WIRELESS COMMUNICATIONS AND MOBILE COMPUTING
Wirel. Commun. Mob. Comput. 2003; **3**:455–463 (DOI: 10.1002/wcm.131)

A cell-based location-sensing method for wireless networks

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Summary

One of the most important applications for mobile commerce is location-based application and the core technology of location-based applications is the location-determination technology. In this paper, we present a location-sensing method, called *cell-based location-sensing method* and its positioning accuracy for the wireless networks with hexagonal structure and mesh structure. In addition, the accuracy of the method is optimized by tuning the transmitting power of base stations. In the optimal transmitting power, an accuracy of within 9.1667% (7.2182%) cell area for hexagonal structure (mesh structure) can be achieved by the cell-based location-sensing method. We believe that the results are useful for deploying wireless networks for location-based applications. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS
location sensing
location determination
location-based applications

1. Introduction

Recently, the wireless networks and the WWW are converging. Mobile commerce is expected to grow at incredible rates as mobile users access the Internet. Not only does mobile computing offer convenience but it also provides new services and applications. One of the most important new services and applications is location-based service and application. It allows mobile users to receive services based on their geographic location or position. These services and applications include emergency rescue, resource tracking and management, tour guide [1], location-sensitive billing, points of interest and so on [2,3].

The core technology of location-based services and applications is the location-determination technology. Many papers [4–9] are dedicated to location-determination methods. These methods can be divided

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Contract/grant sponsor: Ministry of Education, Taiwan, ROC; contract/grant number: 89-E-FA04-1-4.
Contract/grant sponsor: Lee and MTI Center for Networking Research, NCTU, Taiwan.

into two major classes, network-based and handset-based.

The network-based methods collect a handset's signals and determine its location in a centralized server. Some equipments are used to determine the direction and the time delay of the handset signal and calculate its position. Such solutions do not require any modification to handsets but have low position accuracy and high network cost. Typical network-based methods are Angle of Arrival (AOA) [4], Time Difference of Arrival (TDOA) [4], a combination of AOA and TDOA [4], and so on.

The handset-based methods collect signals from the networks by the mobile device and determine the location by the device itself. Typical handset-based methods are Global Positioning System (GPS) [6,7], Assisted GPS (AGPS) [10,11] and Differential GPS (DGPS) [12,13]. They rely on the 24 satellites that orbit around the earth to transmit precise velocity, latitude, longitude and altitude information to the GPS receiver in the handset. The handset reports its location to the service provider over the wireless network. These methods have a higher position accuracy but longer times to first fix (TTFF) and incur cost to handsets.

In addition to the above main classes, there is a cell-based position-determination method. It involves research on coverage problems and power control problems, which has been proposed in some papers [14–16]. In this method, the handset gathers all of the BS signals that it received and transmits the BS identification to the location server. The server then computes the position and forwards it either to the end user or to the location-based service that was requested. The main advantage of the cell-based location-sensing method is the fact that it is available today. As it requires no changes to the existing wireless network architecture, or to the mobile station (MS), it does not substantially increase costs for either network operators or for end users. The cell-based location-sensing technology can be applied to Global System for Mobile Communication (GSM) networks or to IEEE 802.11 wireless LAN. In general, the accuracy of cell-based location sensing increases as the number of cells within range increases, making it more accurate in urban environments for GSM networks.

In this paper, we present an accuracy measure for the cell-based location-sensing method. Two types of cellular networks are considered. One is a cellular network with hexagonal layout and the other is with mesh layout. Next, we optimize the location-sensing accuracy by tuning the base stations' (BSs') transmitting power. That is, we find an optimal transmitting power for BSs such that the MS can be located at the smallest area in the worst case. The remainder of this paper is organized as follows. In Section 2, we present the cell-based location-sensing method in detail. Sections 3 and 4 give the location-sensing accuracy respectively for the hexagonal wireless networks and for the mesh wireless networks. Comparison of the accuracy of hexagonal and mesh structure is given in Section 5. Finally, the conclusion is given in Section 6.

