A Cross-Layer Neighbor-Discovery Algorithm for Directional 60-GHz Networks

Ferhat Yildirim, *Student Member, IEEE*, and Huaping Liu, *Senior Member, IEEE*

***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. In this paper, we propose a cross-layer neighbor-discovery algorithm for directional 60-GHz networks to assist the MAC layer in efficiently using the directional antennas. We utilize linear and circular polarization and their different responses to reflection to synchronize the transmitter and the receiver. This difference in response is used to determine if there is a direct path between the transmitter and the receiver. Based on this knowledge, the direction of the neighboring devices is determined through a cyclic scanning. The proposed algorithm is analyzed based on the usage models defined in the standard for 60-GHz networks.**

***Index Terms*—Directional antennas, neighbor discovery, polarization, 60-GHz communications.**

I. Introduction

THE INCREASING demand for high-speed wireless networks in recent years and exhaustion of spectrum resources have motivated the use of the higher frequency region of the radio spectrum. The 60-GHz band has recently been explored for high-speed short-range wireless network applications [1]–[4]. However, wireless communication using the 60-GHz band faces some challenges that are not present in lower frequency bands. Among these challenges, shadowing is a major one. In lower frequency bands, electromagnetic waves could effectively penetrate through most obstacles in nonline-of-sight (NLOS) environments, but this is unlikely for 60-GHz signals. To mitigate the impact of increased attenuation, shadowing, and multipaths, communication systems using the 60-GHz band favor narrow-beamwidth antennas in the physical (PHY) layer to not only align the signal energy in the appropriate direction for efficient transmission of power but also reduce the channel delay spread and, thus, intersymbol interference (ISI).

Under the IEEE 802.15.3 High Rate Task Group for Wireless Personal Area Networks (WPANs), an alternative Task Group (TG3c) has been working on a PHY-layer standard for 60-GHz networks that would enable wireless communications with more-than-2-Gb/s data rates [5]. Along with an alternative PHY standard, an alternative medium access control (MAC) layer standard for higher frequency networks is also being developed. The MAC defined in IEEE 802.15.3 is designed to be used with omnidirectional antennas in lower frequency wireless networks. Therefore, the IEEE 802.15.3 MAC design needs to be modified for use in 60-GHz networks with directional antennas. Several modifications have been proposed in the literature to adapt IEEE 802.15.3 MAC to the 60-GHz band [6], [7]. In all these attempts, the most challenging problem is still neighbor discovery.

In the traditional MAC design, neighbor discovery is a straightforward process due to the use of omnidirectional antennas. For communications with directional antennas using the 60-GHz frequency band, the direction of a node is also needed to effectively communicate with it. Such information is not needed in the traditional MAC with omnidirectional antennas. Therefore, neighbor-discovery algorithms also need to be modified to acquire the directional information of every neighbor node.

A piconet structure has been assumed for IEEE 802.15.3 WPANs. In such a network, any device can be designated as a piconet controller (PNC) that serves as a central hub to other slave devices [8]. Task Group 3c proposes a set of usage models (UMs) for applications of 60-GHz wireless networks that are foreseen to be used in practice [9]. These models are shown in Fig. 1. Two of the five UMs are designated as mandatory (UM1 and UM5), which consider only a single link between two devices, where directional information is obtained mostly by external means. Most of the existing research is based on these mandatory models [7], which do not require complex neighbor-discovery algorithms due to the limited number of nodes and links involved.

In this paper, we consider all UMs, where many devices could be present in the network and complex directional communication takes place. We propose a neighbor-discovery algorithm for 60-GHz networks with directional antennas. In the proposed algorithm, we utilize the different responses of electromagnetic waves to reflection at 60 GHz to detect if there is a direct path between the transmitter and the receiver. Such information is used both to select an efficient antenna polarization that reduces the multipath effects and to determine the direction of the receiver. Most existing work assumes that the direction information is known *a priori*. Some research has used the Global Positioning System on every node [10] or angle-of-arrival measurements [11]. However, the former is usually not available in indoor environments, and the latter

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The authors are with the School of Electrical Engineering and Computer Science, Oregon State University, Corvallis, OR 97331 USA (e-mail: yildiria@eecs.oregonstate.edu; hliu@eecs.oregonstate.edu).

