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GUIDE-gradient: A Guiding Algorithm for Mobile Nodes in WLAN and Ad-hoc Networks

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Abstract Whereas there is a lot of work related to finding the location of users in WLAN and ad-hoc networks, guiding users in these networks remains mostly an unexplored area of research. In this paper we present the concept of node-to-node guidance and introduce a method that can be used to implement it. This method relies on the computation of a local gradient in the neighborhood of the moving node. We named this protocol GUIDE-gradient, which is a GPS-free and infrastructure-free node-to-node guiding system. In this paper we also discuss how the guiding algorithm can be generalized to node-to-node guidance in multihop ad-hoc networks.

Keywords Ad-hoc · Gradient · Guidance · RSSI · Signal quality · WLAN

1 Introduction

The WLAN IEEE 802.11 (WiFi) standard is one of the great technology success stories of the past decade. Used in research labs a decade ago, WiFi technology is now in a position where it has become as popular as cellular telephony. WiFi has even become the preferred last-mile

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technology of the Internet. Off-the-shelf laptops, PDAs and high-end cellular phones are now usually equipped with WiFi radios. At the same time, metropolitan coverage with WLAN networks is beginning to be deployed, letting WiFi users to roam freely across large areas.

In this paper we consider that the wide availability of WiFi devices enables other possible applications beyond data transmission. We introduce the concept of node-to-node guidance for WiFi equipped devices. Guidance would allow WiFi equipped nodes or users to obtain guiding directions in order to get closer to other WiFi equipped devices. As it will be described below, this concept can be applied to both, WLAN and ad-hoc scenarios.

Guidance, in general, and node-to-node guidance, in particular, remain mostly unexplored areas of research in WLAN and ad hoc networks. Nevertheless, we believe that there are several potentially useful node-to-node guiding applications not available to WiFi users today. For instance, we can consider a user that is currently connected to an access point (AP) at 2 Mbps. Such a user can use a guiding system in order to move closer to the AP and achieve a connection at a higher data rate. In another example, a user printing a document over the air to a WLAN-equipped printer can use a guiding system to get closer to the printer to pick up the print out. Rescue personnel can use a guiding system in order to get closer to a person needing assistance, if that person is carrying a WiFi device. Applications may be as simple as a situation where a WiFi user may just want to get closer to another user.

While in many of these situations the human eye could provide better and simpler guiding means, there are various scenarios where there is a need for an automatic guiding system. For instance, the presence of some obstacles may not allow a user to establish visual contact with another user. In case the target node is not a human but a machine (e.g., APs, robots and printers), the use of an automatic guiding system becomes mandatory. A guiding scenario that requires special attention is the one corresponding to a situation when users are located far away from each other. In this case a large distance may not allow visual contact even when no obstacles are present.

We believe that one reason why there has not been much attention from the research community toward developing guiding systems for WLAN and ad-hoc networks is because developing such systems, from a pure research perspective, appears trivial once a good localization method is available. We argue, however, that most localization systems available today are based on specialized or dedicated infrastructure (e.g., GPS or various APs). This dependency has, in fact, significantly reduced their availability to the larger public since not all mobile devices are currently equipped with global positioning systems, or there might not be enough APs in the area. Furthermore, as it will be detailed below, not all localization systems reported in the literature are suitable to be used as the core of a guiding system.

Before getting into the details of the proposed guiding methods, we now list what we believe should be the desired characteristics of a guiding system in order to make it available to the larger public for both, WLAN and ad hoc networks.

- It should operate with off-the-shelf hardware. In order to avoid extra costs we need a system that does not need extra hardware. In contrast, WiFi is already incorporated in all laptops, most PDAs and many high-end cellular phones.
- It should work everywhere in a distributed fashion. The use of a centralized system cannot be considered because this would limit its availability, fault tolerance and scalability.
- It should minimize the effort needed to reach the target node. By this we mean that the spent time and traveled distance, while closing the distance to the target node, should be the minimum. Ideally, we would like the system to guide users on a rectilinear trajectory pointing directly to the target node.

– It should work with as few as two nodes. We want the guiding system to work even if the moving and target nodes are the only nodes in the network.
– It should require a minimum intervention of the target node. It is desirable that the target node/user remains as passive as possible during the guiding process. Also, there should not be a need to run any extra piece of software in the target node.

GUIDE is a GPS-free and infrastructure-free node-to-node guiding system for WLAN and ad-hoc networks that is built around the desired characteristics described before. Opposite to other potential guiding systems that could be built on top of a localization system, in GUIDE wireless nodes may not know or need to know their absolute location. GUIDE is based on real-time measurements of parameters related to the state of the wireless link. Such readings come from a standard wireless card and are used in order to provide users with real-time instructions about the required changes in direction that need to be applied in order to get closer to the target node. Although various algorithms can be used to obtain guiding directions from link-state measurements, in this paper we focus on a gradient-based method that consistently provided good results. We call this approach GUIDE-gradient.

The rest of the paper is organized as follows. Section 2 presents an overview of different localization systems that could be used in the development of guiding systems. In Sect. 3 we describe the different parameters that can be obtained from a standard wireless card and we also discuss how they can be used in guiding systems. In Sect. 4 we describe GUIDE-gradient and in Sect. 5 we describe its implementation in a Linux box. In Sect. 6 we describe the experiments that were conducted and the obtained results. In Sect. 7 we describe some practical considerations. In Sect. 8 we describe how this work can be generalized to the multihop ad hoc network case. Finally, in Sect. 9, we present our conclusions and ideas for future research.

2 Related Work

Beyond GPS-based guidance, which is discussed later in this section, there are not many examples of guiding systems for WLAN and ad-hoc networks in the literature. However, there are various localization systems that could be used as the core of a guiding system. We now review some of these systems.

Angle of Arrival (AoA) is a technique in which a special receiver can measure the angle on which the signal is picked up from a specific transmitter. These measurements typically take place at the base station where arrays of directional antennas can determine the angle of arrival [1].

Time of arrival (ToA) [2] and Time Difference of Arrival (TDoA) [3] estimate distances by measuring the propagation time of a radio wave traveling from the transmitter to the receiver. ToA and TDoA techniques need tight clock synchronization for accurate distance estimation. The fact that propagation times in WLAN are in the order of hundreds of nanoseconds makes it hard to accurately estimate distances using off-the-shelf WLAN hardware (e.g., a one-microsecond discrepancy represents an error of about 300 m).

Localization systems based on distance estimation are based on measurements of received signal strength (RSSI) [4,5]. RSSI measurements are used, in combination with knowledge about transmitted power and a propagation model to estimate the distance between a transmitter and a receiver. Similar to ToA and TDoA techniques, measurements of signal strength from various receivers and triangulation techniques can be used to reduce the uncertainty of the node's location. Generally, the accuracy of these techniques is as good as the propagation model being used. A drawback of distance-based systems is that the transmitted signal is affected by several factors which are difficult to incorporate in a propagation model. Such factors can be, for instance, diverse obstructions, moving objects, the height and orientation of the antennas, etc. For this reason some proposals for localization systems that are based on received signal strength are based on experimental propagation maps that are obtained beforehand.

The global positioning system (GPS) [6] may appear as the most appealing candidate to implement guiding systems. The GPS system is based on TDoA techniques using various satellites in order to estimate the location of a GPS ground device. Although GPS may be used to implement a highly accurate localization system, it has several drawbacks. First, we need both, the target and moving nodes be equipped with GPS hardware plus a radio link to communicate their coordinates to each other (i.e., cellular or WLAN radios). This fact alone disqualifies GPS for our purposes. Second, GPS receivers substantially increase power consumption in a mobile device. Although it varies according to the manufacturer, a GPS device may continuously drain 50–200 mW from the battery. Finally, GPS remains an add-on device that needs to be bought separately, thus reducing deployment possibilities and increasing costs.

One work worth mentioning is the one recently presented in [7]. In this proposal a mobile node combines both, GPS location data as well as RSSI information in order to estimate the location of an access point. The position estimation is similar to GUIDE-gradient, but its objective and methods are quite different to the system herein described. Furthermore, the use of a GPS device puts this work in a different category compared to GUIDE, which is a GPS-free system.