2. Cell-based Location-sensing Method

Consider a physical layout of the wireless network as shown in Figure 1. The area covered by the BS is called a *cell*. Each cell has the shape of a circle. The signal coverage of the BSs may overlap. The MS can receive a radio signal containing a cell number from the BS, if it is in the signal coverage of that BS. Note that an MS may receive more than one cell number when it is in the signal-overlapping area. For example, as shown in Figure 1, an MS in area *A* can receive the signals from BSs 0, 1, and 6, and in area *B* can receive the signals from BSs 0 and 2. Thus, the signal coverage can be used to determine the MS's location. Suppose that we have a location server maintaining the signal coverage data. The MS sends the list of every BS that is within range back to the location server upon receipt of the signal. The server

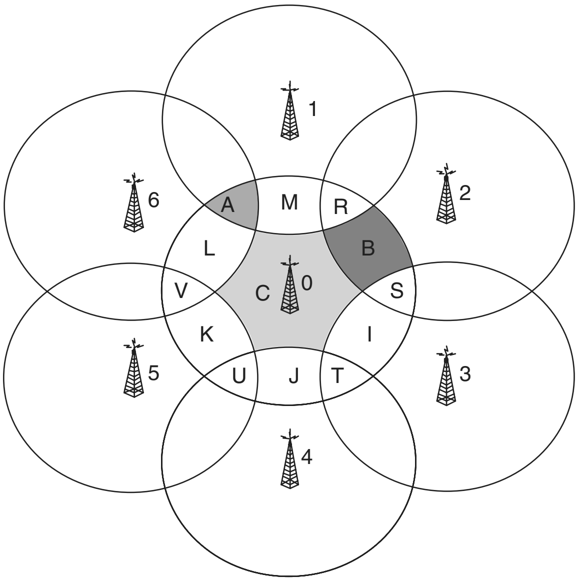


Fig. 1. The physical layout of the wireless network.

then computes the position for the MS. In this way, we can determine the MS's location. This method is known as the cell-based location-sensing method.

Next, we will discuss the accuracy for the cell-based location-sensing method. Consider the wireless network as shown in Figure 1. When an MS reports to the location server that it can receive the signals of BSs 0 and 2, the location server determines that the MS is in area B. This means that we can claim an accuracy of within area B for the MS. Formally, we define a distinguishable area as the area in which every MS receives a unique set of BSs' signals. Then, the accuracy of cell-based location-sensing method can be defined as the size of the distinguishable area. The maximum of all distinguishable areas is the location-sensing accuracy of the given network deployment.

3. Location Sensing for the Network with Hexagonal Structure

In this section, we consider a wireless network in which the BSs are deployed as a hexagon and each BS has the same coverage area with a radius R as shown in Figure 2. For simplicity, assume that the distance between two adjacent BSs is one unit; the accuracy of the location-sensing method in border cells is not considered in this section.

Since the structure of the network is symmetric, without loss of generality, we consider the circle covered by the signal of BS 0 as shown in Figure 1. The circle can be partitioned into 13 distinguishable areas. These areas can be classified into three types:

1. Type 1 area: The mobile station within the area can listen to three BSs' signals. There are six distinguishable areas in the circle that belong to type 1, that is, areas A, R, S, T, U, and V.
2. Type 2 area: The MS within the area can listen to two BSs' signals. There are six distinguishable areas in the circle that belong to type 2, that is, areas B, I, J, K, L, and M.
3. Type 3 area: The MS within the area can only listen to the signal of BS 0. It is at the central region of the circle, that is, area C.

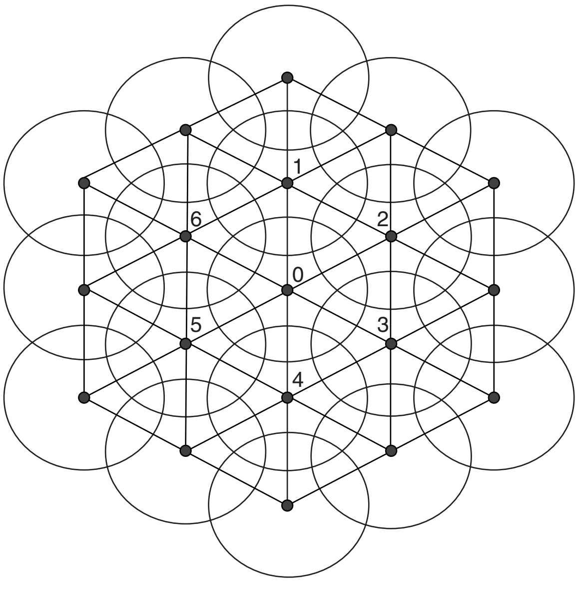


Fig. 2. A wireless network with hexagonal structure.