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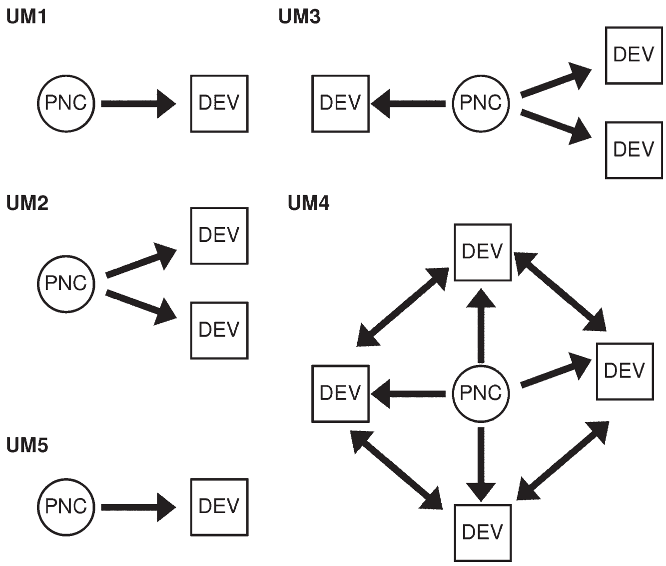

Fig. 1. UMs as defined in [9]. UM1 (uncompressed video streaming from set-top box to HDTV) and UM5 (data download from kiosk to handheld device) are designated as mandatory UMs. UM2 (multiple uncompressed video streaming), UM3 (office desktop environment), and UM4 (conference room ad hoc network structure) are designated as optional UMs.

could be either inefficient or too complex. We use a spatial scan-based algorithm, which compares the time delay of paths from the transmitter and the receiver. The proposed method is resistant to the fluctuations of the channel.

II. Neighbor Discovery for Directional Antennas

In our previous work on improving the performance of high-speed 60-GHz wireless networks [12], linear and circular polarizations are optimized for use in line-of-sight (LOS) or NLOS propagation conditions to reduce the multipath effects. Based on the results of this study, we concluded that, in LOS scenarios, circular polarization significantly improves the error performance by decreasing ISI; however, in NLOS scenarios, linear polarization performs much better than circular polarization. Therefore, in a 60-GHz network with directional antennas, it is important to have knowledge of the propagation condition (i.e., LOS or NLOS) before establishing a link, i.e., if the link between the transmitter and the receiver is LOS or NLOS.

Knowledge of the propagation condition is also important for the proposed neighbor-discovery algorithm with directional antennas. In this section, we briefly discuss the reflection characteristics of polarizations and explain the proposed algorithms to acquire the LOS/NLOS condition and direction information. We assume that all nodes can use both directional and omnidirectional antennas. Although the data transfer needs to be performed using high-gain directional antennas, applications such as neighbor discovery will still utilize omnidirectional antennas, for which a low data rate is sufficient.

A. Polarization Effects in 60-GHz Channels

Polarization of an electromagnetic wave is the 2-D trace of the electric field vector on the plane that is perpendicular to the direction of propagation. The polarization type is classified based on the shape the electric field traces on this perpendicular plane. If the magnitude ratio of the two orthogonal electric field components is constant and there is no phase difference between these components, the wave is linearly polarized. Two special cases for linear polarization are vertical and horizontal polarizations. On the other hand, when the two orthogonal components have the same magnitude but a 90° phase difference, the wave is circularly polarized. Depending on the leading orthogonal component in phase, i.e., the direction of rotation, circular polarization is classified into two subclasses: 1) right-hand circular polarization and 2) left-hand circular polarization [13].

The reflection characteristic of circularly polarized waves is quite different from that of linearly polarized waves [14]. For certain incident angles, the handiness of a circularly polarized wave switches upon reflection [15]. Theoretically, a circularly polarized antenna rejects a cross-polarized incoming wave; in practice, however, the received wave would experience finite attenuation (e.g., 20 dB [16]). Even with this finite attenuation, appropriate use of polarization could lead to significantly reduced channel delay spread and, hence, improved error performance for high-data-rate wireless communications.

