Chapter 15
Routing and Performance of Regular WSNs

15.1 Introduction

We considered the usefulness of regular deployments of WSNs, and it is time now to quantify some of the specific parameters and compare how they perform as compared to a random scheme. An obvious reason to use regular scheme is that a desired area can be covered by fewer SNs and some underlying characteristics are shown in Table 15.1.

15.2 Routing in Regular Topologies

In a 2-D mesh network shown in Fig. 15.1a, routing is very simple as *x* and *y* coordinates of each SN can be used to determine a route from a source SN to a destination and can be easily extended to 3-D mesh networks. The location of BS is critical as all SNs need to transmit their sensed data to it. So, a natural choice is at the center of WSN as SN (0, 0). If you decided to have 4 BSs, then an intuitive solution of placing each of four BS_1 is the four corners. But a better solution is BS_2 as WSN can be divided in four parts as shown by a vertical and a horizontal dotted line such that the area of SNs reporting to different BSs can also be identified and each BS is in the center of their assigned area. That way, the distance from SNs to corresponding BS can be equalized among SNs. In a rhombus topology shown in Fig. 15.1b, routing can be done in a similar way to 2-D mesh.

SN addressing in 2-D hexagonal network is shown in Fig. 15.2a which is simple, but difficult to use for routing among SNs. An alternate addressing in 2-D hexagonal network is shown in Fig. 15.2b by dividing hexagon to equilateral triangles [1] and assigning address of each SN using 3 digits of (*x*, *y*, *z*) as illustrated in Fig. 15.2c [2]. In this scheme,

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Table 15.1 Comparing randomly deployed versus regular topology of WSNs

WSN topology	Randomly deployed	Regular topology
SNs distribution	Random	Uniform
Neighborhood discovery	Use beacon signals to find nearest neighbors within communication range, an involved process	As SNs are uniformly placed, the location of neighboring SNs is built in the system
Routing	Have to find the path with known local neighborhood information	Routing is relatively easy as each node with given address, is located at a location based on the basic topology
Voronoi diagram	Fairly involved process	Easy as SNs are regularly placed, complex if topology is complex

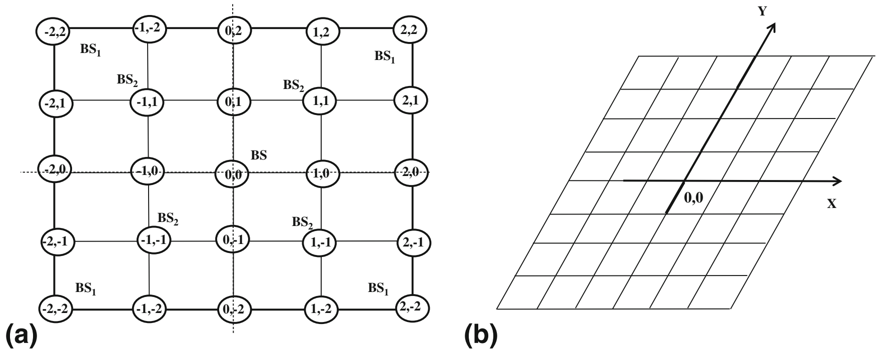


Fig. 15.1 **a** 2-D mesh network. **b** Rhombus topology

$$\mathbf{i}+\mathbf{j}+\mathbf{k}=0, \tag{15.1}$$

and

$$\mathrm{SN}(a,b,c) \text{ is expressed as } = a\mathbf{i}+b\mathbf{j}+c\mathbf{k}. \tag{15.2}$$

As the addressing is not unique, it may be possible that

$$(a',b',c')=(a'',b'',c'') \Leftrightarrow a'\mathbf{i}+b'\mathbf{j}+c'\mathbf{k}=a''\mathbf{i}+b''\mathbf{j}+c''\mathbf{k}. \tag{15.3}$$

Optimal Routing in a hexagonal network is obtained by calculating difference between destination D and source S addresses as follows:

$$\left|\overrightarrow{SD}\right| = \min(|a-c|+|b-c|, |a-b|+|b-c|, |a-b|+|a-c|). \tag{15.4}$$