We observe that guiding solutions based on GPS are not a practical alternative in the context of the node-to-node guiding system that we envision because of various factors. Other techniques based on AoA or experimental propagation maps could provide good and cheap localization, but they require either special hardware or dedicated infrastructure to work properly. Similarly, ToA and TDoA techniques cannot be considered for guiding purposes given the time scale of propagation times in WLAN networks. We conclude that in order to make a guiding system available to the larger public, it is necessary to use off-the-shelf WiFi radios which are already available in many commonly used mobile devices.

3 Standard 802.11 PHY Layer Information

3.1 Channel Status Information

In this section we describe different parameters related to the status of the wireless channel and discuss their potential use in the implementation of a node-to-node guiding system. Since we are only interested in using standard WiFi hardware, we review the parameters whose measurements can be obtained from a standard 802.11 wireless card.

Signal strength. The energy level observed during the last protocol data unit (PDU) reception is reported by means of a parameter known as received signal strength indicator (RSSI). In the 802.11 standard the only restriction on the RSSI values is that there must be a minimum number of levels ranging from 0 to RSSI_Max. This laxity has a number of implications. First, although RSSI is usually a one-byte long parameter (i.e., its value could be somewhere between 0 and 255), chip vendors can choose a convenient value for

RSSI_Max and in practice the full range is not used. Second, chip manufacturers can also choose an appropriate range of signal strength that will be mapped to the set of RSSI values. Third, the quantization step can also be conveniently chosen and it does not need to be constant along the whole range of RSSI values.

As a consequence of the freedom provided by the standard, RSSI readings coming from different chipsets cannot be compared. However, the intended use of this parameter does not need a specific correspondence between its values and the levels of signal strength. RSSI values do not need to be of fine granularity or high precision either. This is due to the fact that the parameter is used in a relative manner, which is enough to carry out the intended tasks. For instance, one vendor may choose an appropriate RSSI value as a threshold in order to determine whether the channel is clear or not.

One more issue worth mentioning is that wireless cards are not usually able to measure a signal strength above 1 mW [8]. The rationale behind this design is that although transmit power can be dozens of times higher, this level of signal strength is good enough to provide connectivity at the highest possible data rate. This means that once the card detects 1mW or higher values, it will show 100% signal strength regardless of how stronger the actual signal is.

Signal quality Signal quality (SQ) is another metric mentioned in the 802.11 (1999) standard. A precise definition of the term is not provided; but it is specified that SQ is related to the DSSS PN code correlation and its value is updated each time a code lock is achieved. Lack of further specifications means that specific implementation details are likely to differ among different chip vendors. Although the specification given by the standard only applies to the DSSS modulation scheme, wireless cards also report readings of signal quality when they transmit using a different modulation technique. Since implementation details are proprietary information, we can only speculate that those values are related to the average correlation between the transmitted and received symbols. In any case, the lack of precise definitions is not a serious issue since the SQ readings are also used in a relative manner.

Data rate The 802.11 standard makes use of adaptive modulation in order to take into account current channel conditions in the transmission process. In this way, high data rates can be achieved at short distances where the signal is strong enough, whereas more-robust-but-lower-rate transmission schemes are used for longer distances. This relation between data rate and distance can help to estimate the relative position of a wireless station. However, each vendor is likely to use different algorithms for rate control so that the association between data rate and distance cannot be generalized for all WiFi chipsets.

3.2 Experimental Maps

In order to determine which metric has the highest potential to be used as the core component of the guiding system, we considered important to study the behavior of each metric in the vicinity of a target node. For this purpose, we created detailed maps of the three metrics

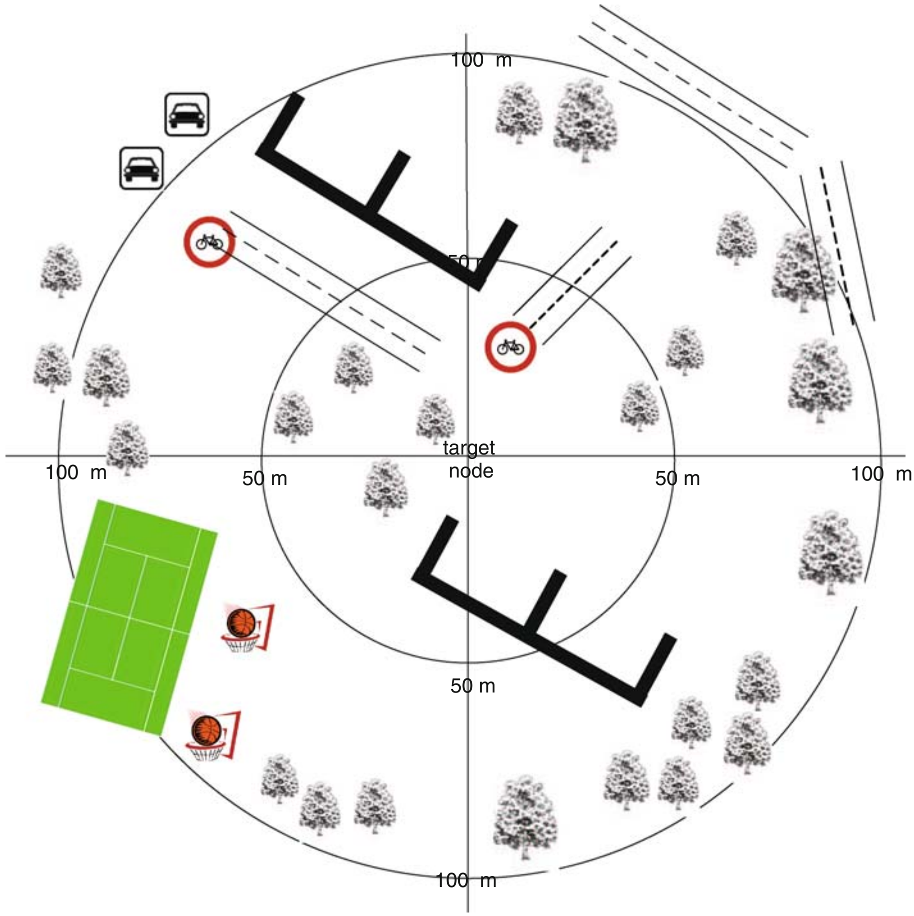


Fig. 1 Sketch of the experimental area

around a target node. The place we selected for these experiments was a semi-open esplanade in our university campus where trees, people and buildings are scattered in the area. Since the propagation maps change depending on the characteristics of each location, the purpose of doing these experiments is only to gather a general look at the guiding problem.

A schematic view of the experimental area is shown in Fig. 1, and an aerial photo in Fig. 13. The two rectangular constructions correspond to two *fronton* courts with thick tall walls. In order to build the associated map for each metric, we positioned the target node (a WiFi equipped laptop) in a central location of the experimental area as shown in Fig. 1. We then positioned a moving node (another user carrying a laptop) at different locations within a square of (200×200) m^2 centered at the target node. We took samples every 5 m in order to construct a map for RSSI, signal quality and data rate. Each map consisted of 1,600 measurements taken at different locations of the experimental area. Given the observed variability of each metric, even at the same location, we took several samples of the metric in order to get an average value at each point in the map.

