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PhyCon: Discovering Physical Connectivity for Indoor WLAN Using Mobility

Marco A. Gonzalez · Javier Gomez · Francisco Garcia · Victor Rangel

Abstract The concept of connectivity in wireless networks is a well-established term referring to the ability of nodes to communicate with other nodes directly or through other nodes working as relays. In this paper, a different aspect of connectivity is presented named physical connectivity, which we defined as the ability of nodes to physically reach other nodes, not only through open spaces, but also through corridors, doors, rooms, etc. For indoor wireless local area networks (WLANs), we believe that awareness of physical connectivity is a key factor for developing emerging applications such as guiding, localization, tracking, physical routing, etc. Related studies only consider the problem of direct connectivity or line-of-sight (LOS), however, we consider physical connectivity should span beyond LOS conditions enabling nodes to reach other nodes through any path available. In this paper a novel method to discover physical connectivity named PhyCon is presented. PhyCon combines node mobility and the inverse-square relationship between received signal strength and distance to discover physical connectivity paths among wireless users. Results from simulations and testbed experiments show PhyCon can discover a high percentage of physical connectivity paths using normal mobility behavior of users found in indoor WLAN.

Keywords Connectivity · Indoors · RSSI · WLAN · Mobility

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1 Introduction

In recent years, WLANs have been involved in different fields of human activity going far beyond a simple replacement or complement of wired networks [1]. New applications for indoor and outdoor WLAN have been expanded contributing to the development of ubiquitous computing. Examples of these applications include health monitoring [2], rescue missions [3], intrusion detection [4], social networks [5], guiding for mobile nodes [6–8], localization [9], etc. Many of these applications require proximity information to work properly, understanding proximity as the ability of two nodes to establish how far/close are to each other. The use of proximity information, for example, might allow mobile nodes be tracked and/or localized inside a WLAN by knowing their proximity with other nodes having known positions [10]. In wireless sensor networks (WSN), sensor measurements can be correlated in the space domain having proximity information of sensors deployed in the same region.

In order to estimate proximity or distance among nodes, several techniques have been proposed in the literature using various estimation methods. These methods are usually classified into range-free and range-based methods. Range-free schemes are based on proximity and connectivity schemes. For instance, two nodes are said to be near to each other as long as they are within transmission range. Although the use of trilateration techniques [11] can increase the precision of range-free methods, they usually provide less precision than range-based methods. Range-based approaches, on the other hand, use various techniques to estimate the distance between two nodes. Numerous range-based approaches also use a trilateration technique to enhance the accuracy of location estimation. Performance of both types of methods is usually affected by obstacles, which impact the propagation of radio waves for indoor environments producing effects such as attenuation, diffraction and reflection, resulting in distance and location estimation errors. Both range-free and range-based methods, however, cannot tell whether two nodes are able to reach each other through a path in the presence of obstacles. Therefore, it is easy for these two methods to confound proximity (i.e., distance) from physical proximity using signal measurements only. For example, let us consider the scenario shown in Fig. 1 where node A measures the same signal strength from a far away node having a clear path and a nearby node behind a wall. In this case, node A cannot distinguish the availability of a walking path to either node by signal strength measurements only.

In this paper the concept of Physical Connectivity Path (PCP) is introduced, which is defined as the possibility of nodes to physically reach other nodes not only through open spaces, but also through corridors, corners, doors, etc. Related studies consider the problem of discovering line-of-sight (LOS) conditions among wireless devices based on statistical approaches by considering the variability of the received radio signal. However, even if LOS methods discover physical connectivity, they do so only in cases when nodes see each other.

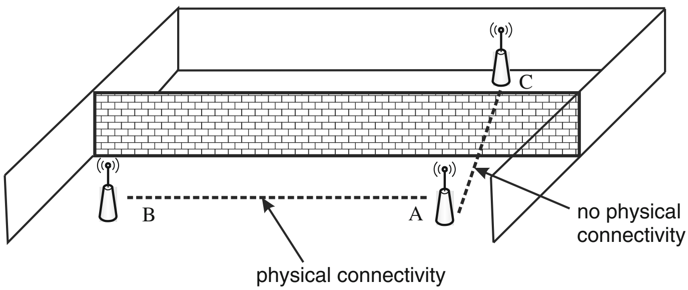

Fig. 1 Physical connectivity detection problem

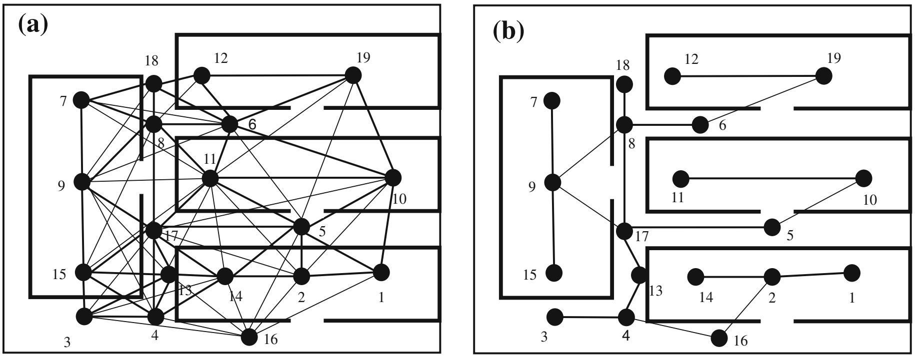

Fig. 2 Indoor WLAN connectivity graph (**a**), physical connectivity graph (**b**)

We consider physical connectivity should span beyond LOS conditions, enabling nodes to reach other nodes through any path available. In this paper we introduce PhyCon, which is a novel method that combines node mobility and the inverse-square relationship between signal strength and distance to discover physical connectivity paths among wireless nodes.

Figure 2a shows a typical indoor Wi-Fi radio connectivity graph where black rectangles represent rooms of an indoor building. The discontinuity in the perimeter of each rectangle represent doors available at each room while the separation between rectangles represent corridors. Nodes (represented as small circles in this figure) are connected to other nodes as long as they are within transmission range. In this figure, for example, for node 3 to communicate with node 1 we need a route formed by various intermediate nodes working as relays, also known as multi-hop routing. Two nodes are said to be connected as long as there exists a route that connects them. Figure 2b, on the other hand, shows a physical connectivity graph of the same indoor layout of Fig. 2a. As it can be seen in Fig. 2b, a physical connectivity graph can be obtained from the graph in Fig. 2.a by selecting edges having a walking path only. Similar to the multihop routing example of Fig. 2.a, there is also the concept of a physical connectivity route. This is, for node 3 to reach node 1, it is better to first reach node 4, then reach node 16, then reach node 2, and finally, reach node 1. PhyCon also introduces the concept of physical connectivity cost, which we define as a function of the time needed for one node to reach another node at a given speed (e.g., walking speed). By associating a physical connectivity cost to each PCP and applying a path optimization mechanism, PhyCon is able to replace PCPs having higher costs with PCPs having lower cost, thus optimizing physical connectivity graphs.

In order to discover physical connectivity PhyCon defines the *LOS-RSSI* range (that will be discussed in Sect. 3.1), which is a RSSI range of values reached only by links having line-of-sight conditions (LOS), where *RSSI* is the signal strength from the link between a mobile and static nodes obtained directly from the WLAN radio interface. In PhyCon, a mobile node that is close enough to a transmitting static node can temporarily reach the *LOS-RSSI* range, thus establishing LOS conditions. Once a mobile node detects LOS conditions consecutively with two static nodes as it moves, the time interval between the two LOS detections can be used to determine the availability of a physical path between the two static nodes involved. Figure 3 depicts how mobile node M^k discovers a Physical Connectivity Path (PCP) between static nodes S_i and S_j by traveling along the trajectory $p_0 \to p_1 \to p_2 \to p_3$, detecting LOS conditions with nodes S_i and S_j at points p_0 and p_3, respectively. After discovering several PCPs connecting various static nodes, physical connectivity subgraphs can be obtained from

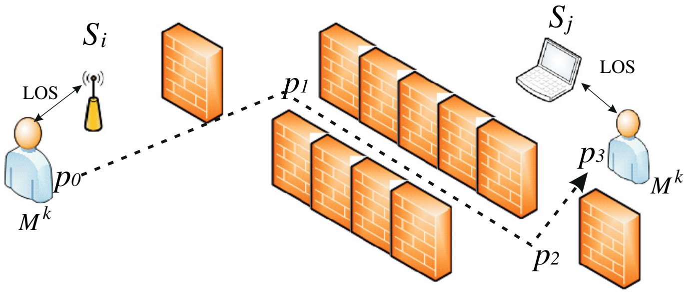

Fig. 3 Detecting physical connectivity between two static nodes

a traditional radio connectivity graph (see Fig. 2b). Edges of these subgraphs are characterized by being available walking paths inside the indoor network.

