $\lceil \cdot \rceil$ or $\lfloor \cdot \rfloor$ operations.

B. Computational Overheads

The computational complexity for obtaining optimal $\mathcal{N}_{\text{L-Re}}$ is $O(\mathcal{N})$ because it is a sequential search from $\mathcal{N} = 1$ up to $\mathcal{N} = 360$ with the given $\theta_{\text{H-Re}}$. Thus the computational complexity of the poposed dynamic multi-level beam training is $O(\mathcal{N}_{\text{L-Re}} + \mathcal{N}_{\text{H-Re}} + 2) = O(N)$ (polynomial-time). Since our algorithm takes $O(N)$, the potential overhead due to iterative computation is small, and should be negligible.

IV. Performance Evaluation

To simulate the operation and running time of the beam training algorithms, the required time for one training signal transmission should be known and let this value be defined as t_c. Then, assume that the single transmission of a feedback signal takes t_c time as well. This assumption is reasonable due to the fact that (i) the MCS0 data rate is used for training signal transmission in IEEE 802.15.3c and (ii) all control signals have the same packet structure. Thus the time intervals to transmit training signals and feedback signals are the same. In wireless systems, if the communication modes change from Tx to Rx (or vice versa), a SIFS duration is considered (denoted by t_{SIFS}). Now, the running time for brute-force search is:

$$t_{\text{brute-force}} = 2(\mathcal{N} + 1) \cdot t_c + 4 \cdot t_{\text{SIFS}} \tag{5}$$

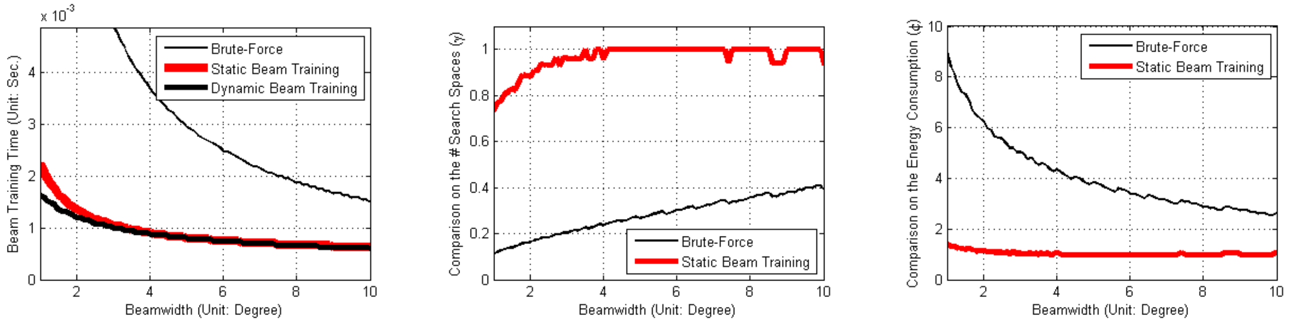
because of the fact that $2(\mathcal{N} + 1)$ training signals are transmitted with time t_c and there are four tx and rx mode changes. Here, due to the fact that $\mathcal{N} = \left\lceil \frac{360}{\theta_{\text{H-Re}}} \right\rceil$, (5) can be updated to:

$$t_{\text{brute-force}} = 2(\lceil 360/\theta_{\text{H-Re}} \rceil + 1) \cdot t_c + 4 \cdot t_{\text{SIFS}} \tag{6}$$

and the time for multi-level beam training becomes:

$$t_{\text{multi-resolution}} = 2\left(\mathcal{N}_{\text{L-Re}} + \left\lceil \frac{\lceil 360/\mathcal{N}_{\text{L-Re}} \rceil}{\theta_{\text{H-Re}}} \right\rceil + 2\right) \cdot t_c + 8 \cdot t_{\text{SIFS}} \tag{7}$$

because $2\left(\mathcal{N}_{\text{L-Re}} + \left\lceil \frac{\lceil 360/\mathcal{N}_{\text{L-Re}} \rceil}{\theta_{\text{H-Re}}} \right\rceil + 2\right)$ training signals are transmitted with time t_c and there are eight Tx and Rx mode changes. To compute t_c, assume that our control training/feedback packet size is 552 bits based on the generic IEEE 802.15 standards [1]. According to the specification, the data rate for transmitting this single training packet is 27.5 Mbps which is modulation and coding scheme level 0



(a) Beam Training Time (b) Comparison on the # Search Spaces (c) Comparison on the Power Consumption

Fig. 2. Performance evaluation.