Figures 2, 3, 4 show the resulting maps for signal quality, RSSI and data rate, respectively. The X-Y plane of these figures corresponds to the experimental area and the Z axis to the

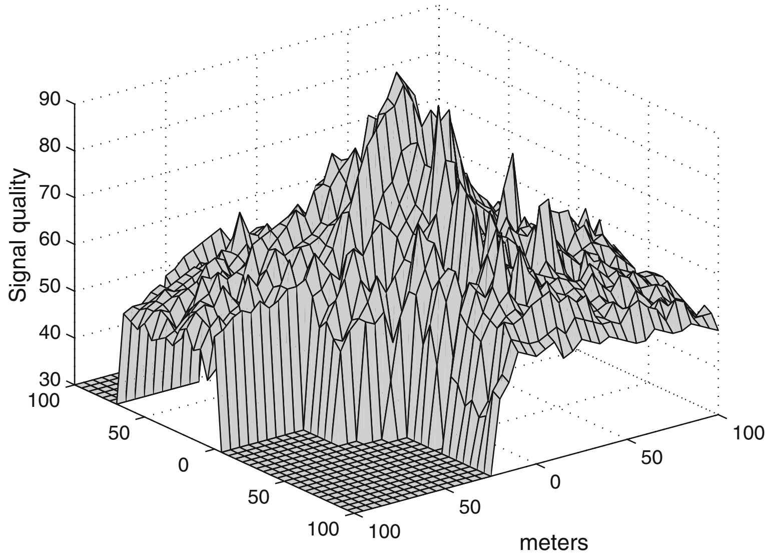


Fig. 2 Signal quality map

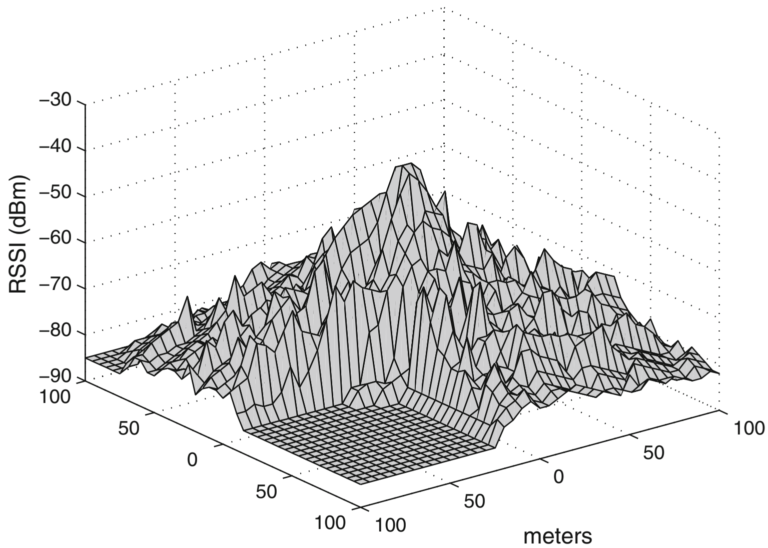


Fig. 3 RSSI map

value of the metric at each point. For comparison purposes, we selected a 60-unit scale for the vertical axis in all three maps. By looking at Figs. 2, 3, 4 it can be observed that there is some general behavior observed for all three metrics. First of all, they present, as expected, a maximum value of the metric at the location of the target node, and the value of the metric decays as we move away from it. All three maps exhibited blind spots behind the *fronton* walls, where slow fading conditions blocked even the minimum reception.

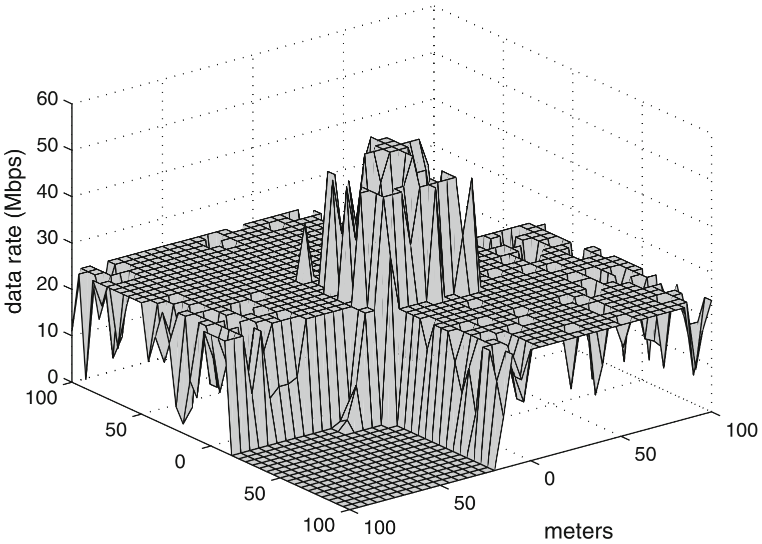


Fig. 4 Data rate map

We note that unlike RSSI and signal quality maps that look similar to the eye, data rate measurements show large areas where there was no variation in the measured data rate. To highlight this point, we show in Fig. 5 level-like data-rate curves from a top view of the data rate map. This behavior has direct guiding implications because it means that even large movements of the moving node may not translate into changes of the measured data rate, thus providing no new information about in which direction to move. For instance, a node roaming in the 24 Mbps region can potentially walk a long distance before it gets a different data rate reading. Similarly, once a node reaches the 54 Mbps region, it is basically blind and has no other guiding means to get closer to the target node. We consider that after looking at Figs. 4, 5 the observed behavior reduces the usefulness of data rate as a candidate for a guiding system and it will not be considered any further.

Looking now at the maps of signal quality and RSSI shown in Figs. 2, 3 we can observe that they are quite similar, with signal quality having a larger maximum value than RSSI. Both maps show a lot of variability from point to point, and they also present various points with local maximum values. Having a high variability, as we will see later, is helpful for guiding purposes because even small movements result in different readings of the metric, however the presence of local maximums will also turn out to be the most difficult problem to solve in the design of efficient guiding systems.

4 A Guiding Algorithm for WLAN Users

As mentioned before, we consider that a key characteristic of a guiding system to be widely accepted and used by wireless users is that it is built on top of standard hardware. It should not require added hardware or dedicated infrastructure to work properly. At the same time, it should not require significant intervention of the target node and its implementation should not originate extra costs. In this section we describe GUIDE-gradient, a guiding system that is built around all these premises.

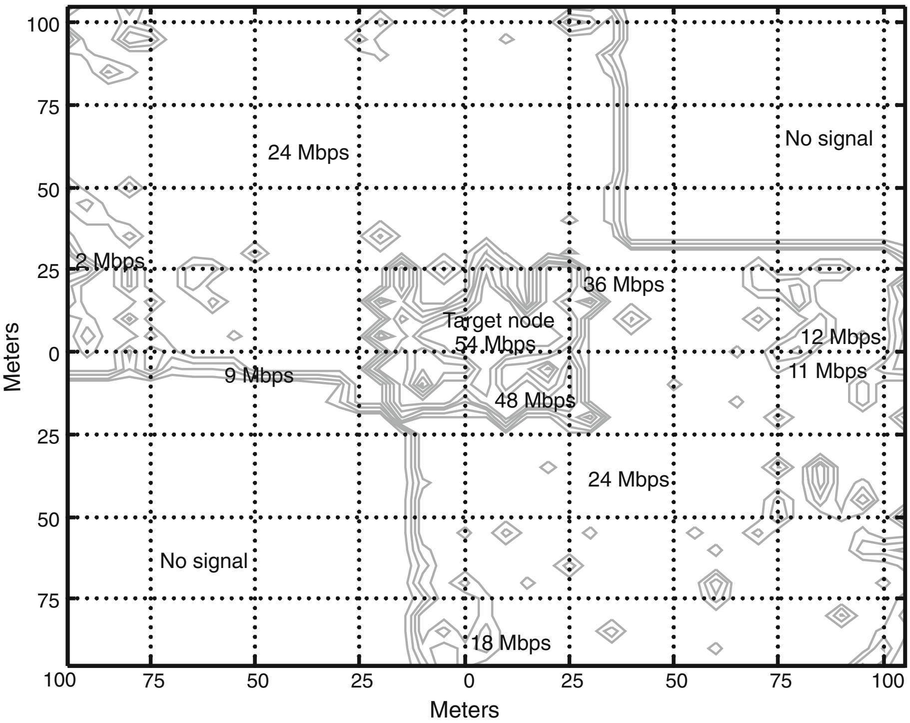


Fig. 5 Experimental propagation map

There might be many ways to tackle the guiding problem. A straightforward one is to use distance estimation and triangulation in order to estimate the target's position. Another approach is to try to determine a vector pointing toward the target node (i.e., a gradient vector). We initially considered both methods, but the gradient-based approach consistently yielded the best results. Consequently, we focus on the gradient-based technique which is fully described and evaluated in the following sections. The interested reader is referred to [9] which contains the description of a guiding method based on distance estimation and some early comparisons with the gradient-based approach.