We envision that guiding nodes within indoor areas will be the main application of PhyCon. However node tracking, localization and even social applications can also benefit from it.

For guiding applications in indoor areas, a possible guiding method is to construct a PCP graph using PhyCon to identify available walking paths connecting nodes in a building. Because PhyCon discovers not only the availability of a PCP connecting a pair of nodes, but also the identities and walking distances of intermediate nodes found in LOS along such paths, PhyCon provides the basic clues for a node to be aware it is moving on the right direction as long as it finds such intermediate nodes in its path. As a localization method, PhyCon does provide some location information. Even if PhyCon cannot tell the exact location of a node within a building, PhyCon can tell the walking distance among nodes, as well as telling which nodes are likely located within the same room. In cases where one node can be placed in a particular room by other localization systems, PhyCon can, as a consequence of LOS conditions and short walking distances, establish which other nodes are also likely located in the same room. Similarly, current RSSI based schemes require a localization infrastructure network made of various fixed nodes to operate. Opposite to this, PhyCon requires no infrastructure, thus making it easier to deploy. PhyCon can also be used as a tracking method. A mobile node can be tracked inside a building by knowing its relative location at different times. While a node moves in the building, it will temporarily reach LOS conditions with some static nodes found in its path. For cases in which the position of such static nodes can be obtained by other means, PhyCon can estimate the path of the mobile node. For cases where the exact locations of the static nodes are unknown, PhyCon can, at least, provide the identities and walking distances of nodes found along its path. Finally, PhyCon can also be used in social network applications, providing information about the identities of other persons likely located within the same area, or within a certain distance.

The rest of the paper is organized as follow. In Sect. 2, related methods to detect proximity and LOS conditions found in the literature are discussed. Section 3 describes PhyCon, including various experiments to define the *LOS-RSSI* range to detect LOS conditions between mobile and static nodes. Section 4 shows the results obtained by simulations using a discrete simulator and results of experiments on a real indoor scenario. Finally, in Sect. 5, we present our final remarks.

2 Related Work

While we did no find in the literature a topic or work equivalent to what PhyCon is trying to achieve, there are other areas that present some similarities. In particular, we compared

PhyCon with ad hoc routing, localization methods and schemes to discover Line-of-sight (LOS). We compared PhyCon with ad hoc routing because the realization of $PCPs$ involves the discovery of intermediate nodes along $PCPs$; nodes that will be quite useful for guiding applications, for example. Regarding localization, traditional localization systems can potentially be used as guiding applications. Finally, because the main building block of PhyCon is the ability to discover LOS conditions between nodes, we found important to review existing methods in the literature to estimate LOS conditions. Now we review these three areas.

Routing is a term traditionally used in ad hoc networks to refer to the ability of nodes to communicate with other nodes directly or through other nodes working as relays. Routing information is useful in order to know whether some nodes are isolated from the network and to determine the best route to send a packet from a sender node to a destination node [12,13]. The connectivity concept discussed in this paper, however, is different from the traditional routing term used in ad hoc networks. In this work we are considering physical connectivity or physical routing, defined as the identification of a path so that two nodes can physically reach each other not only through open spaces, but also through corridors, corners, doors, etc. However, although different in meaning and operation, there are aspects that make routing in ad hoc networks and physical routing alike. For example, PhyCon also introduces the concept of a physical route that indicates the best possible path for two nodes to reach each other. Similarly, as will be show later, one way to model a physical route is to indicate the identities of nodes found along such physical route, similar to traditional multihop routing in ad hoc networks. However, the purpose of having intermediate nodes in a physical route is only to provide clues so a node finding those intermediate nodes in LOS knows it is moving along the correct path towards its target destination node. To the best of our knowledge there is no related work in the literature dealing with this type of physical routing, which we consider is a key factor for developing future applications such as guiding, localization, tracking, etc.

Another related area to the physical connectivity problem addressed in this work is localization. Localization systems can be classified as range-based or connectivity-based systems. On one hand, range-based systems can be subdivided into four categories depending on which method is used to estimate or measure the distance between transmitter and receiver. These methods are based on measuring one of the following parameters: Time of Arrival (ToA), Time Difference of Arrival (TDoA), Angle of Arrival (AoA) and Signal Attenuation (SA). A location system based on ToA, e.g. [14] and [15], estimates distances by measuring the signal propagation delays between the end points of a radio link. In contrast, TDoA systems, e.g. [16], estimate the user location by computing the time difference of arrival of a signal propagating from one transmitter to three or more synchronized receivers. Location systems using AoA, e.g. [17], require special receivers in order to determine the angle on which radio signals arrive from a transmitter. Location systems based on SA, e.g. [18], estimate the distance between transmitters and receivers by using signal attenuation measurements. These methods involve propagation models and triangulation or lateralization techniques to estimate the node position. Radio-fingerprinting systems are based on SA methods, e.g. [19], and they operate by prerecording signal strength information from multiple base stations providing an overlapping propagation map within an area of interest. In general, the downside of location systems using range-based methods is that they may require additional infrastructure. Besides, they can exhibit extreme inaccuracies due to signal propagation problems. On the other hand, connectivity-based methods (also known as range-free methods), e.g. [20] and [21], only depend on connectivity conditions. If the number of hops separating a pair of nodes can be determined then a set of distance estimates can be generated. Given such a set, node location can be solved using analytical methods. Most of these solutions require some nodes to be placed at known positions, called anchors, in order to set up a coordinate reference system to establish absolute positions. However, even if both types of localization methods can establish the location of nodes within an indoor wireless network, they cannot identify the availability of a physical path or route between pairs of nodes in the network.

The other related area to physical connectivity is proximity. Proximity is a term usually associated by a function that satisfies a particular geometric condition. The most common proximity metric used in the literature is the Euclidean distance between two points. A common method to detect proximity is by contact, which refers to a situation where two nodes can exchange information directly without requiring intermediate nodes [22]. However, although related, proximity methods cannot tell whether there is a physical path connecting two nodes. The only area dealing with this problem is the work related to discovering LOS conditions of wireless links. This is, when the link connecting two nodes is said to have LOS conditions, it basically means the two nodes see each other and are located in the same space (i.e., room, office, lab, etc.). There are various works in the literature related to the LOS discovery problem. Infrared has been commonly used to detect whether a link presents LOS conditions or not. Infrared communications require that transmitter and receiver be located in the same room so that the infrared signal can reach the receiver [23]. Generally, any obstacle can be detected when an infrared link goes down since infrared signals cannot penetrate materials such as concrete, wood, steel, brick, etc. In [24] the authors propose a localization method where a robot moves autonomously using landmarks equipped with radio frequency chips and infrared leds. A drawback of this method is the dependence of using dedicated infrastructure and specific hardware to work properly. Other methods to detect links in LOS conditions are based on statistical approaches. In [25], multiple base stations were deployed in an area to define the LOS statistical distribution of ToA measurements between a mobile node and base stations. ToA measurements can be compared to the predefined LOS statistical distribution of ToA in order to establish LOS conditions or not. This methodology is usually applied in outdoors environments in order to detect nodes moving through a partially obstructed path (near-line-of-sight, NLOS), under the premise that signal metrics such ToA and RSSI measurements vary more in NLOS than in LOS conditions. The main drawback of statistical approaches is the need of pre-studying the behavior of signal propagation in the area of interest. Exploring if a radio signal can be modeled by a well-known distribution is another way of addressing the LOS detection problem. In [26], variations of RSSI over LOS conditions are described by the Rician distribution. The authors in [27] propose to detect LOS conditions in cellular environments by exploiting the Rician factor estimation. In [28], NLOS conditions are modeled using a Rayleigh distribution. However, results in [29] show that for frequencies lower than 4 GHz for indoors under LOS conditions, the amplitude of a signal can be modeled with both the Rician and Rayleigh distributions, thus it cannot be used to differentiate between LOS conditions and NLOS conditions with popular 2.4 GHz 802.11b/g radios. On the contrary, the study performed in [30] concludes that distribution of RSSI measurements is difficult to fit to a well-known distribution for indoor environments. However, even if LOS methods discover physical connectivity, they do so only in cases when nodes see each other. We consider physical connectivity should span beyond LOS conditions enabling nodes to reach other nodes through any path available.