Note that the radius R of the circle is assumed to be bounded within $[1/\sqrt{3}, \sqrt{3}/2]$. This is because (i) if $R < 1/\sqrt{3}$, then there exist some areas that are not covered by any signal (see Figure 3a); (ii) if $R > \sqrt{3}/2$, then the type 2 area, for example area B, will be separated into two subareas (see Figure 3b).

The accuracy of cell-based location-sensing method depends on the size of the distinguishable areas. A smaller area means more positioning accuracy. In the following text we will find the size for each distinguishable area. Let $\angle abc$ denote the angle of a, b, c and $\Delta_{a,b,c}$ denote the triangle of a, b, c. Let $s(X)$ denote the area of X, for example, $s(\Delta_{a,b,c})$ denotes the area of triangle $\Delta_{a,b,c}$. Thus, the area of the shaded region of A, as shown in Figure 4, can be determined by

$$\frac{1}{2}\theta_1 R^2 - s(\Delta_{i,j,0})$$

where R is the radius of the circle, $\theta_1 = \angle i0j$. The $s(\Delta_{i,j,0})$ can be obtained by

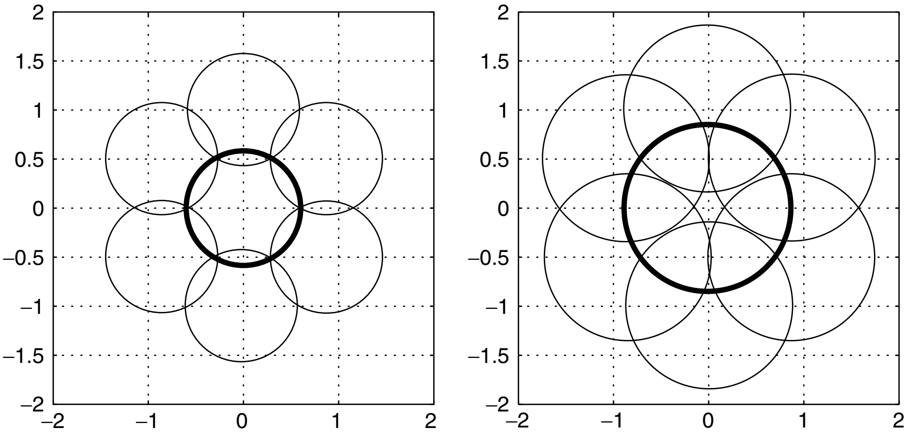
$$\begin{aligned} s(\Delta_{i,j,0}) &= \frac{1}{2}\left[2R\sin\left(\frac{\theta_1}{2}\right)R\cos\left(\frac{\theta_1}{2}\right)\right] \\ &= R^2\sin\left(\frac{\theta_1}{2}\right)\cos\left(\frac{\theta_1}{2}\right) \end{aligned}$$

Thus, the area of A is

$$s(A) = 3\left[\frac{1}{2}\theta_1 R^2 - s(\Delta_{i,j,0})\right] + s(\Delta_{i,j,k}) \quad (1)$$

where $s(\Delta_{i,j,k})$ can be computed by

$$\begin{aligned} s(\Delta_{i,j,k}) &= \frac{\sqrt{3}}{4}\left[2R\sin\left(\frac{\theta_1}{2}\right)\right]^2 \\ &= \sqrt{3}R^2\sin^2\left(\frac{\theta_1}{2}\right) \end{aligned}$$



(a) $r = \frac{1}{\sqrt{3}}$ (b) $r = \frac{\sqrt{3}}{2}$

Fig. 3. Hexagonal layout with $R = 1/\sqrt{3}$ and $R = \sqrt{3}/2$.