4.1 GUIDE-Gradient

In this section we describe GUIDE-gradient which does not require any localization means to operate.

4.1.1 The Core of the Algorithm

The derivation presented here assumes that the behavior of a proximity criterion (i.e., RSSI or signal quality) can be modeled using a smooth surface, with only one maximum located at the target node's location. At least this model should reasonably hold in open spaces where there are not many obstructions that could produce significant signal reflections.

The basic idea behind GUIDE-gradient is to determine an empirical gradient vector that points towards the position that corresponds to the maximum of the surface. A mobile user

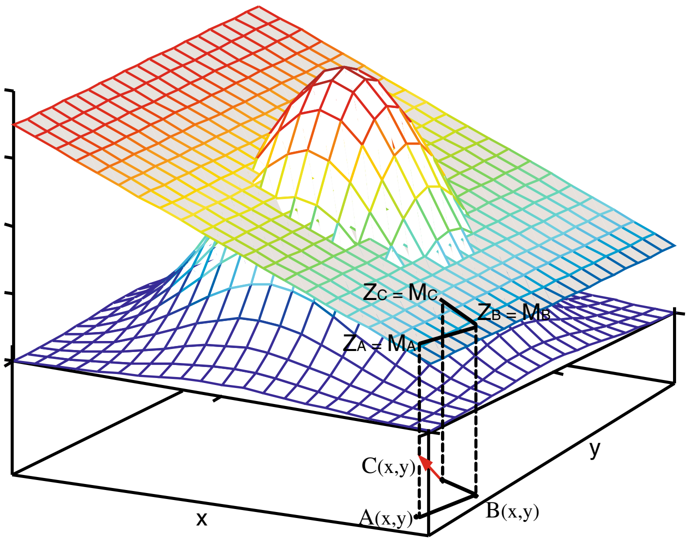


Fig. 6 Gradient approximation using the last three non-collinear measurements

can use this direction in order to get closer to the target. To this end, there are many possible ways to compute a gradient (e.g., [7, 10]). As it will be explained below, we propose to use three non-collinear measurements in order to compute an approximation of the gradient in the neighborhood of the sampling points. This method is illustrated in Fig. 6 where the shown surface serves for illustration purposes only.

Let us consider a situation where, as a result of its last two movements, the trajectory followed by a mobile has the shape of an equilateral triangle. Let us also consider that measurements of a proximity criterion were taken at its vertexes. Let us denote by $A = (x_A, y_A)$, $B = (x_B, y_B)$ and $C = (x_C, y_C)$ the vertexes of the triangle and by M_A, M_B and M_C the corresponding measurements. Assume that A was the initial position and C the final one. Thus, after two non-collinear movements we have the following three triplets (x_A, y_A, M_A), (x_B, y_B, M_B) and (x_C, y_C, M_C).

In order to determine the gradient vector let us start by considering that in the three-dimensional space X–Y–Z (dimension Z corresponds to the measurements) there exists a plane which is completely defined by the three triplets just mentioned. The equation of such a plane in its usual form is given by $ax + by + cz = 1$. Solving this equation for z yields

$$z = \frac{1}{c} - \frac{a}{c}x - \frac{b}{c}y \tag{1}$$

and applying the ∇ operator results

$$\nabla z = -\frac{a}{c}\hat{i} - \frac{b}{c}\hat{j}. \tag{2}$$

The gradient vector given by (2) points towards the position in the X–Y plane corresponding to the maximum of the surface. Therefore, it can be used to determine the direction of the next movement. However, in early experiments we realized that it did not make sense to determine this vector with high accuracy since a human would not be able to follow guiding directions below 30° in practice. As a result of this limitation, we decided that it was not necessary to compute the gradient with such a fine granularity, and we performed the quantization procedure described below.

Let us denote by $\overrightarrow{AB}$, $\overrightarrow{BC}$ and $\overrightarrow{AC}$ the displacement vectors considering the movements from A to B, B to C and A to C, respectively. Let us consider the dot product between the gradient and each one of these displacement vectors, but let us take into consideration only whether the result was positive or negative. As an example, let us review which conditions satisfy the following inequalities,

$$\nabla z \cdot \overrightarrow{AB} < 0, \tag{3}$$

$$\nabla z \cdot \overrightarrow{BC} > 0 \quad \text{and} \tag{4}$$

$$\nabla z \cdot \overrightarrow{AC} < 0. \tag{5}$$

The gradient will have a positive projection on a displacement vector if the angle between them is in the interval $[-90°, 90°]$. Therefore, the solution region to the system of simultaneous inequalities (3)–(5) can be found as the overlapping of three half planes (see Fig. 7). This region contains all gradients that satisfy conditions (3)–(5) and the quantization procedure consists in representing this set with a single quantizing vector. Other conditions regarding the sign of the dot product between the gradient and the displacement vectors lead to other solution regions and other quantizing vectors.

Now consider Inequality (3), it can be expanded as

$$\left(-\frac{a}{c}\hat{i} - \frac{b}{c}\hat{j}\right) \cdot ((x_B - x_A)\hat{i} + (y_B - y_A)\hat{j}) < 0, \tag{6}$$

which can also be written as

$$-\frac{a}{c}(x_B - x_A) - \frac{b}{c}(y_B - y_A) < 0 \tag{7}$$

or

$$\left(\frac{1}{c} - \frac{a}{c}x_B - \frac{b}{c}y_B\right) - \left(\frac{1}{c} - \frac{a}{c}x_A - \frac{b}{c}y_A\right) < 0. \tag{8}$$

From (1) we can observe that (8) is equivalent to the condition $M_B - M_A < 0$. Proceeding in a similar way for (4) and (5) we can conclude that the set of inequalities (3)–(5) is equivalent to

$$M_B - M_A < 0 \tag{9}$$

$$M_C - M_B > 0 \tag{10}$$

$$M_C - M_A < 0 \tag{11}$$

This result enormously simplifies the computations since it implies that we only need to check the sign of three differences in order to determine whether the gradient lies in a region or not. Once the region where the gradient lies is found, the corresponding quantization vector can be assigned.

With the method just described we can obtain a quantized gradient that points towards the maximum. This vector, however, is given in terms of its $X-Y$ components. It turns out to be more convenient to give the direction of the next movement is in terms of the angle between the quantized gradient and the direction of the last movement (which is given by vector $\overrightarrow{BC}$). This angle can be easily computed from their dot product, i.e.,