In summary, while reported routing, localization and proximity methods provide information about the location of nodes and some clues about whether or not some nodes might be located in the same room. They cannot establish whether there is a physical path connecting any pair of nodes located in different rooms unless nodes are provided with floor maps, for example. PhyCon fills these gaps introducing a PhyCon-Mobility criterion so mobile nodes are able to temporarily detect their own LOS conditions with static nodes by using the *LOS-RSSI* range as well as discovering physical paths among static nodes by considering the time interval between consecutive LOS detections with static nodes. More important, PhyCon achieves these goals using normal mobility behavior of nodes found in indoor wireless networks. We consider PhyCon represents a simple and efficient way to discover physical connectivity routes among nodes for indoor environments that can trigger an array of emerging applications including physical routing, guiding, etc.

3 PhyCon

This section describe PhyCon, a mobility based method capable of discovering physical connectivity paths among static nodes for indoor wireless networks. PhyCon is composed of two main components that are line of sight (LOS) detection and Physical Connectivity Paths (PCP) detection. Now each component will be explained in detail.

3.1 LOS Detection

In this section a set of experiments will be described in order to determine the range of RSSI values to detect LOS conditions between a mobile node and a static node. The use of this range will be used later in Sect. 3.2 by PhyCon to discover physical connectivity paths among static nodes. As will be shown later, this method allows PhyCon to discover a high percentage of physical connectivity paths using normal mobility behavior of users found in indoor WLAN.

There are several radio propagation models to describe the behavior of a signal in different propagation environments. In general, RSSI decreases as the distance between nodes increases. In a building with walls, furniture, doors and other obstacles, it is expected that a link reaches its maximum RSSI value when the distance between two nodes is shortest and no obstacles are present, being it a case of LOS conditions that will be considered in the rest of this work. Similarly, when a radio signal propagates through a fully blocked path, a maximum RSSI value can be obtained also when the distance between two nodes is shortest. This latter case is named NO-LOS conditions which differs from NLOS where there may be partial LOS conditions. In order to define the range of RSSI values in LOS and differentiate them from NO-LOS conditions we analyzed the behavior of RSSI values between mobile and static nodes under LOS and NO-LOS conditions for indoor environments. We selected two places to perform the experiments: the third floor of the Institute for Research in Applied Mathematics and Systems (IIMAS) and a laboratory building, both located in our main university campus. These buildings represent a typical indoor layout where two common types of walls in buildings are found: drywall (panel made of gypsum plaster) and brick walls.

To illustrate LOS conditions of a link, we used the scheme shown in Fig. 4.a where the third floor plan of IIMAS building is shown. A mobile node (e.g., a user carrying a laptop) was positioned at the point labeled as *base* located in the corridor. A static node was positioned at point p_1, where there is a direct view between both nodes. To represent NO-LOS conditions we consider two cases: a) a path blocked by a drywall and b) a path blocked by a brick wall. The scheme for drywall is similar to LOS conditions, the only variation is that a static node was positioned at point p_2, inside room *302*. The wall of this room to the corridor is a drywall 60 mm thick. To represent NO-LOS conditions using a brick wall we used the third floor of the laboratory building. The layout of this floor is shown in Fig. 4b where we positioned a static node at point p_3. The wall of the laboratory to the corridor, labeled as "corridor 1", is a

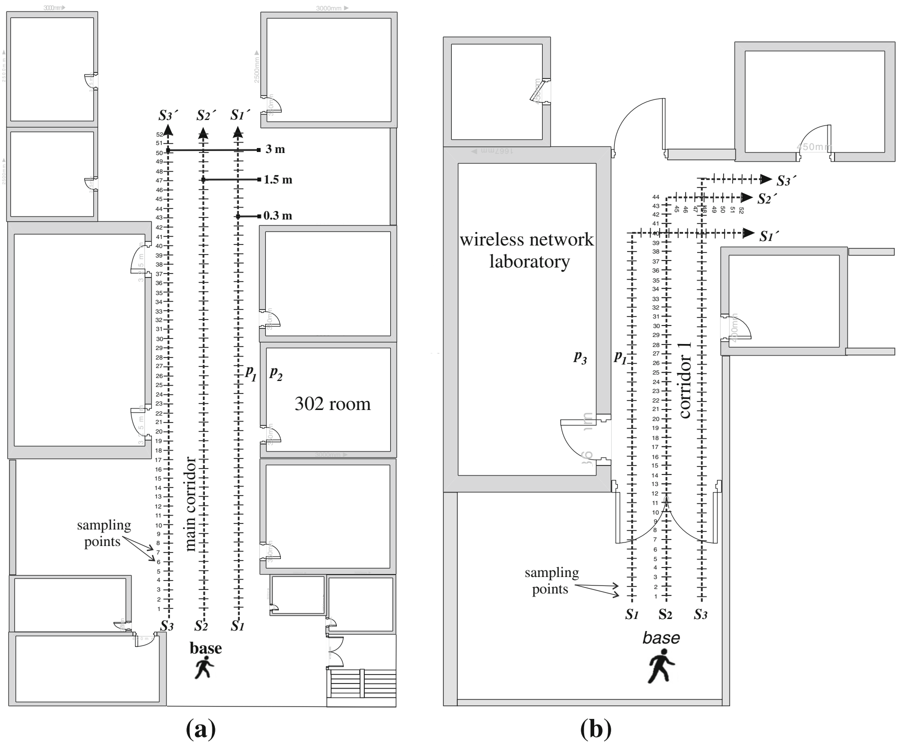

Fig. 4 Scheme of experiments realized to determine the *LOS-RSSI* range. **a** Floor layout of the experiments inside of the IIMAS building (LOS and drywall). **b** Floor layout of the experiments inside of the laboratory building (brick wall)

brick wall 160 mm thick. Again a mobile node was positioned at the point labeled as "base". Points p_2 and p_3 represent two cases where distance between a mobile node's trajectory and static node's location in NO-LOS conditions is shortest.

In order to study possible trajectories that a mobile node can follow throughout the selected corridor, three trajectories were considered for each case. These trajectories are $S_1 \rightarrow S_1$', $S_2 \rightarrow S_2$', and $S_3 \rightarrow S_3$', marked by dashed lines in Fig. 4a, b, respectively. The distance traveled by the mobile node along each trajectory was approximately 52 m.

Because different 802.11 commercial cards can show some variability while taking measurements of radio signal parameters, four commercial devices equipped with different 802.11 chipsets were used in the experiments:

- Dell Inspiron laptop with an Intel PRO/Wireless 3945ABG 802.11g chipset.
- Sony Vaio laptop with Atheros AR9285 802.11g chipset.
- Hp Mini 1101 laptop with Ralink RT2500 802.11g chipset.
- Cisco Broadband Router with Broadcom BCM5352 802.11g chipset.