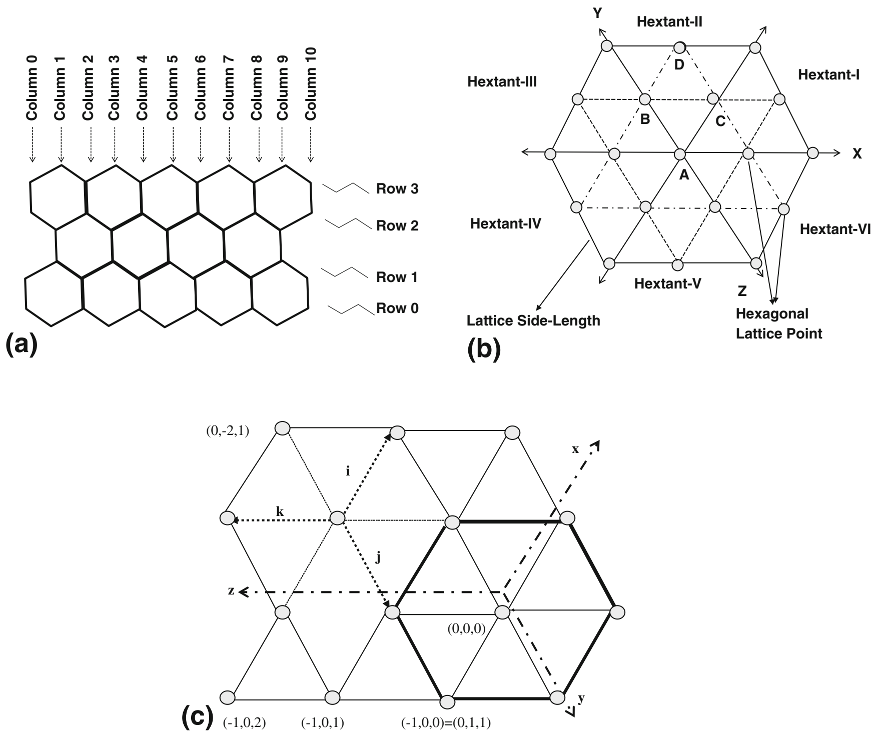


Fig. 15.2 **a** Addressing in hexagonal network. **b** Alternative way of SN addressing. **c** Use of coordinates shown for addressing SN

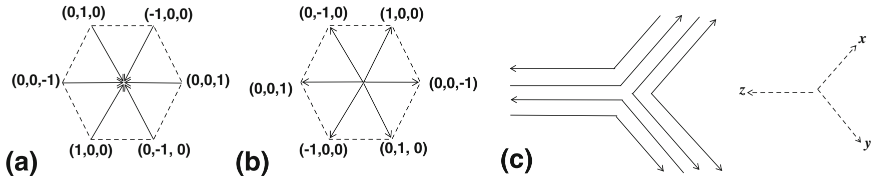


Fig. 15.3 **a** Addressing in hexagonal network. **b** Outgoing edges from (0, 0, 0). **c** Routing of the packets [3]

Optimal routing in a hexagonal network can be done by following Fig. 15.3c and calculating distance between S and D [3].

Addressing in 2-D triangular network can be done similar to a hexagonal network described earlier and is shown in Fig. 15.4a. So, routing can also follow hexagonal networks. Such a network has been simulated following a transmission schedule [4] of up to H transmissions are scheduled during every time slot using spatial reuse and Fig. 15.4b shows cumulative distribution of distance between receiver SNs and other sender SNs for networks of size $H = 5$ (90 SNs),