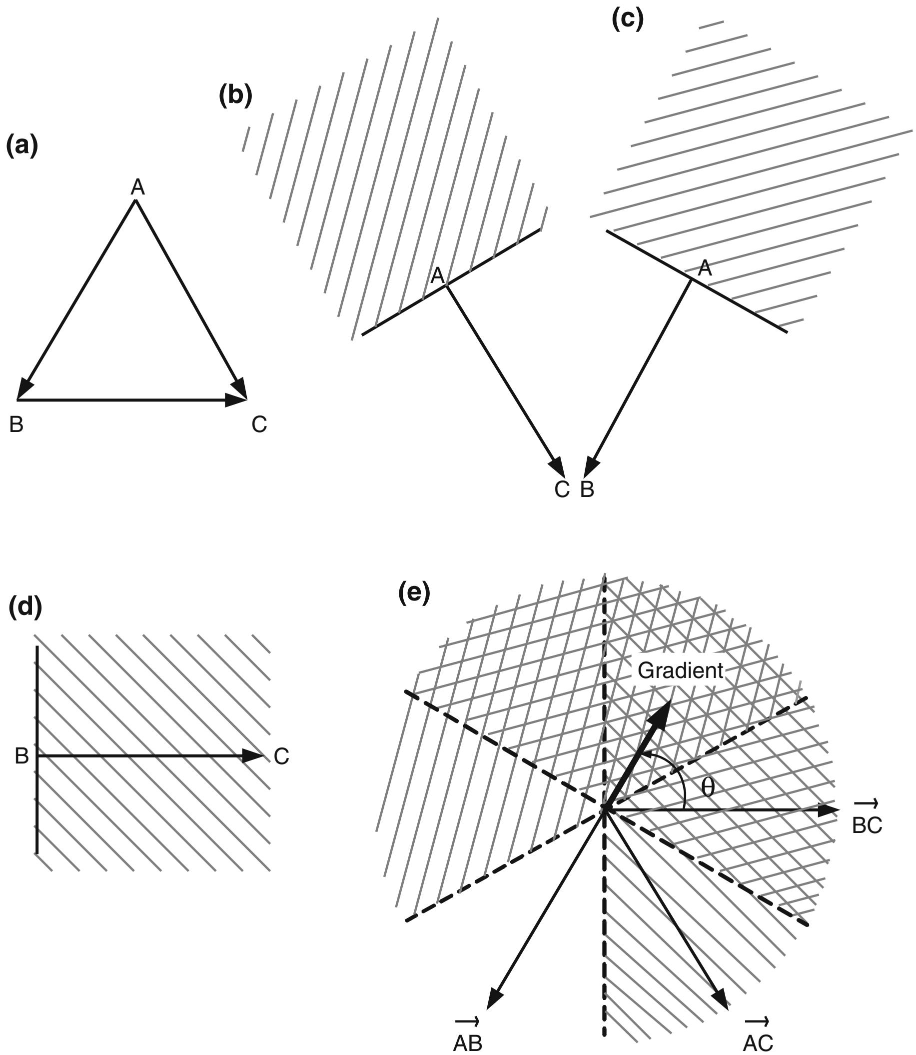


Fig. 7 **a** Displacement vectors, **b** region $\nabla z \cdot \overrightarrow{AC} < 0$, **c** region $\nabla z \cdot \overrightarrow{AB} < 0$, **d** region $\nabla z \cdot \overrightarrow{BC} > 0$ and **e** the solution region and the corresponding quantizing vector

$$\cos\theta = \frac{\nabla z \cdot \overrightarrow{BC}}{\mid \nabla z \mid\mid \overrightarrow{BC} \mid}. \tag{12}$$

4.1.2 The Guiding Algorithm

We introduce GUIDE-gradient, a guiding algorithm based on the following three basic movements: (a) if after a movement the proximity criterion improved, then the mobile can continue ahead without trajectory changes, (b) if the criterion remained the same, then the mobile is commanded to randomly turn 60° clockwise (CW) or counterclockwise (CCW) and, (c) if

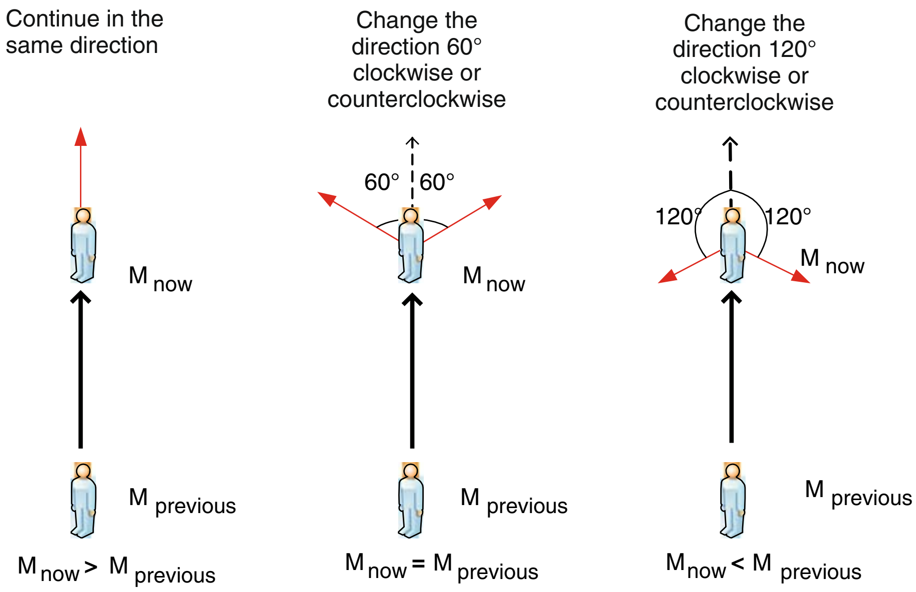


Fig. 8 Trajectory decisions in GUIDE-gradient. The variables M_{now} and M_{previous} stand for the current and the previous measurements, respectively

the criterion worsened, then the mobile is commanded to turn 120° and move again in order to create an equilateral triangle (in fact, as depicted in Fig. 10, two triangles can be created) and use the result described in the previous section in order to find the direction of the next movement. Figure 8 illustrates the three situations.

It is worth mentioning that we selected to move 60° when the value of the metric was the same in the current and previous locations, and move 120° when the value of the metric was higher at the current location compared with the previous location. These decisions will create evenly distributed sampling points as illustrated in Fig. 9.

In what follows we describe how all these elements are put into practice in the guiding algorithm.

GUIDE-Gradient Algorithm

Inicialization.

- Measure M_A.
- Move straight c meters in a randomly chosen direction. Measure M_B.
- Randomly turn 120° CW or CCW. Move straight c meters. Measure M_C.
- Use the turning direction selected in the previous step and $\{M_A, M_B, M_C\}$ in order to find the the direction of the next movement by looking up the corresponding entry in Table 1.

Loop:

- Move straight c meters. Do $M_A \leftarrow M_B$ and $M_B \leftarrow M_C$. Measure M_C.
- Compare M_C and M_B. The following cases are possible:
- Case $(M_C \geq M_B)$
  There is no change of trajectory.

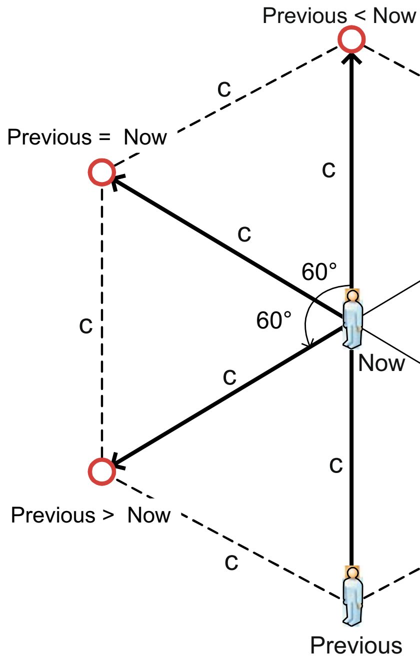


Fig. 9 Spatial distribution of the sampling points

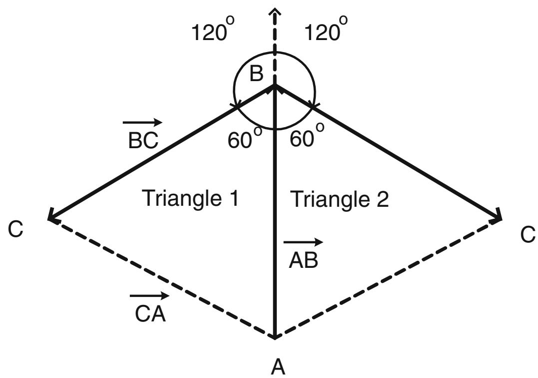


Fig. 10 Virtual *triangles* created with three non-collinear measurements

– Case ($M_C == M_B$)
Randomly turn 60° degrees CW or CCW.
– Case ($M_C \leq M_B$):
Randomly turn 120° CW or CCW. Move straight c meters. Do $M_A \leftarrow M_B$ and $M_B \leftarrow M_C$. Measure M_C.
Determine the new moving direction from Table 1.
– Go back to *Loop* if the target has not been reached.

We implemented the guiding system based on the described algorithm. The corresponding implementation details and experimental results are reported in the following section.

