Multi-hop network neighbor discovery and beamforming using directional antennas in 802.11ad WLANs.

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Abstract

Directional antennas are preferred for efficient wireless communications in the 60-GHz spectrum. Recent efforts to adapt high-data-rate medium access control (MAC) protocols from standards that are designed for operation in the lower frequency bands face challenges in acquiring the location of nearby devices in a network. Furthermore the currently used directional MAC protocols utilize the use of omnidirectional antenna which results in the decrease in the range of the neighbor discovery. We propose a protocol that utilizes omnidirectional antenna to avoid shadowing but completes the neighbor discovery using directional communication resulting in far better range then the currently available protocols.

1 Introduction

The increasing demand for high-speed wireless networks in recent years and exhaustion of spectrum resources has led the use of higher frequency region of radio spectrum. The 60 GHz spectrum is recently being explored for high-speed short range communication. However, 60 GHz communication faces some challenges that are not present in the lower frequency spectrum. One of the major challenges is the shadowing effect. Due to atmospheric attenuation and oxygen absorption at 60 GHz the signal path loss is high. In order to compensate for the high path loss, directional antennas or beamforming techniques are utilized in 60 GHz communication [1][2][3]. Luckily, due to the large free-space path-loss, a directional feature allows for spatial-reuse in the 60GHz system [4], i.e. numerous links working on the same band are able to coexist.

In the traditional MAC design, neighbor discovery is a straight forward process. In the traditional MAC they use omnidirectional antennas whereas in 60 GHz communication, use of directional antennas, mean that the location of a node is also needed for effective communication. Therefore, neighbor-discovery algorithms also need to be adequately changed to acquire the directional information of every neighboring STA.

The early work on neighbor discovery can be viewed as part of the MAC protocols and be categorized in the following two broad categories: (1) random access based approach; and (2) synchronized search based schemes. IEEE 802.11 MAC protocol is very popular, several approaches have been proposed for directional wireless links by modifying IEEE 802.11 MAC protocol. These approaches however, utilize directional transmission and omnidirectional reception of RTS control packets. Thus, the maximum range within which a node can discover a neighbor is much less than the range with an approach where both transmitter and receiver use the maximum gain. 802.15.3c is another IEEE MAC protocol that utilizes a similar neighbor discovery algorithm.

Previous work

In standards like 802.11ad and 802.15.3c, [5][6] both Omni-directional and directional antenna is utilized. The transmission is usually carried out using directional antennas whereas the reception is omnidirectional. Hence, this decreases the range upto which a node could be discovered. (it is usually in the order of hundreds to thousands of meters).

In [7], TDMA MAC protocol with configurable control slots is used for neighbor discovery. This is efficient for closer neighbors and has small channel overhead. But if the distance is higher the STAs further away would take more network entry time.

Two issues that have not been addressed by other neighbor discovery protocols are, First to fully exploit the spatial diversity gains possible due to the use of directional antennas, it is essential to shift to the exclusive usage of directional antennas for the transmission and reception of all the MAC layer frames. This would facilitate maximal spatial reuse and will efface the phenomena of asymmetry in gain. Second, in the presence of mobility the MAC protocol should incorporate mechanisms by which a node can efficiently discover and track its neighbors. [8] Proposes a MAC protocol to deal with both the complete usage of directional antenna and mobility issues but the convergence time of this protocol might be too much for effective communication.

[9] Proposed a method to use both directional and Omni-directional antennas at the same time. Nodes exchange neighbor information with omnidirectional antennae, and neighbor information beyond the reach of omnidirectional antennae are collected using directional antennae.

One key performance measure is how long it takes to discover all the neighbors given that nodes do not have priori knowledge where their neighbors are. [10] Considers this issue in neighbor discovery in ad-hoc networks and proves that directional antennas do not take longer time then Omni-directional antennas. There are a total of three neighbor discovery mechanisms proposed in this paper.

In [11] you can see that the lower the beamwidth of a directional antenna the more overhead is associated with the communication. You can further see that using directional antenna to send and Omni-directional antenna rather than directional antenna on both ends of the transmission greatly reduces the overhead.

In [12] both Direct neighbor discovery and Gossip based neighbor discovery is utilized in a slotted, synchronous system. Analysis and simulation of the algorithms show that nodes discover their neighbors much faster using gossip-based algorithms than using direct-discovery algorithms. Furthermore, the performance of gossip-based algorithms is insensitive to an increase in node density.