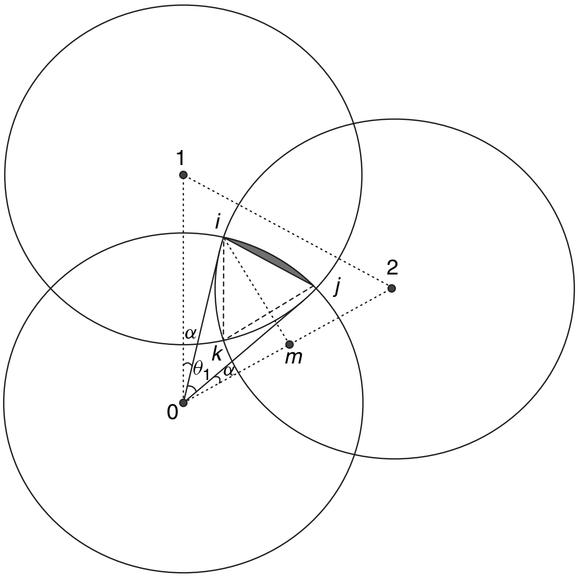


Fig. 4. A type 1 area for hexagonal structure.

Then, replace $s(\Delta_{i,j,0})$ and $s(\Delta_{i,j,k})$ in Equation (1). We have

$$
\begin{aligned}
s(A) &= 3\left[\frac{1}{2}\theta_1 R^2 - R^2 \sin\left(\frac{\theta_1}{2}\right)\cos\left(\frac{\theta_1}{2}\right)\right] \\
&\quad + \sqrt{3}R^2 \sin^2\left(\frac{\theta_1}{2}\right) \\
&= R^2\left[\frac{3}{2}\theta_1 + \sqrt{3}\sin^2\left(\frac{\theta_1}{2}\right)\right. \\
&\quad \left. - 3\sin\left(\frac{\theta_1}{2}\right)\cos\left(\frac{\theta_1}{2}\right)\right]
\end{aligned}
$$

Note that θ_1, can be rewritten as a function of R as follows.

Consider the triangle $0im$. The lengths of line segments $\overline{0i}$ and $\overline{0m}$ are R and $1/2$, respectively. Thus,

$$
\begin{aligned}
\cos(\theta_1 + \alpha) &= \frac{1}{2R} \\
\theta_1 + \alpha &= \cos^{-1}\left(\frac{1}{2R}\right) \qquad (2)
\end{aligned}
$$

Note that $\angle 102 = \pi/3$. Then,

$$\theta_1 + 2\alpha = \frac{\pi}{3} \qquad (3)$$

From Equations (2) and (3), we have

$$\theta_1 = 2\left[\cos^{-1}\left(\frac{1}{2R}\right)\right] - \frac{\pi}{3} \qquad (4)$$

Replace θ_1 in Equation (1) by $\theta_1 = 2[\cos^{-1}(1/2R)] - \pi/3$. Thus, the area of A can be rewritten as a function of R (denoted as $f_A(R)$) as follows:

$$
\begin{aligned}
s(A) = f_A(R) = R^2 &\left[\frac{3}{2}\theta_1 + \sqrt{3}\sin^2\left(\frac{\theta_1}{2}\right)\right. \\
&\left. - 3\sin\left(\frac{\theta_1}{2}\right)\cos\left(\frac{\theta_1}{2}\right)\right]
\end{aligned}
$$

where $\theta_1 = 2[\cos^{-1}(1/2R)] - \pi/3$.

Similarly, as shown in Figure 5, the area of B can be obtained by

$$f_B(R) = 2\left[\frac{1}{2}\theta_2 R^2 - s(\Delta_{s,t,0})\right] - 2f_A(R)$$

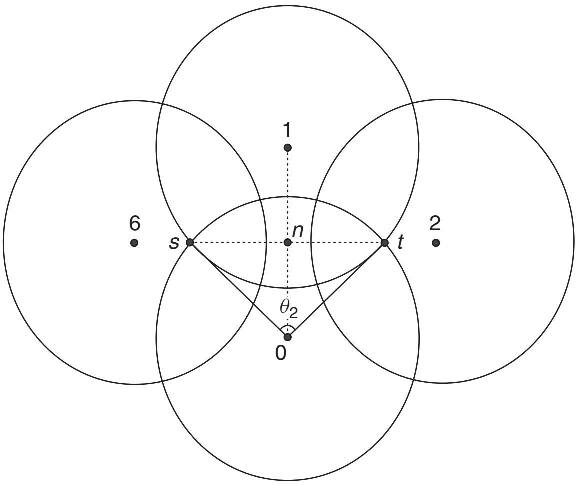


Fig. 5. A type 2 area for hexagonal structure.