In LOS environments, the direct path would most likely provide the strongest signal power at the receiver since it has undergone no reflections nor any losses other than the free-space path loss. The multipaths, on the other hand, are attenuated due to reflections and the longer distance they have traveled through to reach the receiver than the LOS component. The overall attenuation of multipath components could significantly be increased with the use of circular polarization. Depending on the incident angle of each reflection, the handiness of the circular polarization might switch, leading to greater attenuation at the receiver antenna. This increased attenuation leads to smaller delay spreads and, hence, better error performance. In NLOS environments, on the other hand, the communication link depends on the reflected paths between the transmitter and the receiver. In such scenarios, using linear polarization would provide better results than using circular polarization.

Discussion of efficient use of polarization and modification of the 60-GHz channel model to incorporate the effects of polarization can be found in [12]. In the next section, we use the reflection characteristics of different polarizations to acquire knowledge of the propagation conditions.

B. Detection of the Presence/Absence of a Direct Path

To determine the propagation conditions of the links, we exploit the different reactions of linearly and circularly polarized waves to reflections. Using a dual-polarized antenna [17], [18], a test frame is sent in all directions with linear and circular polarizations with transmit power

$$P_T = P_{T,l} = P_{T,c} \tag{1}$$

where $P_{T,l}$ and $P_{T,c}$ represent the transmit power for linearly and circularly polarized test frames, respectively. To avoid interference, these transmissions may occupy different time slots or different frequency bands. The receiver is also equipped with a dual-polarized antenna, which can detect both linearly and circularly polarized waves; however, the handiness of the circularly polarized antenna is inverted with respect to the transmitter antenna in the detection stage. Under this setup, the power of the first received path with linearly and circularly polarized receive antennas can be written as

$$P_{R,l} = P_{T,l} - L_p - L_{\mathrm{ref}} \tag{2a}$$
$$P_{R,c} = P_{T,c} - L_p - L_{\mathrm{ref}} - K_{\mathrm{cr}} \tag{2b}$$

where L_p is the propagation path loss, L_{ref} is the loss due to possible reflections, and K_{cr} is the cross-polarization rejection ratio of the antenna.

In LOS scenarios, it is expected that the first arrival path is the direct path; hence, $L_{\mathrm{ref}} = 0$. Even with a finite K_{cr}, e.g., a typical value of about 20 dB, $P_{R,c}$ is significantly attenuated due to cross handiness. The power difference between the two test frames is expressed as

$$\delta_R = P_{R,l} - P_{R,c}. \tag{3}$$

Since the propagation path loss is the same, regardless of the polarization of the wave, classification of the communication environment can be made easily: If $\delta_R \leq K_{\mathrm{cr}}$, the environment is LOS; otherwise, it is NLOS.

Although the reflection losses to the same path for linear and circular polarizations could slightly differ, this difference is negligible when compared with K_{cr}. This algorithm differentiates LOS and NLOS by detecting the presence or absence of a reflection for the first arrival path using the unique reflection characteristics of circular polarization. The result of this detection is reported back to the transmitter by sending either an acknowledgement (ACK)/LOS or an ACK/NLOS frame. The transmitter, upon receiving either of the ACK frames, switches the antenna polarization accordingly, i.e., circular polarization for LOS and linear polarization for NLOS.

C. Detection of Transmission Direction

Once the condition of the wireless channel is determined, the system needs to locate the most efficient direction of transmission to the receiver. This direction should be along the direct path for the LOS case and the strongest path for the NLOS case. In LOS scenarios, the direct path has a unique time delay, which will be used to identify this particular path. On the other hand, in NLOS scenarios, neither the time delay nor the received power (i.e., measurable quantities at the receiver) is unique. Therefore, a more complex approach is needed for NLOS propagation conditions. One should note that, based on the proposed UMs, LOS communication topology is dominant, although NLOS cases still exist.