[13] Proposed a completely directional neighbor discovery mechanism called SAND. Unlike many proposed directional neighbor discovery protocols, SAND de-

pends neither on omnidirectional antennas nor on time synchronization and furthermore stores the neighbor discovery information in a central location for future usage.

Paper contributions

In this paper, we propose a new synchronized neighbor discovery protocol that overcomes the limitations of existing protocols.

1. **Full exploitation of directional transmissions:** Our neighbor discovery algorithm would be using directional transmission and directional reception which has three advantages over omnidirectional reception and/or transmission. (a) it helps frequency reuse. (b) The range for neighbor discovery increases since the omnidirectional range is much less. (c) It solves the issue of asymmetry in gain which occurs due to difference in gains. Asymmetry can decrease the network throughput.
2. **Locating and tracking neighbors under mobility:** Under mobility our MAC protocol offers a mechanism for a node to locate and track its neighbor.
3. **Help with Beamforming:** Our protocol carries out the first phase of the Beamforming. The sector sweep phase of the Beamforming is already carried out by this protocol only the Beam refinement phase (optional) would need to be carried out for data transmission.
4. **Compatibility with 802.11:** Our protocol is already compatible with the 802.11 MAC. The protocol proposed in this paper is an extension of the 802.11ad MAC protocol and hence solves the compatibility issues with the current standards while in the meantime increasing the range by a huge amount.

System Model

A. **Network Topology.**

Wireless in-door mmWave networks (e.g. WPANs/WLANs) have centralized network structure. In 802.11ad draft the personal basic service set (PBSS) consists of one PBSS control point (PCP) or access point (AP) and N ($1 < N < 254$) non-PCP/non-AP DMG STAs (Nodes). In PBSS, the PCP controls the Beacons and schedules the channel access such that every STA knows from where and when to expect the packets so STAs can direct their antennas to the appropriate direction at the right time.

B. **Directional Antenna Model.**

There are two models for directional antennas: The flat-top model that neglects the sidelobe effect [14] and the 3D cone plus sphere model that considers the sidelobe effect [15]. Since realistic antenna models are complex and can be modeled with two-dimensions, in our paper we would be using two dimensional cone plus circle model assuming all STAs are in the same plane. The antenna gain of the mainlobe and the sidelobe are different with the gain of the mainlobe being considerably higher than the gain of the sidelobe.

C. **802.11ad MAC**

As specified in 802.11ad [5], the time is divided into Beacon Interval by the PCP/AP. Subdivisions within the beacon interval are called access periods. Different access periods within a beacon interval have different access rules. The access periods are described in a schedule that is communicated by the PCP or AP to the non-PCP and non-AP STAs within the PBSS.

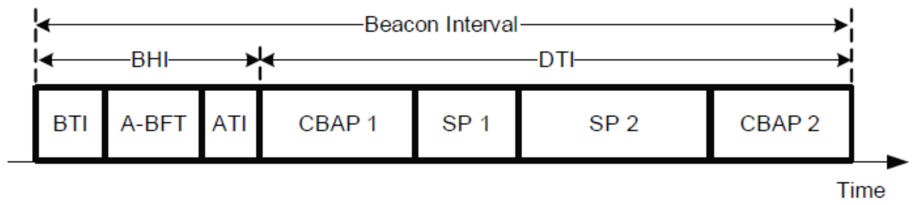

Figure 1

As shown in Fig.1, The subdivisions within the Beacon Interval (BI) are called access periods. The schedule communicated by the PCP or AP can include the following access periods:

- **BTI:** An access period during which one or more DMG Beacon frames is transmitted. Not all DMG Beacon frames are detectable by all non-PCP and non-AP STAs. Not all beacon intervals contain a BTI. A non-PCP STA that is a non-AP STA shall not transmit during the BTI of the PBSS of which it is a member.
- **A-BFT**: An access period during which beamforming training is performed with the STA that transmitted a DMG Beacon frame during the preceding BTI. The presence of the A-BFT is optional and signaled in DMG Beacon frames.
- **ATI:** A request-response based management access period between PCP/AP and non-PCP/non-AP STAs. The presence of the ATI is optional and signaled in DMG Beacon frames.
- **DTI:** An access period during which frame exchanges are performed between STAs. There is a single DTI per beacon interval. The DTI, in turn, comprises contentionbased access periods (CBAPs) and scheduled service periods (SPs).