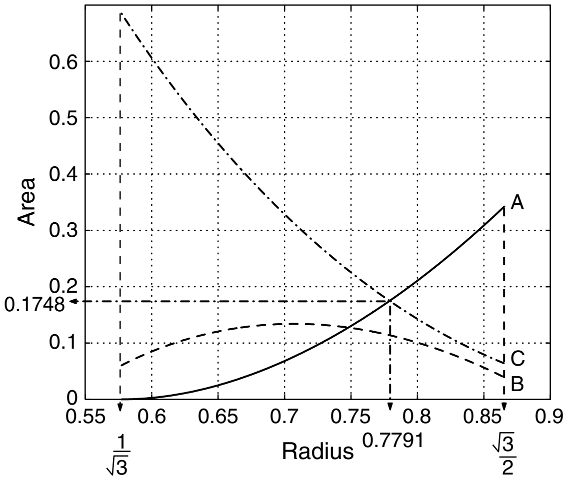


Fig. 6. Accuracy of the network with hexagonal structure.

where $s(\Delta_{s,t,0}) = 1/2R\sin(\theta_2/2)$ and $\theta_2 = \angle s0t = 2\cos^{-1}(1/2R)$.

Finally, area of C can be found by

$$f_C(R) = \pi R^2 - 6f_A(R) - 6f_B(R)$$

Note that the accuracy of cell-based location sensing is the maximal size of distinguishable area in the system. That is, the accuracy $e = \max\{f_A(R), f_B(R), f_C(R)\}$. We can claim an accuracy of within area e for the hexagon wireless network with radius R.

If the transmitting power of BS can be adjusted, then the coverage of BS will vary. Let us consider how to arrange the coverage of BS such that the accuracy is optimized. This problem is equivalent to finding a radius R such that $e = \max\{f_A(R), f_B(R), f_C(R)\}$ is minimized. That is,

$$\begin{aligned} z &= \min_{\frac{1}{\sqrt{3}} \le R \le \frac{\sqrt{3}}{2}} e \\ &= \min_{\frac{1}{\sqrt{3}} \le R \le \frac{\sqrt{3}}{2}} \max\{f_A(R), f_B(R), f_C(R)\} \qquad (5) \end{aligned}$$

Figure 6 shows the functions $f_A(R)$, $f_B(R)$, and $f_C(R)$, for $1/\sqrt{3} \le R \le \sqrt{3}/2$. The function $f_A(R)$ is an increasing function and the function $f_C(R)$ is a decreasing function where $1/\sqrt{3} \le R \le \sqrt{3}/2$. Let R^* be the radius such that $f_A(R^*) = f_C(R^*)$. Thus,

$$\max\{f_A(R), f_B(R), f_C(R)\} = \begin{cases} f_C(R) & \text{if } \dfrac{1}{\sqrt{3}} \le R \le R^* \\ f_A(R) & \text{if } R^* \le R \le \dfrac{\sqrt{3}}{2} \end{cases}$$

and the minimum of $\max\{f_A(R), f_B(R), f_C(R)\}$ occurs at $f_A(R) = f_C(R)$. By numerical method, we find $R = 0.7791$ such that $f_A(R) \approx f_C(R)$. In the optimal layout, areas of A, B and C are $(f_A(R), f_B(R), f_C(R)) \approx (0.1748, 0.1138, 0.1748)$. The area of a cell in the optimal layout is $\pi \times R^{*2} = 1.9069$. Thus, we can claim an accuracy of within $0.1748/1.9069 = 9.1667\%$ cell area for the optimal layout.

4. Location Sensing for the Network with Mesh Structure

Next, we consider a wireless network in which the BSs are deployed as a mesh shape. Assume that each BS has the same coverage area with a radius R, the distance between two adjacent BSs is one unit and the accuracy location sensing in border cells is not considered in this section. In addition, we assume that the radius R of the circle is bounded within $[\sqrt{2}/2, 1]$. This is because (i) if $R < \sqrt{2}/2$, then there exist some areas that are not covered by any signal; (ii) if $R > 1$, then the cell-based location-sensing method will fail.