To determine the direction of transmission, we propose a pseudosynchronization scheme between the transmitter and the receiver to distinguish between the different paths received by the receiver. In this scheme, the transmitter applies a time stamp to every packet it sends according to its local clock. The period of this local clock should be of appropriate length so that it does not interfere with several adjacent transmission cycles. Moreover, the resolution of the timer should be high enough to distinguish the shortest time delay, i.e., direct path in the LOS case. High-frequency timers exist with resolutions of as high as 13 ps [19], which is enough to detect the difference of time delay in 60-GHz channels where the minimum delay is typically on the order of nanoseconds. If the environment is LOS, the first received path is the most efficient path for communications. The receiver pseudosynchronizes its internal clock with the time stamp on the received test frame. If the environment is NLOS, the receiver takes the strongest received path as the most efficient path, which is not necessarily the first one received. The shortest reflected path might have a higher reflection loss than a slightly longer reflected path. Upon detecting the incoming test frame, the receiver also pseudosynchronizes its internal clock with the time stamp on the received frame based on the LOS/NLOS information. In either the LOS or the NLOS case, after pseudosynchronization, there will be an offset between the internal clocks of the receiver and the transmitter, and this offset corresponds to the propagation delay of the most efficient path. This pseudosynchronization information is sufficient to find the most efficient direction to the receiver.

TABLE I
TRANSMITTER–RECEIVER PSEUDOSYNCHRONIZATION

Time step	Transmitter local clock	Receiver local clock
t_0	tx_0	–
t_1	$tx_0 + t_{p1}$	tx_0
$\vdots$	$\vdots$	$\vdots$
t_n	$tx_0 + t_{p1} + t_d$	$tx_0 + t_d$
t_{n+1}		$tx_0 + t_{p2} + t_d$

We assume that the communication environment is divided into a predefined number of sectors, each with a certain angular spread (i.e., the sectored cell approach). The transmitter consecutively sends a probe frame with a time stamp from each sector in a circular fashion. After transmission in each sector, the transmitter stops and listens for a possible ACK frame from the intended receiver. In this fashion, all the sectors will be swept, and all possible directions are covered. The receiver will most likely receive more than one probe frame from different sectors. However, each time a probe frame is received, the time stamp on the frame is compared with the local clock. When the time stamp and the local clock match, the receiver replies with an ACK frame, indicating the correct direction of transmission. A matching probe time stamp and receiver internal clock indicates that the transmitter has sent the probe frame using the sector that contains the most efficient path that was detected in the testing/synchronization process.

The pseudosynchronization of the transmitter and the receiver is illustrated in Table I. At time t_0, the transmitter sends out an omnidirectional test frame with time stamp (according to its internal clock) tx_0. The receiver at t_1 receives this frame and resets its internal clock to tx_0; meanwhile, the internal clock of the transmitter has advanced by t_{p1}, which is the propagation delay of the specific path. After t_d seconds, the transmitter sends out another packet (a probe frame) this time; however, it uses a directional antenna and sweeps through all sectors in the horizontal plane. At time t_n, the instant this transmission occurs, the internal clocks of the transmitter and the receiver are $tx_0 + t_{p1} + t_d$ (time stamp on the frame) and $tx_0 + t_d$, respectively. The receiver at t_{n+1} receives this packet after t_{p2}, which is the propagation delay of the current path. If the transmitter has selected the correct direction to transmit, t_{p1} would be equal to t_{p2}, and the time stamp of the second frame will match the internal clock of the receiver. This will trigger the transmission of an ACK frame by the receiver, indicating that the correct direction of transmission has been found by the transmitter. The data transmission is carried afterward. In the case of unequal t_{p1} and t_{p2}, the receiver waits for the next probe frame.

This approach flawlessly works in LOS scenarios. However, in NLOS scenarios, since the time delay for each path is not unique, further processing is required. A multipath, which might have experienced several reflections from the transmitter to the receiver, can have the same time delay with another multipath, whose path is completely different from the first one. This is not the case for the direct path in a LOS scenario since there is only one path directly going from the transmitter to the receiver, and it has its own unique time delay. Therefore, in LOS scenarios, once the time stamp matches at the receiver, the transmitter can stop its cyclic scanning since there is no possibility of finding another direct path. In NLOS scenarios, however, even though there is a time stamp match in the receiver, cyclic scanning should be continued until the whole neighborhood is scanned. To identify each transmission, a sector identification (ID) number is also transmitted within the probe frame. The receiver records the received strength and the sector ID every time the time stamp matches its internal clock. The ID number of the sector that has the strongest reception with the correct time delay is transmitted back to the receiver to indicate the correct direction of transmission. Although very unlikely, it is still possible that two sectors have the same delay and received power characteristics in the NLOS scenario. In such cases, the receiver randomly selects a sector that has a time delay match and replies back to the transmitter. Since these sectors have the same received power and time delay, any one of them could be used for communication.