D. **802.11ad Beamforming**

Beamforming (BF) is used by a pair of STAs to achieve necessary link budget for subsequent communication. BF training is a bidirectional process in which the BF training frames are transmitted to provide the necessary signaling to allow each STA to determine the appropriate antenna system settings for both the transmission and reception.

To compensate for the high propagation loss at 60 GHz, a high antenna gain is necessary. As the antenna gain increases, the antenna beamwidth becomes narrower. Beamforming must be performed to achieve necessary antenna gain and to find the best path and possibly to avoid obstacles in 60 GHz.

As specified in 802.11ad [15] and as shown in Fig. 2, Beamforming training of STAs may be composed of a Sector Level Sweep (SLS) and a beam refinement protocol (BRP) phase. In the SLS phase the initiator of the beamforming sends a training frame from each of its sectors and the responding STA can receive in a quasi-omni mode to find the best transmitting sector for the initiator STA. Similarly, the responder sends out training frame from each of its sectors and the initiating STA can receive in a quasi-omni mode to find the best transmitting sector for the responder STA. Sector sweep feedback information is then exchanged between the

Two devices to inform each of them their best sector IDs. In the BRP phase, the STA trains its antenna arrays and improves its antenna array configuration to fine-tune their beams to achieve the best data rate.

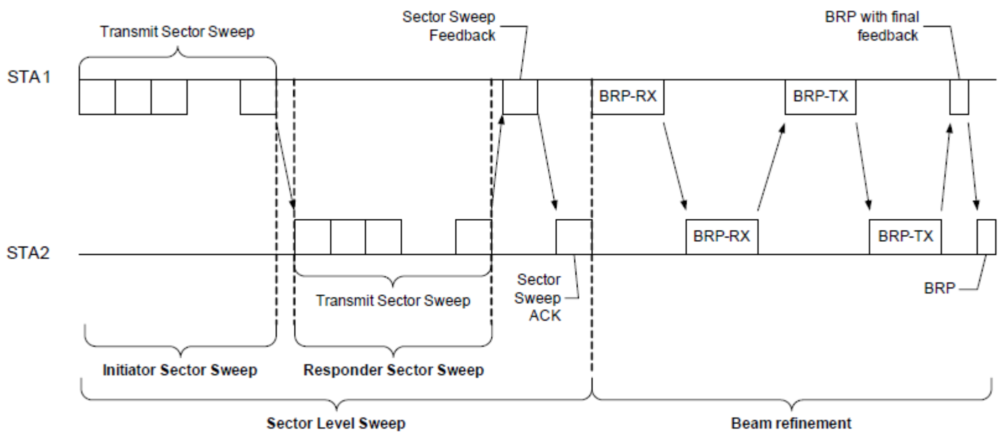

Figure 2

Network Neighbor Discovery Protocol

802.11ad draft [15] explains how the beamforming training is partitioned into different access periods of BI. Using the already proposed standard and making few alterations, we have proposed a Neighbor Discovery Protocol which drastically increases the distance upto which the AP can communicate with minimal effect on the quality of the network.

A. Discovery

During the BTI, the PCP/AP is the initiator and starts the beamforming with the initiator sector sweep. All the non PCP/AP STAs listen in the omni direction during the BTI while the PCP/AP does an initiator sector sweep. A-BFT phase is slotted as shown in Fig. 3. All the STAs that received the initiator SLS randomly chooses a time slot in the ABFT. During that time slot the STA performs responder sector sweep and receives a feedback from the PCP/AP confirming the successful SLS phase of beamforming and also informing the responder of its best sector. The BRP phase of the beamforming may be performed during the scheduled DTI access period.