Similarly, the circle covered by the signal of BS 0 can be partitioned into 21 distinguishable areas as shown in Figure 7. These areas can be classified into four types:

1. Type 1 area: The MS within the area can listen to four BSs' signals, for example area D. There are four distinguishable areas in the circle, belonging to type 1.
2. Type 2 area: The MS within the area can listen to three BSs' signals, for example area E. There are

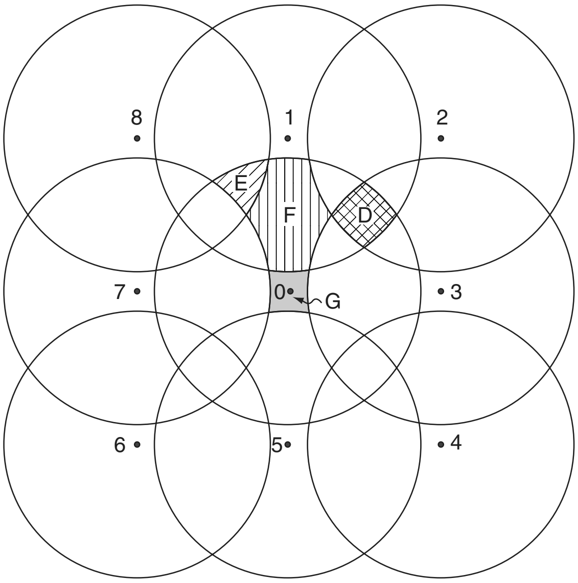


Fig. 7. A wireless network with mesh structure.

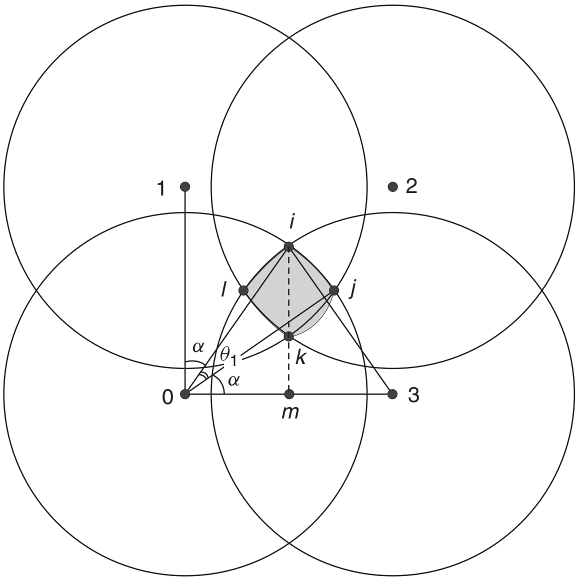


Fig. 8. Area D for mesh structure.

12 distinguishable areas in the circle, belonging to type 2.

3. Type 3 area: The MS within the area can listen to two BSs' signals, for example area F. There are four distinguishable areas in the circle, belonging to type 3.
4. Type 4 area: The MS within the area can only listen to the signal of BS 0. It is at the central region of the circle, that is, area G.

The area of D, as shown in Figure 8, can be determined as

$$f_D(R) = 4\left[\frac{1}{2}\theta_1 R^2 - s(\Delta_{i,j,0})\right] + s(\square_{i,j,k,l}) \quad (6)$$

where $\theta_1 = 2\cos^{-1}(1/2R) - \pi/2$, $s(\Delta_{i,j,0}) = R^2\sin(\theta_1/2)\cos(\theta_1/2)$, and $s(\square_{i,j,k,l})$ denotes the area of square i, j, k, l and $s(\square_{i,j,k,l}) = 4R^2\sin^2(\theta_1/2)$.

The area of E, as shown in Figure 9, can be determined as

$$f_E(R) = \frac{1}{2}\left\{2\left[\frac{1}{2}\theta_2 R^2 - s(\Delta_{s,t,0})\right] - f_D(R)\right\} \quad (7)$$

where $s(\Delta_{s,t,0}) = \sqrt{2}/2R\sin(\theta_2/2)$ and $\theta_2 = \angle s0t = 2\cos^{-1}(\sqrt{2}/2R)$. The area of F, as shown in Figure 10, can be determined as

$$f_F(R) = 2\left[\frac{1}{2}\theta_3 R^2 - s(\Delta_{u,v,0})\right] - 2f_D(R) - 4f_E(R) \quad (8)$$