We considered four combinations of mobile and static nodes involving the mentioned devices as follow: For the first and second combination, a user carrying the Dell Inspiron laptop was used as mobile node, and the Cisco Broadband Router and the Sony Vaio laptop as static nodes, respectively. For the third and fourth combination, a user carrying the Hp Mini 1101 laptop was used as mobile node, and the Cisco Broadband Router and the Sony Vaio laptop as

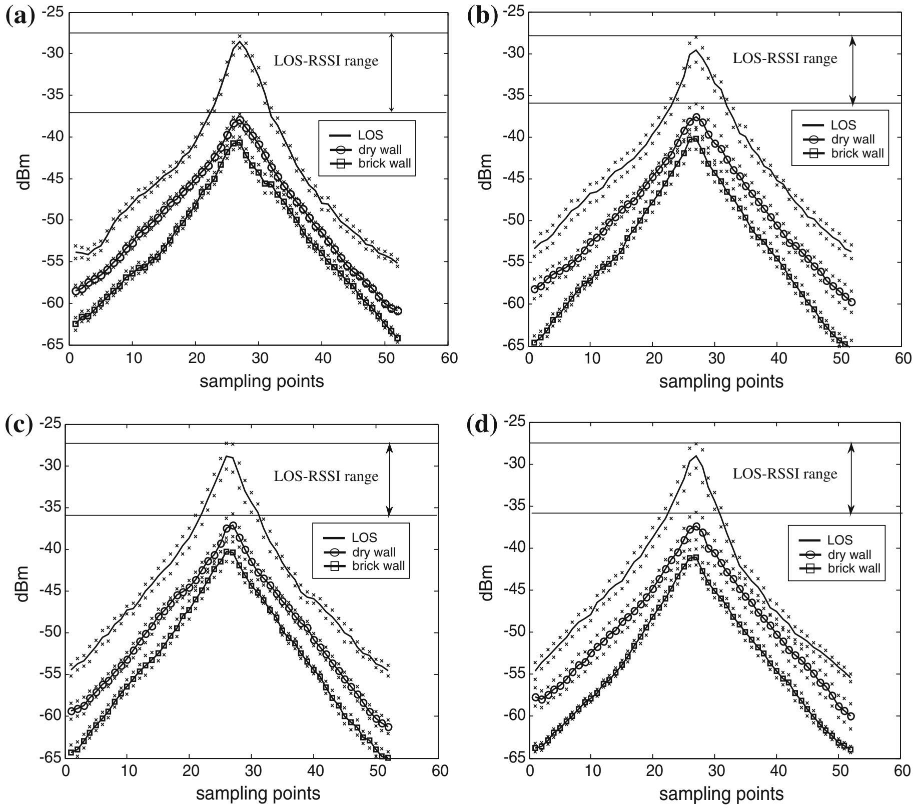

Fig. 5 Mean values of RSSI under LOS conditions, NO-LOS conditions using drywalls and brick walls, along trajectories of 52 sampling points using different 802.11 chipsets. **a** Intel versus Broadcom. **b** Intel versus Atheros. **c** Ralink versus Broadcom. **d** Ralink versus Atheros

static nodes, respectively. For each combination, we considered LOS conditions and NO-LOS conditions using drywall and brick walls cases as described before. During our experiments mobile nodes sent ping packets to static nodes every 0.5 sec.

For each chipset combination, a mobile node traveled various times along the three possible trajectories at a constant speed of approximately 1 m/sec, always starting from its defined initial point to its defined end point. The mobile node took RSSI samples from the received ping messages at every 1 m, approximately, thus each trajectory had 52 sampling points. Mean values of each of the 52 sampling points were estimated and the results are shown in Fig. 5 along with their respective 95 % confidence intervals.

Results in Fig. 5a–d show an increase of RSSI values as the distance between mobile and static node decreases. As it is expected, the maximum RSSI value is reached when the distance between the mobile and static nodes is shortest for all four combinations. On the other hand, it can be observed that there is a range of RSSI values having LOS conditions which cannot be reached by any NO-LOS cases (both drywall and brick walls). We named this range the *LOS-RSSI* range having a range of values [-34 dBm, -27 dBm] for 802.11b/g cards. Thus, the presence of a RSSI value measured within the *LOS-RSSI* range enable us to distinguish between LOS versus NO-LOS conditions as follow:

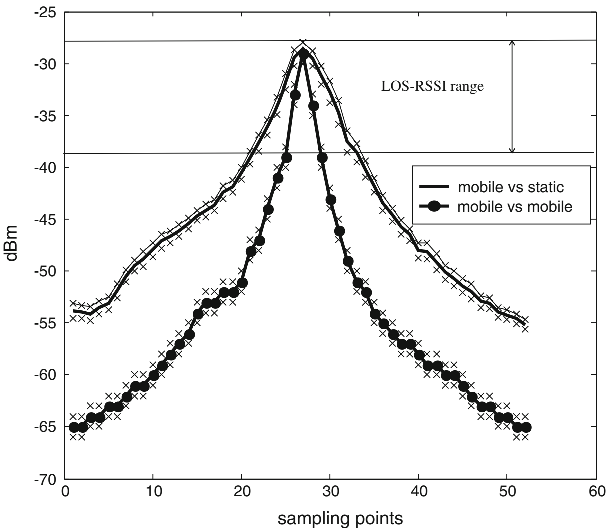

Fig. 6 Mobile-static versus mobile-mobile static experiments of LOS and NO-LOS conditions

$$\begin{aligned} -34\,dBm &\le RSSI, \quad \text{LOS conditions.} \\ -34\,dBm &> RSSI, \quad \text{NO-LOS conditions.} \end{aligned} \tag{1}$$

Because of signal fluctuations introduced by the wireless channel, we took various RSSI measurements at each location to obtain a more representative RSSI value.

It might happen that two mobile nodes pass each other as they move in a corridor. For example, from the scheme shown in Fig. 4a, if a mobile node travels the trajectory $S_1 \rightarrow S_1'$ while simultaneously a second mobile node travels the trajectory $S_3' \rightarrow S_3$, either mobile node will erroneously consider the other node is static and in LOS. To solve this problem we now present the behavior of RSSI values as two mobile nodes pass each other in a corridor (see Fig. 6). As it can be seen in Fig. 6, the *LOS-RSSI* range remains similar to the mobile-static case; what changes however is that the rate of change of RSSI values doubles over time compared with the mobile-static case. This behavior is used by PhyCon to detect and discard *PCP*s among mobile nodes.

In order to study the probability of error (i.e., a link having an RSSI value within the *LOS-RSSI* range that is actually blocked by a wall), we estimate the normal probability density function (PDF) of the maximum RSSI values reached in each of the experiments, see Fig. 7. In this figure, we can observe that the probability of claiming a link is in LOS conditions when it is actually in NO-LOS conditions is only 10.2 %. As a result we conclude that the *LOS-RSSI* range is a simple and practical way to differentiate between LOS and NO-LOS conditions for nodes located in close proximity for indoor WLAN. The only problem with this method is that a mobile node can miss static nodes in LOS if it does not pass near enough to be within the *LOS-RSSI* range. This situation is unlikely to happen in office buildings where rooms and corridors typically show small dimensions. However, this situation will appear in large indoor places where rooms can be quite big such as airports, malls, etc. However, even if a mobile node misses to detect a node in LOS, it is possible that other mobile nodes having different trajectories will make the detection. At this point it is important to mention that PhyCon involves a collaborative approach such that once a mobile node discovers a PCP, it

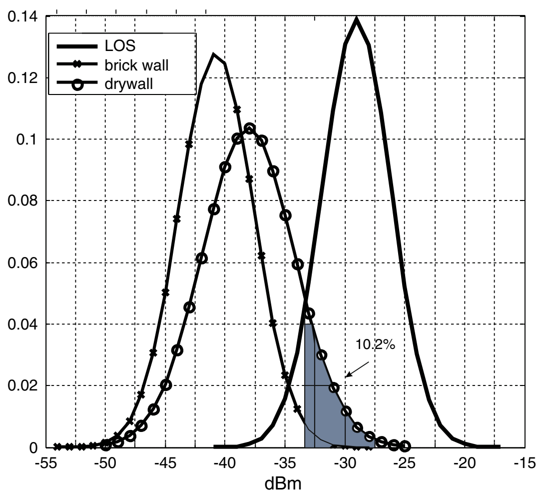

Fig. 7 PDF of the maximum RSSI value reached during the experiments of LOS conditions

uploads this information in a local server so this information can be shared and used among all nodes implementing PhyCon.