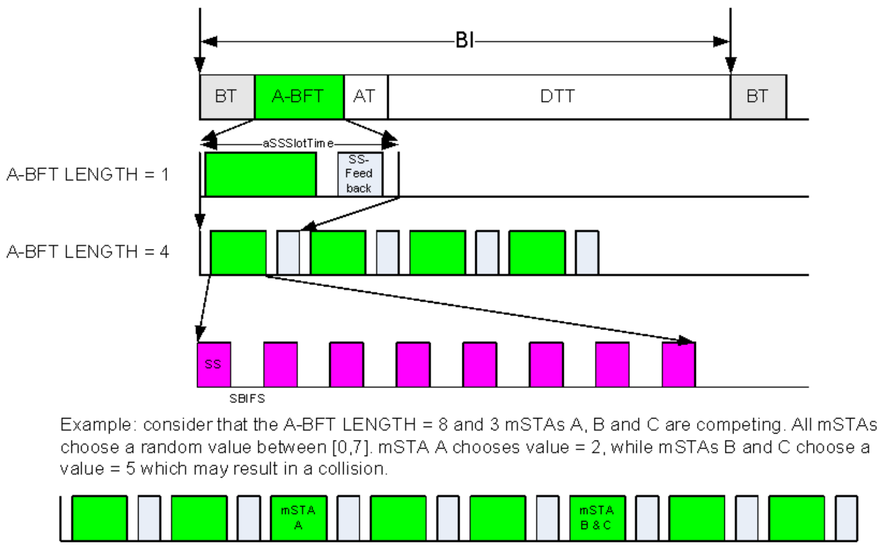

Figure 3

B. Employing Multi-Hop

As explained before, in the currently employed protocols the transmission is directional whereas the reception of the nodes is omnidirectional (DO neighbor discovery). Our protocol utilizes directional transmission and directional reception (DD neighbor discovery). Fig. 4 (a) shows a network randomly populated with STAs. The STAs within the inner green circles are the ones that are DO Neighbors and can be accessed by the AP even when the STA is receiving in the omnidirectional. The DD Neighbors that are outside the inner green circle but inside the outer circle can be accessed using a Multi-Hop discovery technique that utilizes DO Neighbors to forward the location of the AP, consequently leading to the DD STAs to listen in directional mode.

Simulation Results

Fig. 4 shows the simulation carried out to evaluate this protocol. Fig. 4 (b) shows the AP doing the sector sweep during BTI when all the nodes are listening in omnidirectional mode. Fig. 4 (c) shows each of the DO neighbors performing their own sector sweep during the A-BFT time period. Each of the DO neighbors sector sweep packet also contains the location of the AP. Since the DD neighbors did not receive any packets from the AP, the sector sweep packets from the DO neighbors are the only way for the DD neighbors to know the location of the AP.

Furthermore, The location received by the DD neighbors is not exact. This is because the location received is from a Multi-hop and approximations are used to calculate the angle and the distance between two nodes. Even though the location is not precise the DD neighbors gets a good idea of the location of the AP and they can easily direct their Antennas in the direction of the AP.