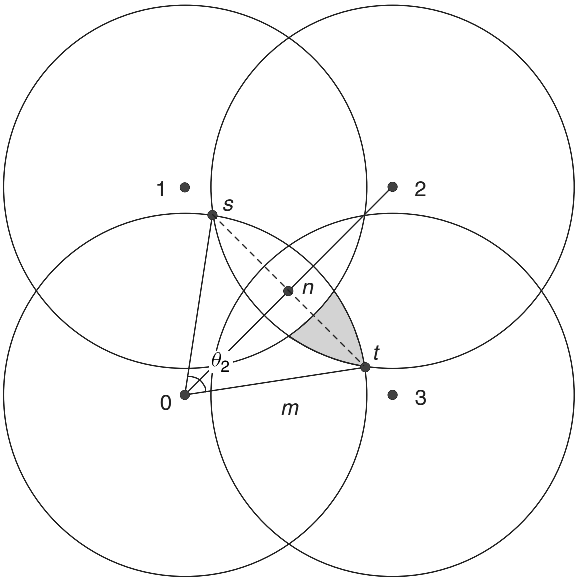


Fig. 9. Area E for mesh structure.

where $s(\Delta_{u,v,0}) = 1/2R\sin(\theta_3/2)$ and $\theta_3 = \angle u0v = 2\cos^{-1}(1/2R)$. Finally, the area of G is

$$f_G(R) = \pi R^2 - 4f_D(R) - 12f_E(R) - 4f_F(R) \quad (9)$$

Thus, the accuracy for mesh structure is $e = \max\{f_D(R), f_E(R), f_F(R), f_G(R)\}$. Next, we consider how to arrange the coverage of BS for mesh structure such that the accuracy is optimized. The problem is to find a radius R such that $e = \max\{f_D(R), f_E(R), f_F(R), f_G(R)\}$ is minimized.

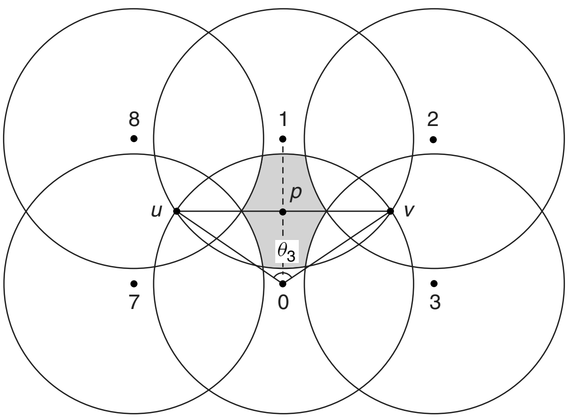


Fig. 10. Area F for mesh structure.

That is,

$$z = \min_{\frac{\sqrt{2}}{2} \leq R \leq 1} \max\{f_D(R), f_E(R), f_F(R), f_G(R)\} \tag{10}$$

Figure 11 shows the functions $f_D(R)$, $f_E(R)$, $f_F(R)$ and $f_G(R)$, for $\sqrt{2}/2 \leq R \leq 1$. Let R_1 and R_2 be the radiuses such that $f_G(R_1) = f_F(R_1)$ and $f_F(R_2) = f_D(R_2)$, respectively. Thus,

$$\max\{f_D(R), f_E(R), f_F(R), f_G(R)\}$$
$$= \begin{cases} f_G(R) & \text{if } \frac{\sqrt{2}}{2} \leq R \leq R_1 \\ f_F(R) & \text{if } R_1 \leq R \leq R_2 \\ f_D(R) & \text{if } R_2 \leq R \leq 1 \end{cases}$$

and the minimum of $\max\{f_D(R), f_E(R), f_F(R), f_G(R)\}$ occurs at R_2. By numerical method, we find $R_2 = 0.9389$ such that $f_F(R_2) \approx f_D(R_2)$. In the optimal layout, areas of D, E, F, and G are $(f_D(R_2), f_E(R_2), f_F(R_2), f_G(R_2)) \approx (0.1999, 0.0963, 0.1999, 0.0153)$. The area of a cell in the optimal layout is $\pi \times {R_2}^2 = 2.7694$. Thus, we can claim an accuracy of within $0.1999/2.7694 = 7.2182\%$ cell area for the optimal layout.

5. Comparing the Accuracy of Hexagonal and Mesh Structures

In the previous sections, we found that an MS can be accurately located within 9.1667% (7.2182%) cell area in the optimal hexagonal (mesh) structure. This is under the assumption that the distance between two adjacent BSs is one unit. In this section, we consider that given a fixed number of BSs, which structure gives better accuracy.