III. Application Scenarios and Performance Analysis

A. Usage Models

The algorithm outlined in the previous section is a cross-layer process, which communicates with both the PHY and MAC layers. It gathers and provides information to both layers. Since this algorithm is optimized for the 60-GHz PHY layer, we assess its performance based on the scenarios that are defined by the IEEE Task Group for 60-GHz wireless communications.

The UMs can be found in [9] and are shown in Fig. 1 for convenience. These models are summarized here.

1) UM1: Wireless streaming of uncompressed high-definition video from a source (set-top box, DVD player, game console, etc.) to a high-definition display device. The nodes are fixed, but the link can be LOS or NLOS, and random shadowing caused by human body is possible. The separation between nodes is in the range of 5–10 m in a typical residential environment. The typical required data rate is 3.56 Gb/s for a 1080-p (1920 $\times$ 1080 pixels, progressive) image with a color depth of 24 bits and a refresh rate of 60 Hz. This UM is designated to be mandatory.
2) UM2: Wireless streaming of uncompressed high-definition video from a source to multiple display devices, which are separated by 5 m. The nodes are fixed. One display has a LOS with the source and the other displays are NLOS, and random shadowing caused by human body is possible. Video streams to each display are assumed to have a rate of 0.62 Gb/s, a resolution of 480-p (640 $\times$ 480 pixels, progressive), a color depth of 24 bits, and a refresh rate of 60 Hz. This UM is designated as optional.
3) UM3: WPANs in a typical office setting. A high-definition display device, which is separated from the computer by 1 m, has similar link characteristics as UM1. The printer, which has an NLOS link to the computer, is separated by 5 m. The external storage is assumed to have a LOS link to the computer with a 0.25-Gb/s link in both directions. This UM is designated to be optional.
4) UM4: A wireless ad hoc network in a conference room setup with a central control hub and a projector display device. Several computer nodes that are assumed to be 3 m apart from the central hub are available. The link characteristics between a node and the display device are similar to UM1. A data rate of 0.125 Gb/s is assumed between the controller hub and a computer node in both directions. The data rate between the computer nodes is assumed to be 0.0416 Gb/s for a separation of 1 m. In this scenario, all links are assumed to have a LOS link with the hub. This UM is designated to be optional.
5) UM5: Wireless data download from kiosk to a handheld device over a LOS link with a burst speed of up to 2 Gb/s. The user needs to manually adjust the direction of the antennas; hence, no neighbor discovery is necessary. This UM is designated as mandatory.

Depending on the application, a sufficient wireless link can be established using either one or two directional antennas at both ends of the link. For most of the applications, a unidirectional link is sufficient for high-data-rate transmission (e.g., video from player to screen). In such scenarios, only one directional antenna is sufficient at the source of the data that is being transmitted. This would require only a single execution of the neighbor-discovery algorithm since the receiver uses an omnidirectional antenna. However, some applications require simultaneous bidirectional high-data-rate communications (e.g., file server and computer). In such scenarios, both nodes need to perform the neighbor-discovery algorithm to steer the directional antennas in the appropriate directions.

Based on the UMs previously defined, we can assume that the nodes are mostly stationary or fixed but change in the channel environment or shadowing by moving the human body can alter the PHY-link characteristics between a transmitter and a receiver. Moreover, the use of both directional and omnidirectional antennas helps reduce the number of neighbor detection execution, hence reducing the overhead.

B. Performance

To analyze the performance of the proposed neighbor-discovery algorithm, we initially consider a single node and random events that might require the execution of the algorithm. This analysis is then expanded to N nodes in the WPAN.