(MCS0). Therefore, t_c can be computed as $\frac{552}{27.5\times10^6} =\approx 20.1$ μs and t_{SIFS} is set to 3μs in IEEE 802.15.3c. Based on these parameters and formulations, our simulation is performed using matlab on top of the given IEEE 802.15.3c channel models in [6]. Especially, we used the CM1.3 model and the simulation results are plotted in Fig. 2. As shown in Fig. 2(a), our proposed framework can establish beam links much faster than the brute-force, which is anticipated. In addition, it shows better or equal performance compared to static beam training (as proposed in IEEE 802.15.3c where the number of sectors is set to 8) especially when the beamwidth is narrower. In Fig. 2(b), the y-axis stands for the comparison on the number of search spaces (denoted as γ). If $\gamma = 0.1$, it means the number of search space in our proposed framework is 10 times smaller than the comparing protocols. As can be seen in Fig. 2(b), when the beamwidth is extremely narrow ($1°$), the performance of the proposed framework is almost 9 times better than brute-force. Even though the beamwidth is wide, e.g. $10°$, the performance of the proposed scheme is around 2.5 times better than the brute-force. In addition, it is always better than static beam training (IEEE 802.15.3c spec) when the beamwidth is narrower than $4°$. As discussed in [7], the communication energy consumption, i.e., E_c, of WSNs is much more significant than in-network processing energy consumption, i.e., E_p, thus reducing the number of training signal transmission is also beneficial in terms of energy-efficiency. The E_c is modeled as $E_c = E_c^{\text{Tx}} + E_c^{\text{Rx}}$ where E_c^{Tx} and E_c^{Rx} are the energy consumption of transmitter (Tx) and receiver (Rx), respectively and

$$E_c^{\text{Tx}} = \left(e_{\text{Tx}} + e_{\text{amp}} \cdot d^2\right) \cdot r \text{ and } E_c^{\text{Rx}} = e_{\text{Rx}} \cdot r \qquad (8)$$

where e_{Tx}, e_{Rx}, e_{amp}, d, and r are the energy/bit consumption at Tx (50nJ/bit), the energy/bit consumption at Rx (50nJ/bit), energy consumed in op-amp (100pJ/bit/m^2), distance between Tx and Rx, and number of bits ($r = 552$). With this energy model, our energy consumption simulation is performed and plotted as Fig. 2(c). In Fig. 2(c), the y-axis stands for the comparison on the energy consumption (denoted as ϕ). If $\phi = k$, it means the energy consumption of our proposed framework is k times smaller than the others. When the beamwidth is extremely narrow ($1°$), the performance of the proposed framework is almost 9 times better than brute-force and 1.5 times better than IEEE 802.15.3c beam training. Even though the beamwidth is wide, e.g. $10°$, the performance of the proposed scheme is around 2.5 times better than the brute-force and equal to the IEEE 802.15.3c scheme. In addition, it is always better than static beam training (IEEE 802.15.3c spec) when the beamwidth is narrower than $4°$.

V. Conclusions

This paper proposes a fast and low-power 60 GHz IEEE 802.15.3c link setup mechanism by determining the optimal number of L-Re beams in WSNs. Our $O(N)$ polynomial-time framework dynamically determines the optimal number of L-Re beams in multi-resolution beam training. The performance evaluation shows that the proposed scheme achieves always better performance than brute-force search. In addition, the proposed scheme achieves better performance than IEEE 802.15.3c beam training especially when the beamwidth is narrower than $4°$.

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