3.2 Discovering Physical Connecting Paths (*PCP*s)

In this section we describe how PhyCon uses the LOS detection method described previously to establish physical connectivity paths (*PCP*s) among static nodes for indoor WLAN. To facilitate the explanation, let us define first the notation used by this method.

(1) $t^{LOS}_{M^k_{S_j}}$. Denotes the first time when *LOS-RSSI* range is established between a mobile M^k and a static node S_j.
(2) *Physical Connectivity Path* ($PCP_{S_i-S_j}$). Denotes a physical path between static nodes S_i and S_j $(i \neq j)$ detected by M^k at different times using the *LOS-RSSI* range.
(3) *Length of a PCP* ($t^{PCP}_{S_i-S_j}$). Denotes the time interval between $t^{LOS}_{M^k_{S_i}}$ and $t^{LOS}_{M^k_{S_j}}$.

Figure 8 illustrates how PhyCon discovers a physical connectivity path between two static nodes placed along a corridor. In this figure mobile node M^k travels along the trajectory marked by a dashed line. At point p_2 the link between node M^k and node S_1 reaches a RSSI value included within the $LOS - RSSI$ range and node M^k records time instant $t^{LOS}_{M^k_{S_1}}$ at location p_2. Similarly, at point p_3 the link between node M^k and node S_2 is detected in LOS condition, and node M^k records time instant $t^{LOS}_{M^k_{S_2}}$ occurring at p_3. Thus, the physical connecting path connecting nodes S_1 and $S_2(PCP_{S_1-S_2})$ is detected, creating a new edge of a physical connectivity graph.

3.3 Optimizing Paths in *PCP* Graphs

It might be the case that some PCPs found using the previous method are too long, thus making it difficult for mobile users to travel along such PCP. This is particularly the case if long PCP involve doors and turns that might be difficult to guess for mobile users trying

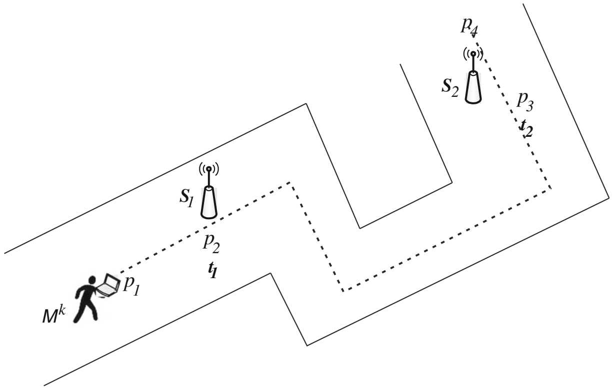

Fig. 8 The PhyCon method

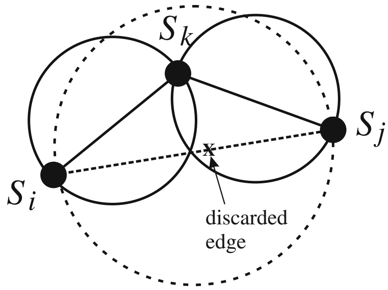

Fig. 9 Proximity condition of a Gabriel Graph

to move along the same PCP. As a result it becomes necessary to replace long PCP when possible to provide mobile users with more clues about the path to follow. This goal can be done by using a path optimization mechanism such as Gabriel Graph (GG) [31]. A GG is a planar graph where two nodes S_i and S_j are connected by an edge if and only if the circle with diameter $|S_i S_j|$ (defined as *search* area) contains no other nodes. This proximity condition implies that if a node S_k is inside the circle with diameter $|S_i S_j|$, then the square distance between S_i and S_j is greater than or equal to the sum of the squared distances between each of these points and S_k, this is,

$$d(S_i, S_j)^2 \geq d(S_i, S_k)^2 + d(S_k, S_j)^2 \tag{2}$$

An example of GG is given in Fig. 9. The edge formed by nodes S_i and S_j is not a Gabriel edge because the dashed circle with diameter $|S_i S_j|$ contains node S_k. On the other hand (S_i, S_k) and (S_k, S_j) are Gabriel edges as their diameter circles $|S_i S_k|$ and $|S_k S_j|$ contain no other nodes, respectively. From this example, as long as a mobile node finds the intermediate node S_k as it moves along a route $S_i \rightarrow S_k \rightarrow S_j$, it is a clue the node is moving on the right path towards S_j. Shorter edges on a path or route have also the characteristic of presenting fewer turns and doors.

In order to discard long PCP it is first necessary to introduce the Physical Connectivity Cost between nodes S_i and S_j as

$$W^{PCP}_{M^k_{S_i - S_j}} = (t^{PCP}_{S_i - S_j})^{\alpha}; \quad 1 \leq \alpha \leq 2 \tag{3}$$

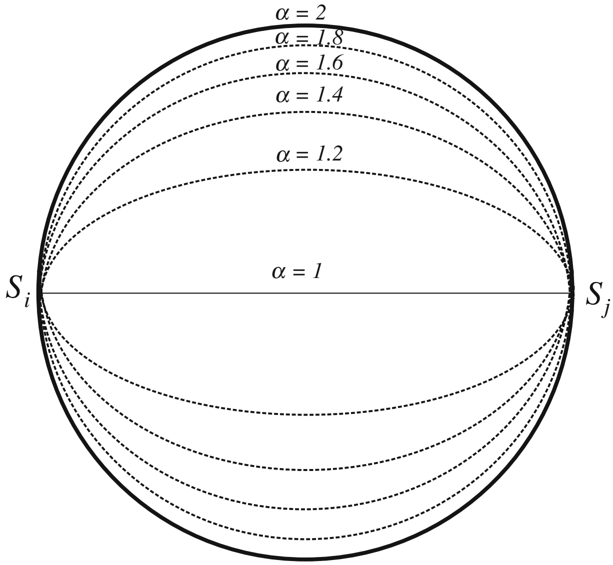

Fig. 10 Varying *search* area in GG

where α is the PCP cost exponent. PCP with higher cost can be replaced by two or more PCPs having lower cost by using the proximity condition given in (2) in terms of physical connectivity cost as follow

$$W^{PCP}_{M^k_{S_i-S_j}} \geq W^{PCP}_{M^k_{S_i-S_k}} + \cdots + W^{PCP}_{M^k_{S_{j-1}-S_j}} \tag{4}$$

where the value of α, given in (3), determines the shape of the *search* area in GG (see Fig. 10). When $\alpha = 2$ the *search* area is a circle, when $1 < \alpha < 2$, the *search* area becomes an ellipse where the size of the area increases as α approaches to 2. When $\alpha = 1$ in Fig. 10 for example, PhyCon looks for intermediate nodes that lie along the $PCP_{S_i-S_j}$. However, when $\alpha = 1.2$ PhyCon looks for intermediate nodes inside the dotted ellipse with $\alpha = 1.2$, and so on.

GG using equation (4) enables PhyCon to optimize PCP graphs, resulting in shorter PCPs and increasing the number of intermediate nodes along PCP. The operation of PhyCon in pseudo code is shown later.