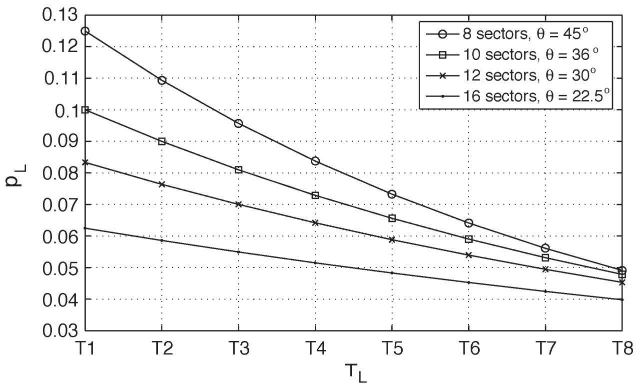

Fig. 2. Probability of detecting the neighbor in the Lth section at time T_L. The location of the neighbor is assumed to be uniformly distributed around the node. The distribution shown here corresponds to an LOS scenario, where, once the neighbor is detected, the neighbor-discovery algorithm terminates, and data transfer begins.

However, note that, N can be as low as 2, which is the case for UM1 and UM5.

We study the performance of the proposed algorithm in a node, which can be either a PNC or a slave device. In the sectored spatial domain, let us assume that the probability of the node detecting the neighbor in any sector is p_s. The probability of locating the neighbor in the Lth sector is

$$p_L = p_s(1 - p_s)^{L-1}. \quad (4)$$

Let T_t be the time spent during the LOS/NLOS detection phase and T_s be the time spent at each sector for direction detection. The total time spent for detection of the neighbor at the Lth sector is expressed as

$$T_L = T_t + LT_s \quad (5)$$

where the probability of neighbor detection within T_L is defined in (4). If we define the maximum number of sectors as N_s, which is related to the beamwidth of the directional antenna, and assume that p_s is uniformly distributed over all sectors, i.e., $p_s = 1/N_s$, we can rewrite (4) as

$$p_L(l) = \frac{(N_s - 1)^{l-1}}{N_s^l} \quad (6)$$

which is the probability mass function of T_L, $L = 1, \ldots, N$. Fig. 2 shows this distribution for different values of the antenna beamwidth. The probability of locating the neighbor at time T_L decreases as the beamwidth decreases and L increases. This is expected for a scanning algorithm. Several existing works have proposed a random search algorithm for neighbor discovery using directional antennas [20]. However, this would yield to a more complex algorithm. The probability distribution in Fig. 2 suggests that it is more likely that the location of the neighbor is detected in the earlier stages of the scanning algorithm, compared with the later steps of the scanning process. In the limiting case, where there is only one sector, i.e., the omnidirectional case, the probability of locating the neighbor in the first (and only) sector is 1.

In the case in which the neighbor is LOS with the node, the neighbor is detected at time T_L with probability $p_L(L)$. However, if the neighbor is NLOS, as explained in the previous section, the node has to go through all the sectors before detecting the direction of the neighbor. Therefore, the detection happens at time T_L, where $L = N_s$, with a probability of 1.

Once the neighbor is detected, the node can either continue to detect other possible neighbors or start the transmission of data packets. It is possible that, at any random time instant, the neighbor or the node itself changes location, the link between the node and the neighbor becomes obstructed, the channel environment changes, or a new neighbor joins the network. Under such circumstances, a new neighbor detection might be required. The occurrence of an event is random and independent from other events. We assume that the occurrence of such event is a Poisson process with rate λ. These events can occur anytime during the operation of the network and are independent of one another. For such Poisson process, if $n(t)$ represents the number of events that occurred up to time t, then $n(b) - n(a)$ corresponds to the number of events that occurred between time b and a and has a Poisson distribution expressed as

$$P\left[(N(t+\tau) - N(t)) = k\right] = \frac{e^{-\lambda\tau}(\lambda\tau)^k}{k!} \quad (7)$$

where k is the number of events that occurred in time frame τ. For the time duration of τ, under a constant network load, the time allocated for neighbor discovery can be defined as kT_L, and the time allocated for the information transfer is $\tau - kT_L$. We define the time allocation ratio of the network as

$$\eta = \frac{kT_L}{\tau} \quad (8)$$

where 100η represents the percentage of time allocated for the neighbor-discovery algorithm.