At first, we construct two networks with hexagonal structure and mesh structure whose coverage areas are equal. As shown in Figure 12, the distance between two adjacent BSs is fixed to one unit for mesh structure. Then, we adjust the distance between two adjacent BSs for hexagonal structure such that the area of quadrangle e, f, g, h equals the area of square a, b, c, d (see Figure 12). That is, the distances of ef, fg, gh and eh are set to

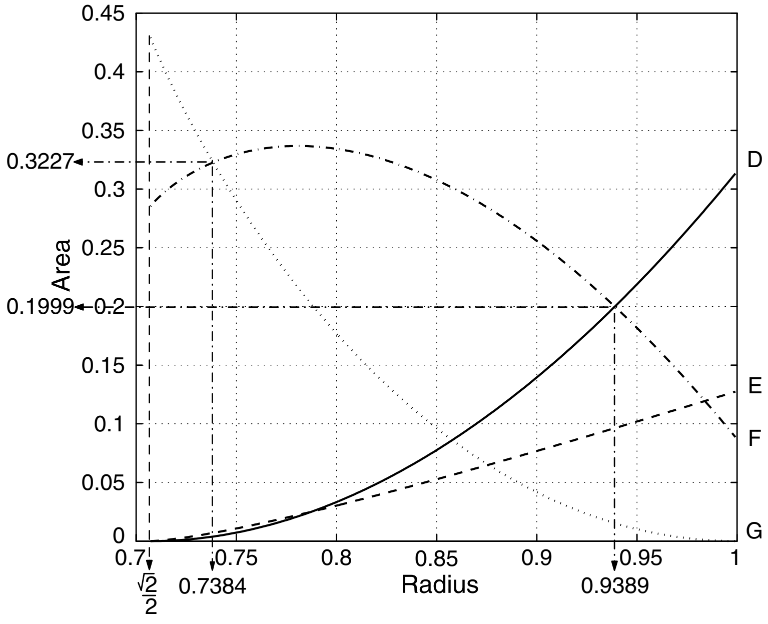
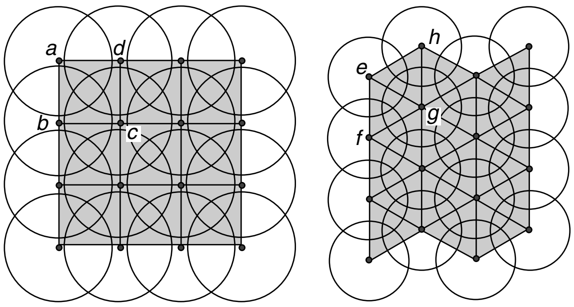


Fig. 11. The accuracy of the network with mesh structure.



(a) (b)

Fig. 12. The fixed coverage for the mesh and hexagonal structures.

be $\sqrt{2/\sqrt{3}}$. Thus, the area of the shaded region in Figure 12(a) is equal to the area of the shaded region in Figure 12(b) and the BS numbers for the two structures are the same.

By applying the same approaches in Sections 3 and 4, we find that the maximal distinguishable areas are 0.2019 (i.e. $z = 0.2019$) for the hexagonal structure and 0.1999 (i.e. $z = 0.1999$) for the mesh structure in the optimal layout. This means that the mesh structure is a little better than the hexagonal structure.

6. Conclusions

In this paper, we have presented a cell-based location-sensing method for wireless networks. The main advantage of the cell-based location method is that it requires no changes to the existing wireless network architecture, or to the MS, and it does not substantially increase costs for either network operators or end users. We also find the optimal layout for wireless networks with hexagonal structure as well as mesh structure. In the optimal hexagonal (mesh) structure where the distance between two adjacent BSs is one unit, an MS can be accurately located within 9.1667% (7.2182%) cell area. In addition, on the basis of a fixed number of BSs and a fixed coverage area, the mesh structure gives a little better accuracy compared to the hexagonal structure in the optimal layout. We believe that these results are useful for deploying wireless networks for location-based applications. The following directions might be interesting for possible future work:

1. Find the accuracy of cell-based location-sensing method for networks with irregular structure and unequal transmitting power of BSs.
2. Find an optimal layout for irregular structure by tuning BSs' transmitting power.

Acknowledgments

This work was supported in part by the Ministry of Education, Taiwan, ROC under grant 89-E-FA04-1-4, and the Lee and MTI Center for Networking Research, NCTU, Taiwan.

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