3.4 Operational Modes

PhyCon operation requires mobile nodes to overhear packets as they move within transmission range of static nodes. In order to mobile nodes to make these measurements it is necessary that static nodes transmit packets with some periodicity. In PhyCon two operational modes are defined to achieve this requirement named passive and active. In passive mode, mobile nodes scan a channel list and wait for beacon frames transmitted from static nodes. Access points and nodes in ad hoc mode usually transmit beacon frames periodically to announce their presence to other nodes. For each received beacon, a mobile node can measure its RSSI value and the source address associated to it. This mode allows mobile nodes to collect RSSI measurements without transmitting any message, and might receive enough information to correctly apply criterion 1 to detect whether or not a static node is in LOS. Active mode is used to obtain RSSI measurements from nodes that do not transmit

PhyCon method
Input: Define α
Output: physical connectivity detected between static nodes
1. mobile node M^k monitors RSSI with static node S_i
if RSSI $\geq$ *LOS-RSSI* range **then**
MS-LOS link is detected
Record $t^{LOS}_{M^k_{S_i}}$
else
Go to step 1.
end if
2. M^k monitors RSSI with static node S_j
if RSSI $\geq$ *LOS-RSSI* range **then**
MS-LOS link is detected
Record $t^{LOS}_{M^k_{S_j}}$
else
Go to step 2.
end if
3. $PCP_{S_i-S_j}$ is detected
4. $t^{PCP}_{S_i-S_j} = t^{LOS}_{M^k_{S_i}}$ - $t^{LOS}_{M^k_{S_j}}$
5. $W^{PCP}_{M^k_{S_i-S_j}} = (t^{PCP}_{S_i-S_j})^{\alpha}$
6. Optimize $PCP_{S_i-S_j}$ by using GG

beacons, which is the case of nodes connected to an AP. Contrary to access point and ad hoc nodes, clients connected to the AP do not always transmit packets, and therefore, their signals might not always be available to obtain RSSI measurements. To solve this problem, a mobile node must first connect to an AP in promiscuous mode and be aware of all nodes currently connected to the AP. This requirement may be made by any software utility designed for network exploration purposes such as nmap [32]. Once this list is obtained, the mobile node might send ping messages to every node in the list, thereby forcing them to transmit. Finally, the mobile node captures all echo reply messages between any node and the access point to obtain RSSI values directly from static nodes connected to the AP.

4 Evaluation and Results

In order to evaluate the performance of PhyCon we conducted a series of experiments, first on a discrete simulator built on Matlab 7.6 and later using a testbed network composed of various PCs, APs and laptops.

4.1 Simulation Experiments

To evaluate the performance of PhyCon we implemented our own discrete simulator on Matlab 7.6. In this implementation we simulated two scenarios of 90 m $\times$ 60 m where two different floor layouts were considered. Floor layout 1 is shown in Fig. 11a. In this scenario we placed 7 rectangles to simulate rooms of variable dimensions. The discontinuity in the perimeter of each rectangle represents the only door available at each room while separations between rectangles represent corridors. The floor layout of scenario 2 is shown in Fig. 11b where we placed 37 rectangles to simulate smaller rooms and, in the same way

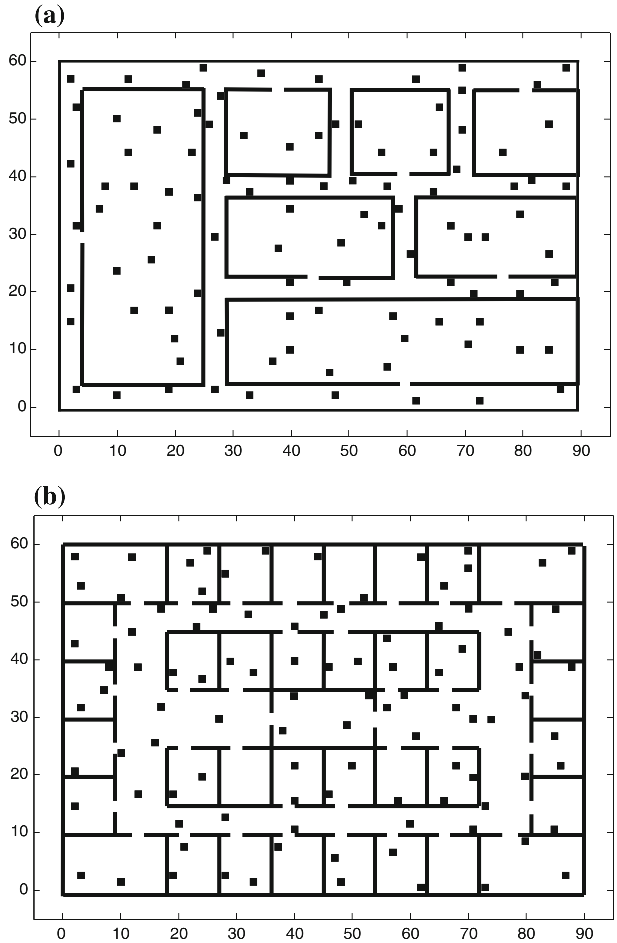

Fig. 11 Floor layouts used to simulate PhyCon method. **a** Floor layout with 7 rooms. **b** Floor layout with 37 rooms

to scenario 1, doors in each room are represented by a discontinuity in the perimeter of each rectangle. In both scenarios 100 nodes were randomly placed and simulation time was 1200 sec. We randomly selected 50 nodes over time to change their location to a new randomly selected location inside the layout, beginning their movements at random times. During the simulation, selected nodes changed their location once moving at a constant speed of 1 m/s. Movements of nodes were allowed only along corridors, inside rooms, and moving from a room to a corridor or vice versa through the respective doors. In the simulations static nodes transmitted at least one beacon frame every second so nearby mobile nodes could measure their signal strength to establish whether or not they were in LOS conditions.

Our simulations focused on measuring the number of PCPs found in the network as mobile nodes move inside the floor layout. During simulations, if a node changed its status from static to mobile, then all its PCPs were deleted before movement began. On the other hand, once a node changed its status from mobile to static, new PCPs connected to it will have to be discovered by passing mobile nodes.

Figures 12a and 13a show the edges of the radio connectivity graph for the floor layout of scenario 1 and scenario 2, respectively. Lines in the figures connect nodes that are within transmission range of each other using an indoor propagation model that considers the number of walls involved between any pair of nodes in the network. As mentioned in the introduction, it is difficult to extract physical connectivity paths from this figure alone, thus motivating the idea of PhyCon. Figures 12b and 13b show the number of *PCP*s detected by PhyCon over time using $t^{PCP}_{S_i-S_j} \leq 20$ s for scenario 1 and scenario 2, respectively. As it can be observed in these figures, all *PCP*s shown refer to available PCPs connecting static nodes in the network. In order to reduce the number of PCPs shown in the figures when no optimization of PCPs is applied (equation 4), we only show PCPs having a maximum length of $t^{PCP}_{S_i-S_j} \leq 20$ s. Applying the optimization method with $\alpha = 2$ on PCPs shown in Figs. 12b and 13b results in the PCPs shown in Figs. 12c and 13c, respectively. As it can be seen in these figures, long PCPs were replaced with shorter PCPs, resulting in physical paths having more intermediate nodes that provide more clues for mobile nodes to follow while moving on a particular PCP.

In order to compare the number of PCPs discovered by PhyCon we also implemented a brute force method in which all possible PCPs were found for $t^{PCP}_{S_i-S_j} \leq 20$ as time passed. Brute force method is based on the travel time required to move from one node to any other node in the network (at a defined speed) according to the corresponding layout. Figures 14a and 15a show PCPs using brute force with $t^{PCP}_{S_i-S_j} \leq 20$ for scenario 1 and scenario 2, respectively. Figures 14b and 15b show the number of PCPs detected by PhyCon and brute force over time using $t^{PCP}_{S_i-S_j} \leq 20$ for both scenarios. In these figures it can be observed that the rate of PCPs detected by PhyCon increases rapidly during the first 200 s of simulation time, slowing the rate afterwards. This behavior is basically the result of having no PCPs detected by PhyCon at the beginning of the simulation. Similarly, it can be observed that the number of PCPs discovered by PhyCon approaches 70–80 % of all existing PCPs obtained by brute force (without optimization). Non detected PCPs in PhyCon were the result of mobile nodes not passing close enough some static nodes in order to discover LOS conditions. Similarly, there is a smaller gap between the number of PCPs discovered by PhyCon and brute force for scenario 2 compared with scenario 1. This behavior is the result of having smaller rooms for Scenario 2, which make less likely that mobile nodes will miss detecting LOS with nearby static nodes as they move within rooms.