In LOS scenarios, T_L represents the detection time that occurred at the Lth sector. However, for the performance analysis, we assume that detection always occurs at the last available sector, i.e., $L = N_s$, creating an upper bound on η. On the other hand, in NLOS scenarios, T_L is already defined with $L = N_s$. The probability mass function of (8) $P[\eta = x]$ after extracting k from (8) can be expressed as

$$P\left[k = \frac{\tau x}{T_L}\right] = \frac{e^{-\lambda\tau}(\lambda\tau)^{\frac{\tau x}{T_L}}}{\left(\frac{\tau x}{T_L}\right)!}. \quad (9)$$

Note that k represents the number of occurred events and is a positive integer. This distribution is shown in Fig. 3. We vary the event occurrence rate from 1 event/s to 100 events/s. Although the UMs described at the beginning of this section define mostly stationary networks, we test the performance of the neighbor detection algorithm in extreme cases. The parameters that were used in this analysis are listed in Table II. In this simulation, we assume that the LOS/NLOS detection duration T_t consists of one test frame and one ACK frame at the base rate transmitted with omnidirectional antennas and their corresponding propagation delays. Similarly, scan duration T_s is assumed to consist of a probe frame at the base rate transmitted with a directional antenna, its propagation delay, and the channel listening period for possible ACK from the neighbor.

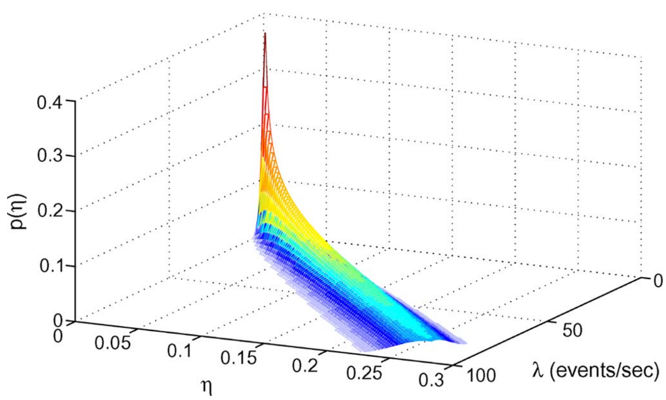

Fig. 3. Probability of η, which is the time allocation ratio of the network, with a changing rate of event occurrence that triggers the execution of the neighbor-discovery algorithm. Event rate λ is defined as the number of events per second. Events could be—but are not limited to—relocation of nodes, change in channel environment, or addition of new nodes to the network. A large λ corresponds to a highly dynamic network environment.

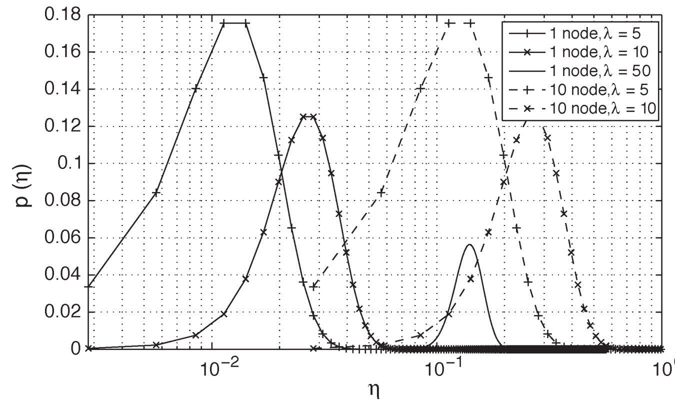

Fig. 4. Snapshot of the probability of η for different event occurrence rates with a single- and a ten-node network. The increase in the node count also increases the time allocated for the neighbor-detection algorithm. In this simulation, we assume a worst-case scenario, where every node performs a neighbor discovery and updates its information when an event occurred and made one node execute the algorithm. Under such scenario, we observe the upper bound on the time allocated for the neighbor-discovery algorithm.