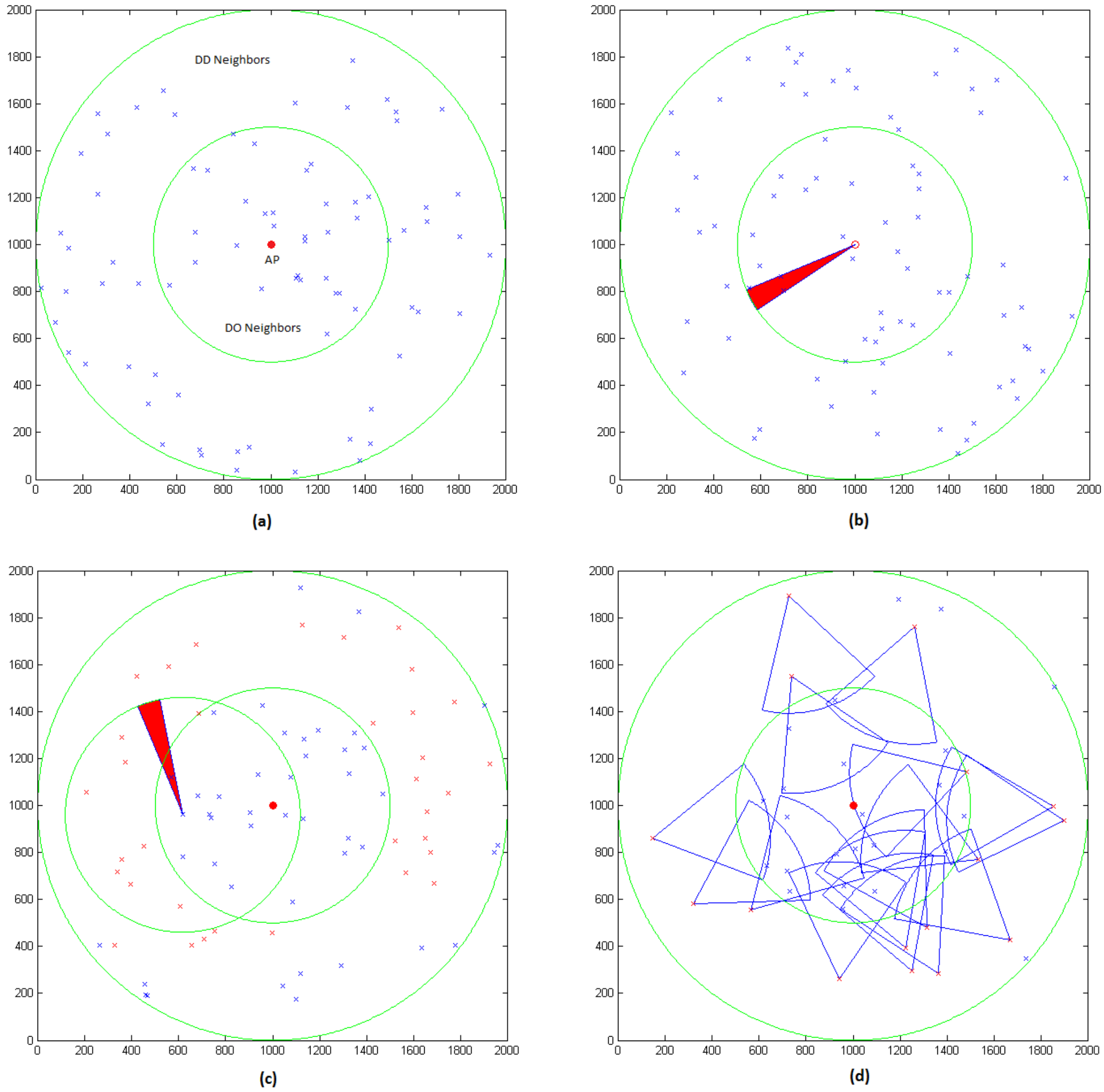

Figure 4

Fig. 4 (d) shows the DD neighbors pointing towards the AP. This happens after they have received the location of the AP. The DD neighbors, to make the network discovery easier would be using slightly larger beamwidth angle (between 30 to 60 degrees). This would have a small effect on the gain of the channel but would still easily comply with the quality of a Very High Throughput (VHT) networks. At the end, The AP performs another sector level sweep that can be received by all DO neighbors and all DD neighbors that have their antennas directed towards the AP.

What has to be noted is that not all DD neighbors can be detected using our technique. As shown in Fig. 4 (d) some of the DD neighbors did not receive the sector sweep packet from any of the DO Neighbors and hence were not able to direct their antenna towards the AP. The percentage of DD neighbors detected depends on a number of parameters. One of the major one is the number of DO neighbors available for multi-hoping. After extensive simulation, this phenomenon is shown in Fig. 5.

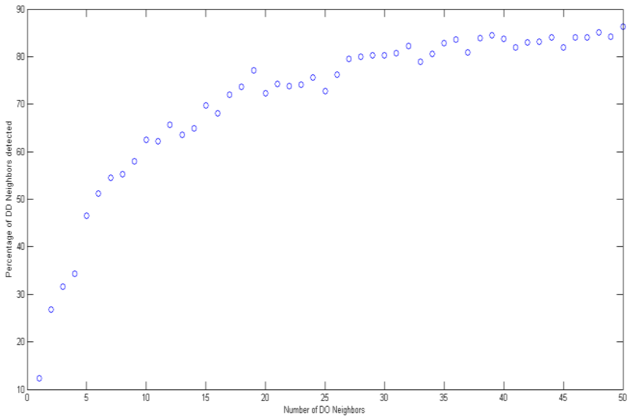

Figure 5: Showing the relationship between the percentage of DD Neighbors detected and Number of DO Neighbors

It can very well be concluded from Fig. 5 that communicating with all the DD neighbors would not be practically possible. Even 15 DO Neighbors are enough to detect upto 70 percent of the DD Neighbors that were previously ignored or not communicated with before.

Conclusion

Our protocol delivers on all the contributions we proposed earlier and most importantly it effectively increases the range at which the network discovery can be carried out. Our protocol is also compatible with the currently used 802.11ad. In fact, it is an extension of that MAC protocol and hence can easily be implemented. The simulation results show that the range increases quite nicely without any noticeable effect on the quality of the network.

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