4.2 Testbed Experiments

For the implementation and testing of PhyCon, a WLAN was deployed on the third floor of the laboratory building mentioned in Sect. 3.1. The wireless network in this floor was composed by 16 static nodes (13 desktop PCs and 3 APs) and 13 nodes that occasionally move (laptops). All devices were equipped with 802.11g wireless cards and all desktop PCs and laptops were connected to one of the 3 APs available in that floor to connect to the internet. Laptop clients ran an implementation of PhyCon and were carried by students and professors collaborating in the project. 13 Sony Vaio PCG-71C11U laptops were used as mobile nodes equipped with Atheros AR9285 802.11g chipset. As mentioned before, PhyCon requires software utilities to interact with device drivers in order to retrieve information about RSSI values from wireless links as well as network information such as clients connected to a given AP, available WLANs (scanning) and data packets traveling over a network (sniffers). However, these utilities are independent of PhyCon, which can work with any software tool

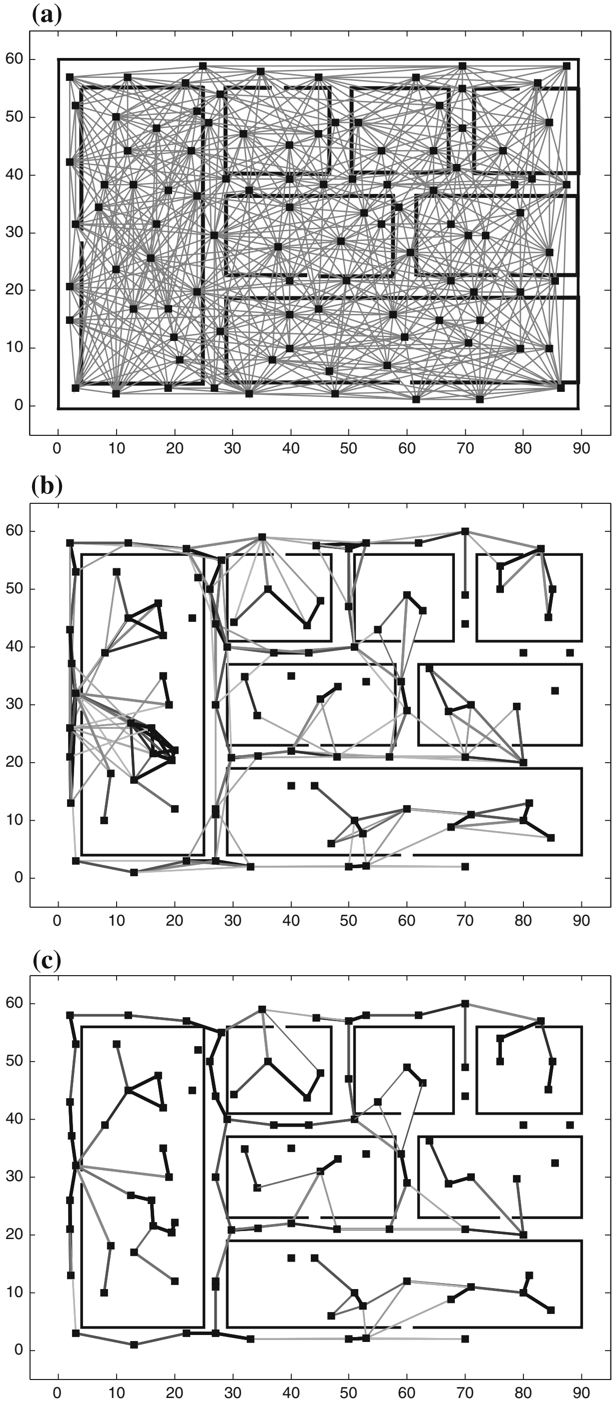

Fig. 12 Simulation of PhyCon method with 100 nodes using Scenario 1. **a** Radio connectivity graph. **b** PCPs detected by PhyCon. **c** PCPs detected by PhyCon applying optimization method

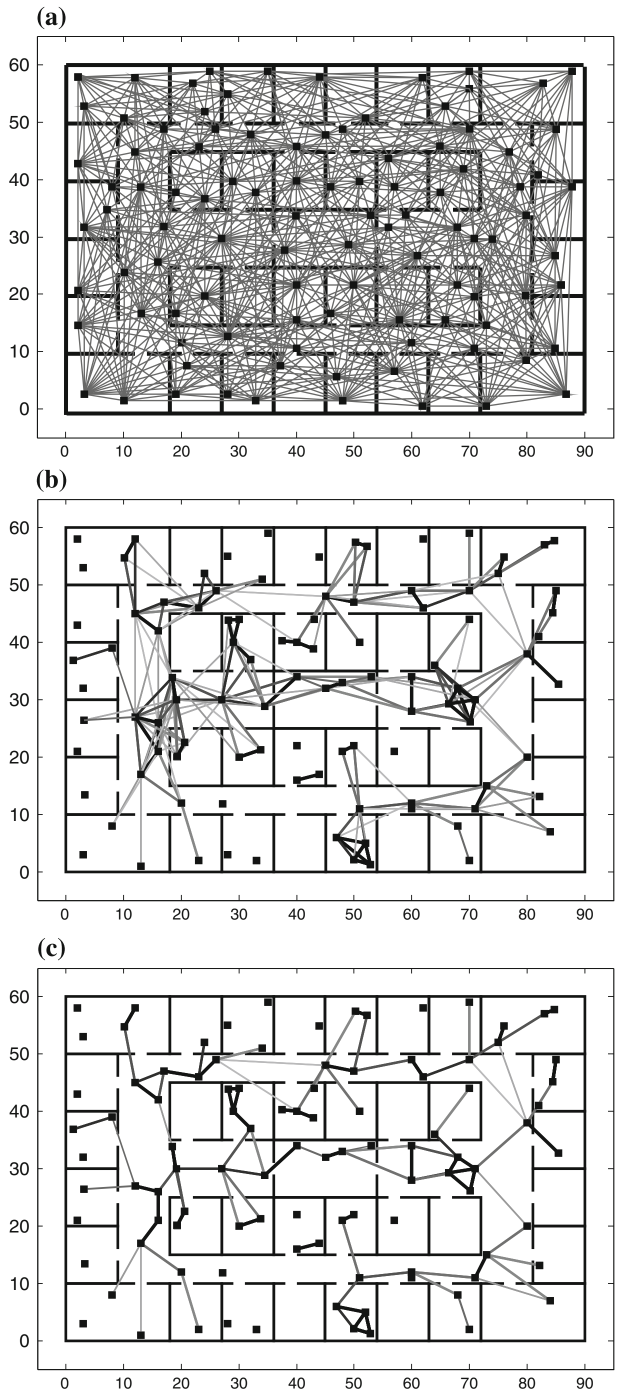

Fig. 13 Simulation of PhyCon method with 100 nodes using Scenario 2. **a** Radio connectivity graph. **b** PCPs detected by PhyCon, **c** PCPs detected by PhyCon applying optimization method

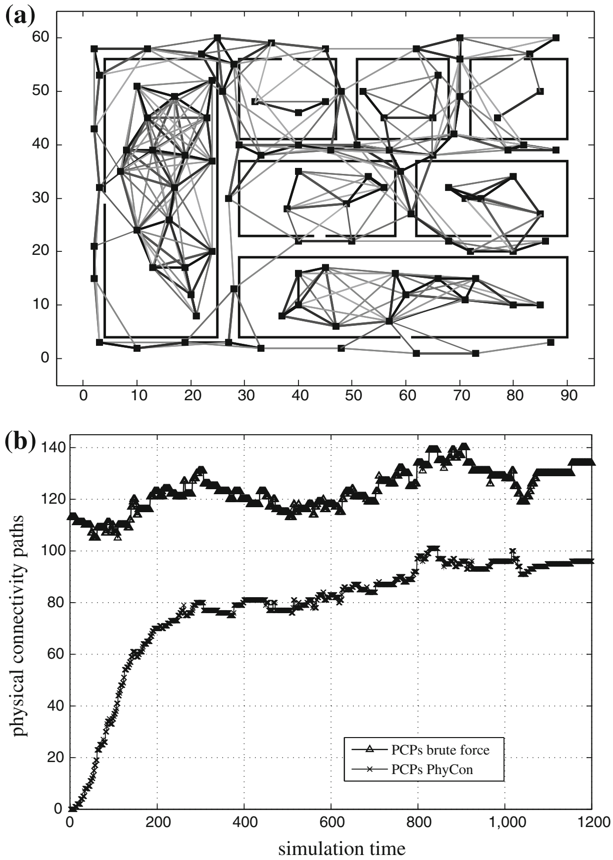

Fig. 14 Simulation of *PCP*s using Scenario 1. **a** PCPs detected by brute force. **b** PCPs PhyCon versus brute force

able to provide such information. To implement PhyCon on the mobile devices we used open source software detailed below.