TABLE II
PARAMETERS OF THE 60-GHz NETWORK AND CHANNEL USED IN THE SIMULATION OF NEIGHBOR DETECTION

Parameter	Value
Size of ACK, L_a	14 bytes
Size of probe L_f	14 bytes
Propagation delay, t_p	9.4 ns
Channel listening delay, t_l	$\sim 2t_p$
Base rate, R_b	54 Mbps
Data rate, R_d	1 Gbps
Transmission duration, τ	1 s
Number of sectors	8

We observe in Fig. 3 that, when the event rate increases, λ, which is the time allocated to the neighbor-discovery algorithm, also increases. Such behavior is expected with an increased number of algorithm execution triggering event occurrences. However, one should note that, in the very extreme case of 100 event/s, the time allocated for the proposed algorithm is less than 30%. Such event rate is unrealistic for the defined UMs and is studied only to observe the variable η in extreme conditions. In a more modest but still highly dynamic network with $\lambda = 10$, the allocated time is less than 10%. In such a network, assuming that the transfer rate is set to 1 Gb/s, with the introduction of the neighbor-discovery algorithm, the data rate is reduced to 0.9 Gb/s in the worst-case scenario.

Fig. 4 shows a snapshot of the analysis in Fig. 3 with different event rates and numbers of nodes. To establish an upper bound for the time allocation ratio of the network in the multiple-node network scenario, we assume that every node executes the neighbor-discovery algorithm when an event occurs. The result of such event might not require the execution of the algorithm on every node; however, by doing so, we obtain the upper bound on the time allocation ratio of the network. From Fig. 4, we observe that, by increasing the number of nodes, the time allocated for the neighbor-discovery algorithm increases up to 40%, depending on the event occurrence rate.

In practical wireless networks for all UM scenarios, an event rate of 1 or 2 event/s is expected, given that the most frequent change might happen with the movement of human bodies, either carrying a node or obstructing a path. Considering this, our analysis shows that, even for a ten-node network, which might be considered a highly populated network according to the UMs, under the worst-case scenario, the time allocated for the neighbor-discovery algorithm is less than 10%. Moreover, such overhead might be compensated by the use of the polarization scheme explained in [12] without increasing the complexity since LOS/NLOS topology information is obtained as a part of the neighbor-discovery process.

IV. CONCLUSION

We have developed a neighbor-discovery algorithm for wireless communication networks with directional antennas operating in the 60-GHz band. This algorithm is a cross-layer scheme for effectively locating the neighbors around a device. It efficiently exploits the unique behaviors of different polarizations in LOS and NLOS environments for improved performance. A novel approach for detecting the presence or absence of a direct path between the transmitter and the receiver has been proposed, which is used to determine if the communications link is LOS or NLOS. Through the overhead and efficiency analysis, we have observed that, even in highly populated and very dynamic networks, the time allocated for the neighbor-discovery algorithm does not exceed 10% in the worst-case scenario. Considering the significant increase in the PHY-layer performance as a result of the efficient use of an appropriate polarization for each specific propagation scenario, this decrease in the network performance is expected to be compensated by the suppressed ISI and the reduced error rates.

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Ferhat Yildirim (S'01) received the B.S. and M.S. degrees in electrical and electronics engineering from Bilkent University, Ankara, Turkey, in 2002 and 2005, respectively. He is currently working toward the Ph.D. degree with the School of Electrical Engineering and Computer Science, Oregon State University, Corvallis.

His current research interests include wireless communications in the 60-GHz spectrum, polarization diversity, and direction detection.

Huaping Liu (S'95–M'97–SM'08) received the B.S. and M.S. degrees in electrical engineering from Nanjing University of Posts and Telecommunications, Nanjing, China, in 1987 and 1990, respectively, and the Ph.D. degree in electrical engineering from New Jersey Institute of Technology, Newark, in 1997.

From July 1997 to August 2001, he was with Lucent Technologies, Holmdel, NJ. Since September 2001, he has been with the School of Electrical Engineering and Computer Science, Oregon State University, Corvallis, where he is currently an Associate Professor. His research interests include ultrawideband schemes, multiple-input–multiple-output orthogonal frequency-division multiplexing systems, and communication techniques for multiuser time-varying environments, with applications to cellular and indoor wireless communications.

Dr. Liu currently serves as an Associate Editor for the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY and the IEEE COMMUNICATIONS LETTERS.