Table 1 Action at point C

$M_B - M_A$	$M_C - M_B$	$M_C - M_A$	Action
(a) Triangle 1 of Fig. 10*			
+	+	+	60° CW
+	+	−	**
+	−	+	120° CW
+	−	−	180°
−	+	+	0°
−	+	−	60° CCW
−	−	+	**
−	−	−	120° CCW
(b) Triangle 2 of Fig. 10*			
+	+	+	60° CCW
+	+	−	**
+	−	+	120° CCW
+	−	−	180°
−	+	+	0°
−	+	−	60° CW
−	−	+	**
−	−	−	120° CW

* Notation: M_A, M_B and M_C denote the value of the metric measured at points A, B and C, respectively
** These cases never happen, when $C > B > A$ it is not possible that $C < A$ and if $C < B < A$ it is not possible that $C > A$

5 Implementation of GUIDE-Gradient

For the implementation and testing of the GUIDE-gradient we used a Toshiba Tecra $A5$ laptop running Ubuntu (kernel 2.6.15–23–386) with an Intel PRO/Wireless 2200BG 802.11 g wireless card. We used Java to implement the application.

GUIDE-gradient makes us of the Linux Wireless Extensions and Wireless Tools [11] to interact with the device driver and retrieve low level information about statistics of the wireless connection (i.e., data rate, signal strength (RSSI) and signal quality), these values are collected by the guiding system at every test point.

Because of slow fading effects we found high variability of the measurements even at the same location. We decided that the guiding system should take several samples at each point until the standard deviation does not change significantly with additional samples. Once the standard deviation stabilizes, we consider the average value of the collected samples to be the representative single value of that test point. We found that the number of samples required for the standard deviation to stabilize was different depending of the scenarios, the distance and the metric being measured. To illustrate this phenomenon we placed two laptops separated by a certain distance and took several samples of signal quality and RSSI. We repeated this experiments for different distances. Figure 11(a–d) show how the time average for the standard deviation converges as the number of samples increases.

Figure 11a, b refer to tests with a 20 m separation using signal quality and RSSI metrics, respectively. For instance, we can observe for both figures that the value of the standard

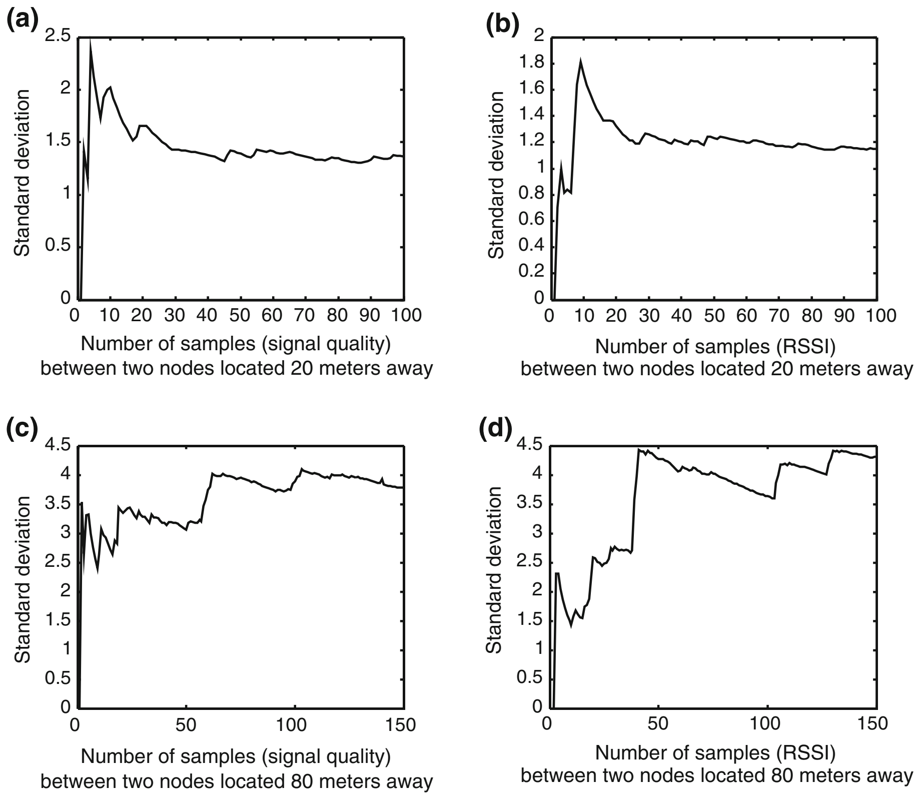


Fig. 11 Standard deviation of signal quality and RSSI between two nodes located 20 and 80 m away of each other

deviation begins to be stabilized after 30 samples. So, after that number of samples we can use the average value of the metric as a representative value. When the distance between the two nodes increases, e.g., 80 m, the standard deviation requires more samples before it stabilizes (see Fig. 11c, d). We theorize that this behavior occurs because the increased distance makes the received signal weaker at the receiver, therefore more suitable to be affected by noise, interference, the environment and moving objects.

Although GUIDE-gradient makes several measurements before calculating a new direction, the user does not notice the delay, since these measurements happen within a second or two. Guiding indications are provided to the user by means of graphical indications and prerecorded voice commands. We observed that, for the average user, the indications provided by the system were easier to follow if we used the familiar image of a clock instead of a scale in degrees. In Fig. 12 we provide a snapshot of the graphical user interface. The interface shows an example of a test area of slightly more than 4,000 m^2.

6 Experiments and Results

6.1 Real Guiding Experiments

The GUIDE-gradient graphical user interface makes use of a satellite image for illustration purposes only. Such image plays no role in the operation of the system. In all guiding

Fig. 12 GUIDE-gradient graphical user interface

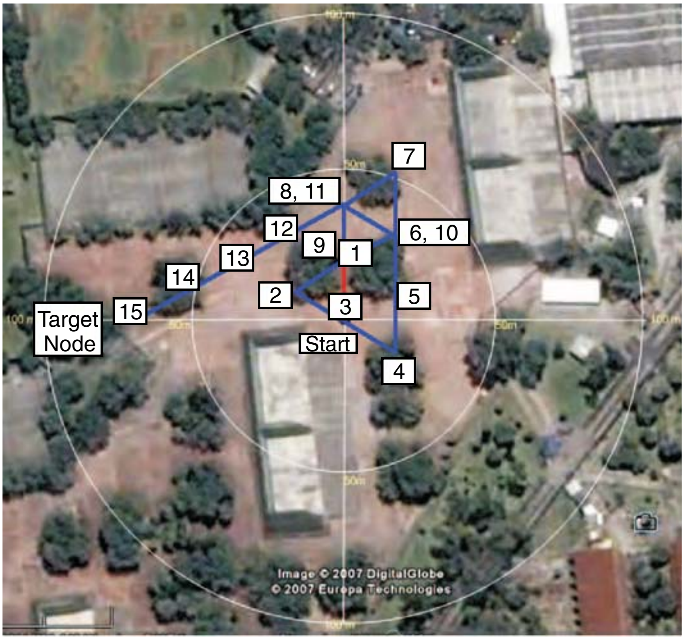
experiments the moving node was initially located at the center of the experimental area and the target node was placed a hundred meters away in an arbitrary position. These points appear in the figures at positions labeled as "Start" and "Target Node" respectively. The distance that the moving node travels between stop points was set to 20 m.

In Fig. 13 we provide an example of the full guiding path while using GUIDE-gradient. In this figure we show the full path followed by the moving node along with the value of the metric measured at each point. In this experiment the user stopped moving when he or she reached a distance of less than 20 m with respect to target node, to mark this stop-point we show a circle around the target node with a 20-m radius. When the program starts, the user must indicate his or her approximate walking speed so that the program can approximately determine the time it takes to move the intended distance.

6.1.1 Experiments with GUIDE-Gradient

Figure 13 shows a guiding experiment using the GUIDE-gradient algorithm with signal quality as the metric. It can be observed that even though there are several guiding impairments, after a few movements the guiding system was able to find the target node. For illustrative purposes we detail the trajectory decisions taken by GUIDE-gradient.