- Linux Ubuntu version 8.04 with Wireless Tools 27+28 pre13-1Ubuntu2.
- Nmap version 4.53-3. Nmap used to determine which clients were available on the network.
- fping version 2.4b2. fping used to send ping packets to a certain number of targets.
- tcpdump version 3.9.8-2. tcpdump used to capture the traffic on the network.

The deployment of nodes in the network is shown in Fig. 16a. Access points are labeled as *AP*, whereas circles denote the rest of the nodes. During the experiments, mobile nodes conducted various movements within the building operating in active mode. It is important to mention that we use only normal mobility behavior of the students participating in the project over a period of 3 h. In the same way to Sect. 4, a maximum value of $t^{PCP}_{S_i - S_j} \leq 20$ sec was defined to reduce the number of PCPs shown in the figure. It can be observed that PCPs shown in Fig. 16a connect pairs of nodes according to available physical connectivity paths.

Figure 16b depicts filtered edges from Fig. 16a by using the PCP optimization method with $\alpha = 2$. Resulting PCPs in this figure represent either obstacle free paths (nodes in the

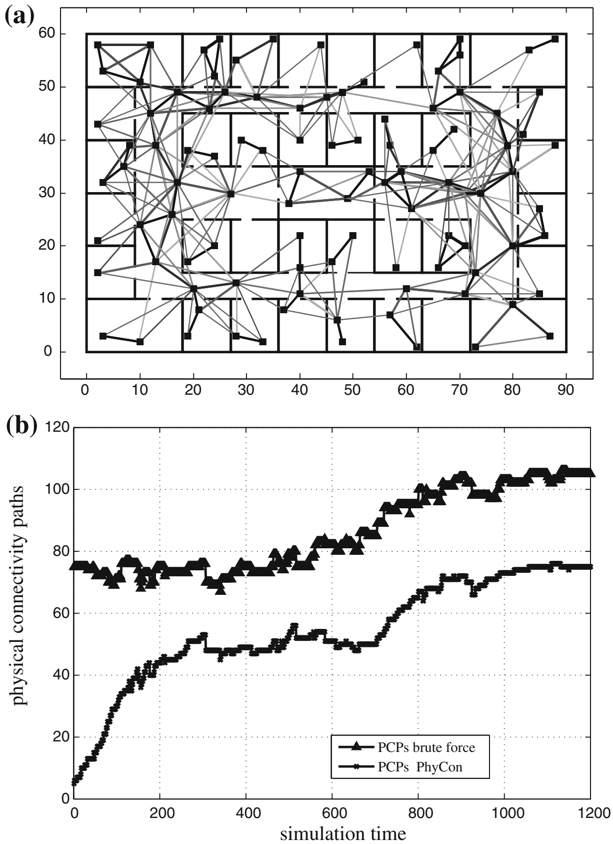

Fig. 15 Simulation of PCPs using Scenario 2. **a** PCPs detected by brute force. **b** PCPs PhyCon versus brute force

same room or corridor) or adjacent obstacle free paths where nodes are located in adjacent rooms and corridors with a common door or corridor between them.

5 Conclusions

In this paper we present PhyCon, a method capable of discovering physical connectivity paths (*PCP*s) among static nodes using only RSSI measurements and normal mobility behavior of nodes found in indoor wireless networks. PhyCon defines a range of RSSI values that can only be reached when a mobile node passes close enough of a static node, thus temporarily establishing LOS conditions. We show that the time interval between consecutive LOS detections by a mobile node enables PhyCon to discover PCPs between static nodes. These PCPs will provide guiding means to allow other mobile nodes to reach other nodes in the network not only through open spaces, but also through a path that might include corridors, turns, doors, etc. PhyCon also introduces an optimization method to discard long PCPs and replace them with shorter PCPs by introducing intermediate nodes in line of sight along the original long PCP. Performance results both in a simulator and in a testbed indicate PhyCon can detect a high percentage of PCPs using normal mobility behavior of nodes

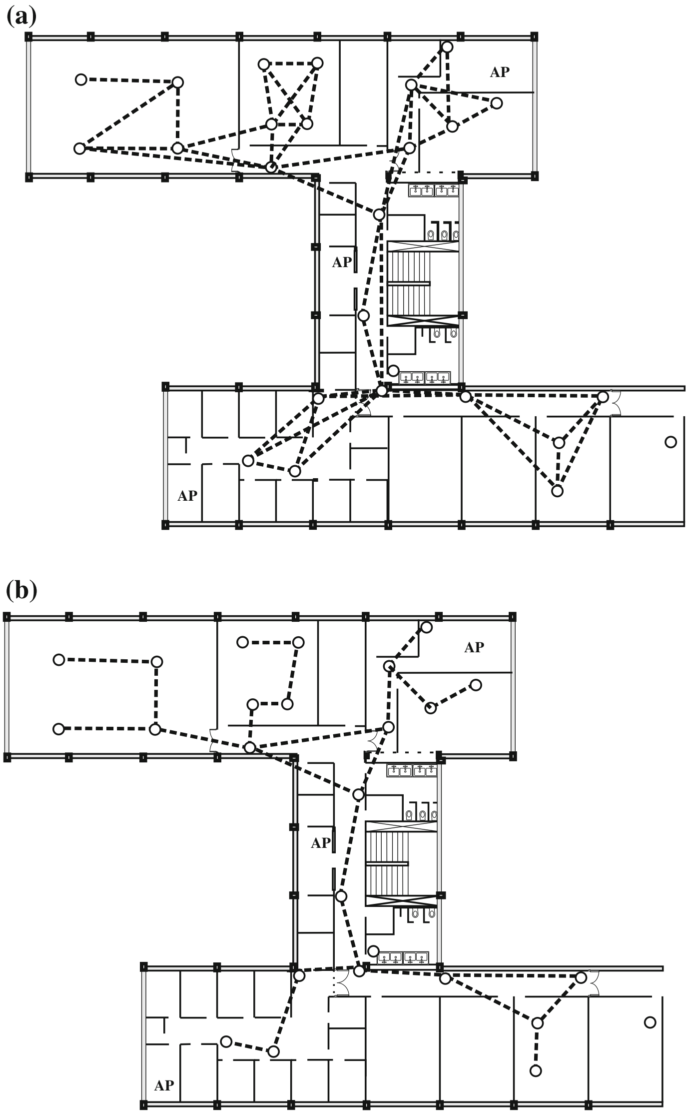

Fig. 16 PhyCon testbed experiments. **a** Physical connectivity paths detected by PhyCon. **b** Physical connectivity paths filtered using $\alpha = 2$

found in indoor wireless networks. To the best of our knowledge there is no related work in the literature dealing with this type of physical routing, which we consider is a key factor for developing future applications in indoor networks such as guiding, localization, tracking, etc.

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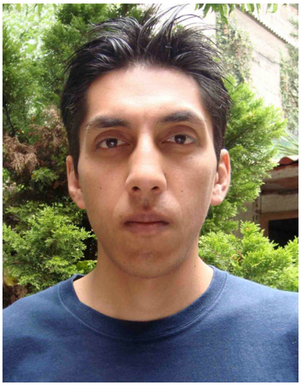

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