- Start. The node measures a link quality value of 59/100 and (randomly) moves to a direction that corresponds to the top of Fig. 13.
- Point 1. The node measures a link quality value of 56/100 which is worse than the one observed at point 0. Therefore, the node turns 120° counterclockwise (CCW) in this case.
- Point 2. The node measures a link quality value of 48/100. Points 0–2 form an equilateral triangle. According to the rules shown in Table 1, the node turns 120° CCW.
- Point 3. The node measures a link quality value of 52/100, which is better than the one observed at point 2, therefore, the node continues moving along the same trajectory.



points	Measured quality
Start	59/100
1	56/100
2	48/100
3	52/100
4	43/100
5	60/100
6	63/100
7	50/100
8	54/100
9	52/100
10	50/100
11	50/100
12	65/100
13	70/100
14	79/100
15	95/100

Fig. 13 GUIDE-gradient experiment (link quality)

- Point 4. The node measures a link quality value of 43/100, which is worse than the one observed at point 3. Therefore, the node turns 120° CCW.
- Point 5. The node measures a link quality value of 60/100. Points 3–5 form again an equilateral triangle. As explained before, the local value of the gradient is computed (using Table 1) which makes the node to continue moving along the same direction (turn 0°).
- Point 6: The node measures a link quality value of 63/100. The node continues moving along the same trajectory.
- Point 7: The node measures a link quality value of 50/100. Therefore, the node turns 120° CCW.
- Point 8: The node measures a link quality value of 54/100. Points 6–8 form an equilateral triangle. According to Table 1 the node turns 60° CCW.
- Point 9: The node measures a link quality value of 52/100. The node turns 120° CCW.
- Point 10: The node measures a link quality value of 50/100. Points 8–10 form an equilateral triangle and according to Table 1, the node turns 120° CCW.
- Point 11: The node measures a link quality value of 50/100. The node changes its direction 60°.
- Point 12–15: link quality in these points continues to get better and better, the node continues moving along the same trajectory eventually reaching the target node within a distance of 20 m.

In Fig. 13 we observe that the moving node manages to get closer to the target node. It is also observed that it moves in circles a few times before heading directly to the target node, this situation could be due to the trees located around the starting position and the presence of local maximums. Both link quality and RSSI measurements are not immune to propagation effects.

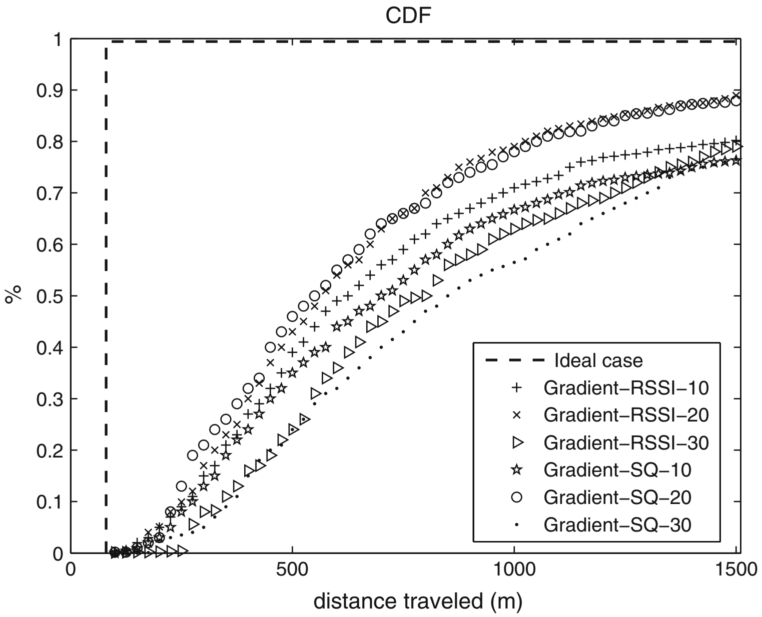


Fig. 14 CDF plots of GUIDE-gradient, 10-m accuracy

6.2 Computer Simulations

We used the data shown in Sect. 3.2 in order to simulate the experimental area and, in this way, perform a large number of guiding experiments. In this section we report our results.

Figures 14, 15, 16 show the CDF of the distance traveled by the mobile node before getting within 10, 20 and 30 m of the target node, respectively. In each figure we show different curves with movements of 10, 20 and 30 m for GUIDE-gradient with signal quality and RSSI. For these experiments we drew a circle with a 100-m radius centered at the target node, then we chose points on the circle with a 5 degree separation as the initial departing points of the moving node. For each departing point, we considered 8 different initial trajectories separated 45 degrees. Therefore, each curve represents the results of about 500 different guiding experiments. Because we have some blind areas behind the fronton courts, we could not perform experiments in points located in those areas. In these figures we also illustrate the performance of an ideal guiding system, in which the moving node moves directly to the target node.

In Fig. 14 we show the performance of GUIDE-gradient for a 10-m accuracy. In this figure we found that the best performance was obtained for 20-m movements, while the worst performance corresponds to 30-m movements. For 30-m movements, we found that the mobile node sometimes moved over the target area (a circle with a 10-m radius) between stop points (remember that in our algorithm the mobile node does not take measurements between points). Surprisingly, moving with 20-m steps achieved better performance compared with 10-m steps. We believe that this happens because 10-m steps result in many more intermediate stops during the guidance, where noisy measurements may mislead the guiding algorithm as opposed to moving with 20-m steps.

In Fig. 15 the target area is larger compared with Fig. 14 (i.e., a circle with a 20-m radius). The curves corresponding to 20-m steps obtained the best performance again. The

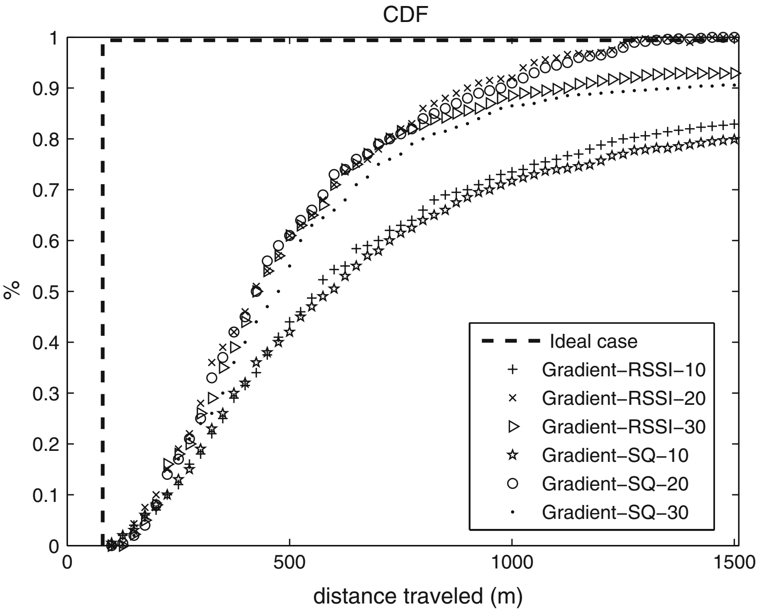


Fig. 15 CDF plots of GUIDE-gradient, 20-m accuracy

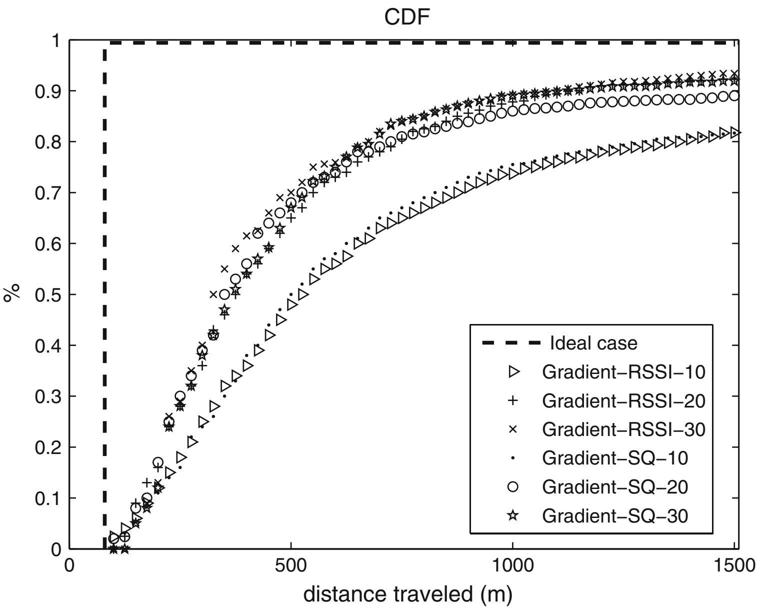


Fig. 16 CDF plots of GUIDE-gradient, 30-m accuracy

curves corresponding to 30-m steps obtained better performance compared with Fig. 14. We believe that this situation occurred mainly because the mobile node over-passed the target area less frequently compared with Fig. 14.

In Fig. 16 we increased the target area to a circle with a 30-m radius. In this figure the curves with steps of 20 and 30 m obtained the best performance, while the curves with 10-m steps obtained lower performance.

Looking at Figs. 14, 15, 16 we conclude that using 10-m steps for GUIDE-gradient with signal quality and RSSI may not be a good design choice. This happens because from point to point, there may not be enough variability of the metric being measured. This, in turn, will create more triangles in the guidance where the mobile node wastes time. Similarly, performance of guiding using large steps improves as the target area becomes similar or larger in size than the step size.

7 GUIDE-Gradient Considerations

There are a number of considerations that are taken into account for a correct operation of GUIDE-gradient in some practical situations. In particular, the following two situations are considered in our system.

As explained in the operation of GUIDE-gradient, mobile nodes always move along rectilinear trajectories according to the directions given by the system. In open areas, this may not be a difficult task to fulfill, however, in semi-open or indoor areas, obstacles may not allow a user to move along the desired trajectory. For instance, it may happen that a mobile node finds a wall and it is forced to move to one side. Moving along a different trajectory from the one specified by the system clearly misleads the guiding system, since the location estimated by the system and the real location of the user will be different. In such cases it is necessary that the user has a way of telling the system which trajectory is actually using.

In GUIDE-gradient this is done by using the graphical user interface shown in Fig. 12. When an obstacle blocks the user's intended trajectory, the user should come to a stop, click on the Reset option and visually select a new clear trajectory. The Reset option has the effect of restarting the guiding process, keeping no memory of previous movements. In Fig. 17 we show an example of this situation when after reaching point 3, a large building does not allow a user to continue moving forward as indicated by the algorithm. At that point the user stops, resets the algorithm and then starts moving along the chosen trajectory. In Fig. 17 points 1' to 3' and points 1" to 12" correspond to two separate and independent attempts to reach the target node.

The second situation is related to what happens if during the guiding process a mobile user losses its link to the target node by moving out of range. This situation will be a common case when the mobile user is located at the edge of the target node's range. In this case we took a simple solution where the mobile user returns to its previous point in case it losses the link with the target node.

8 On Node-to-node Guidance in Ad hoc Networks

In this section we comment on how the guiding system can be generalized to multi-hop ad hoc systems. Similar to WLAN technology, so far there has not been significant research related to guiding users in ad hoc networks. In ad hoc networks there may be several intermediate nodes, working as relays in the communication path between the moving and the target node. Figure 18 illustrates an example of a multi-hop route involving two intermediate nodes. While the guiding problem in multi-hop ad hoc networks may appear far more complex than the simpler WLAN (single-hop) problem that we have been addressing, it

points	Measured quality
Start	55/100
1'	57/100
2'	59/100
3'	61/100
Reset	60/100
1''	57/100
2''	63/100
3''	67/100
4''	65/100
5''	70/100
6''	70/100
7''	68/100
8''	72/100
9''	77/100
10''	84/100
11''	82/100
12''	91/100

Fig. 17 Example of GUIDE-gradient where an obstacle not allowed to continue the trajectory desired

can be easily solved if we split the multi-hop problem in various single-hop pieces. Assuming that a routing protocol can find a route between the moving and the target nodes, the moving node needs only to get closer to the first node in route (node A in Fig. 18) using GUIDE. Upon reaching the first node in route, the moving node now gets closer to the second node and so on until the target node is finally reached.

In a multi-hop context, the moving node needs only to be aware of the identities (i.e., IP or MAC addresses) of the intermediate nodes in the route as it gets closer to the target node. Most routing protocols for ad hoc networks provide such information in different ways. For instance the DSR routing protocol [12] includes the full list of nodes each packet should visit as it travels from source to destination. Distance vector based protocols (e.g., AODV [13]) do not provide the full list of intermediate nodes in routes, but each intermediate node is aware of the identity of the next one in route only. However, this problem can be solved in various ways including the addition of extra signaling or by means of overhearing traffic and figuring it out which node is relaying packets to which other node.

9 Conclusions

Node-to-node guidance in WLAN and ad-hoc environments is a research topic that has just been barely addressed by researchers. However, we identified a number of useful applications that would be possible if common wireless devices had such guiding capabilities. We envision many possible applications that range from everyday tasks to critical ones.

At first glance it may seem that guiding functions can be incorporated in a wireless device by means of specialized hardware only. However, in this work we have shown that it is feasible to use standard WiFi devices in order to provide a reasonable guiding experience. The

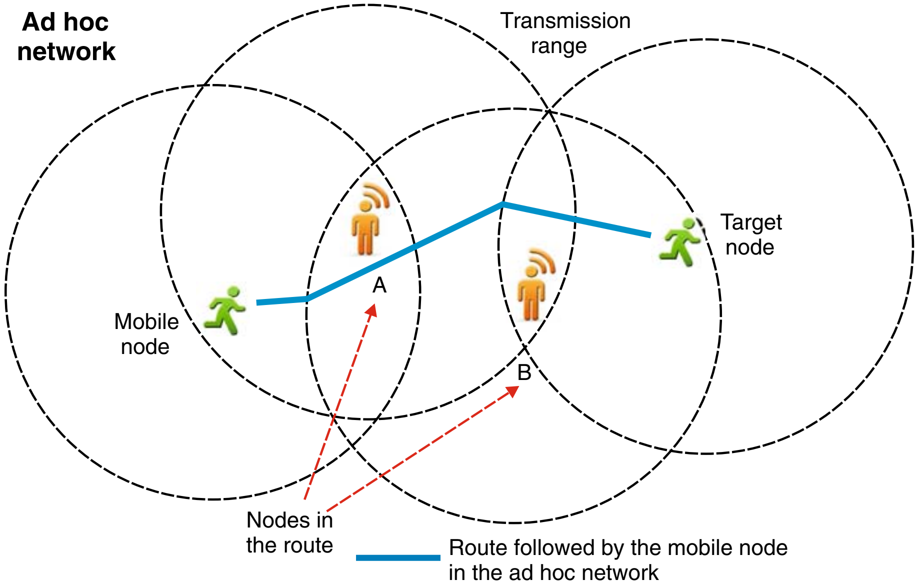


Fig. 18 Guiding users in a multi-hop environment

solution explored in this paper is based on monitoring of real time information regarding the status of the wireless link. Such information can be easily retrieved from any 802.11 wireless interface so that the described system can be easily deployed.

We developed and evaluated an approach for implementing a guiding functionality in a wireless device. This approach is based on the computation of local gradient in the neighborhood of the moving node. In fact, in our implementation we used a simplified computation with good results. We found the performance of guiding using larger steps improves as the target area becomes similar or larger in size than the step size.

It is worth mentioning that use of standard WiFi communication equipment for measurement purposes is not a straightforward task and it has several limitations. In addition, signal measurements are affected by noise, multipath interference and signal attenuation due to obstructions. All these factors make it necessary to take several measurements and process them to obtain a reliable estimate of the metric being measured. Ideally, we would like that the number of measurements be very low and the temporal misleading be as short as possible. This is part of our future work in this topic. In future research we also plan to study the particularities of node-to-node guidance in mobile ad hoc networks.

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