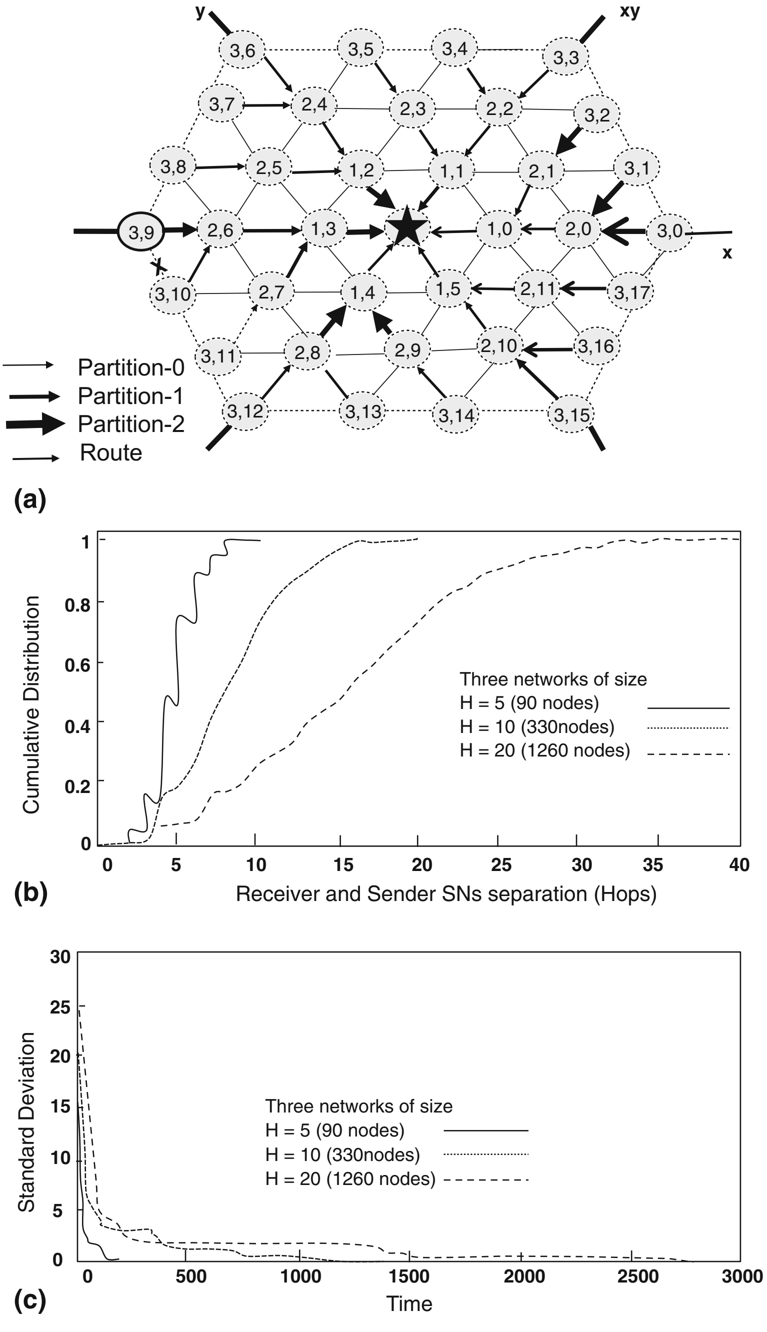


Fig. 15.4 a Addressing in triangular network. **b** Separation between receiver SNs and simultaneous sender SNs. **c** Convergence of clocks

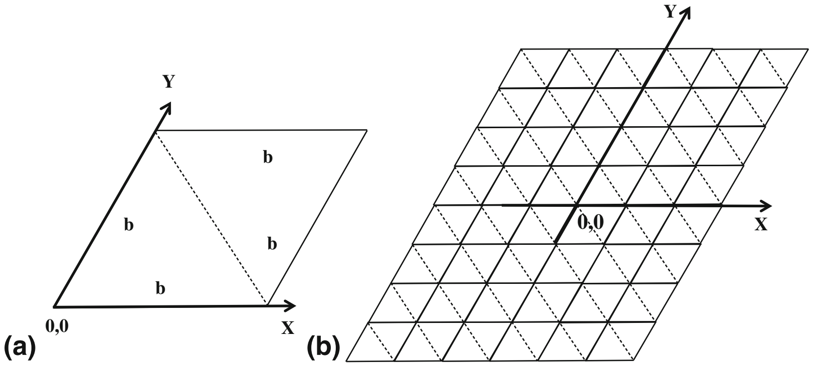


Fig. 15.5 **a** Rhombus divided into 2 triangles. **b** Routing in rhombus network

H = 10 (330 SNs) and H = 20 (1260 SNs), with more than 2 hop separation between SNs. A slow divergence of synchronization is observed in Fig. 15.4c. A rhombus topology can be obtained by combining two triangles (Fig. 15.5a), and thus, the same routing scheme can be utilized (Fig. 15.5b).

In WSNs, absolute address of each SN is not required and in fact relative address within the area is considered adequate. For relative location, some SNs are selected as reference points and are called anchor nodes. Selection of appropriate anchors is critical as they ought to be well-distributed inside the area where WSN has been deployed. Anchor placement in 2-D mesh network is done [1] by first determining virtual coordinates (VCs) of each SN that represents minimum hop distances with respect to a set of anchor nodes. Having two corner SNs at the bottom of a 2-D mesh makes all SNs to have unique VCs while their random placement leads to the same coordinates for several SNs. The effect of placing anchors at bottom two corners is shown in Fig. 15.6a, with all SNs have a unique VC. Random location of anchor modes (Fig. 15.6b) leads to several SNs with the same VC.

Figure 15.7 shows placement of anchor nodes in a triangular topology. Figure 15.7a has distance between two anchors of 6 hops following a zigzag path while anchors are placed on a straight line in Fig. 15.7b. Figure 15.8a indicates unique VCs in a triangular network if anchors are placed on straight edge and in Fig. 15.8b the dotted lines show region of identical VCs. Figure 15.9 identifies SNs region in triangular network using VCs. Dominating setin triangular topology is given Fig. 15.10a with density of 1/3 and Fig. 15.10b with density of 6/19 [5]. Figure 15.11 shows SNs deployed in hexagonal grid with dotted region shows SNs with identical VCs due to anchors placed on zigzag line in (a) and (b) illustrates different regions when anchors are placed on straight line. Identification of SNs region using VCs for hexagonal network [4] is shown in Fig. 15.12a while Fig. 15.12b shows spanning tree with a maximum distance of 3 to BS [6]. Figure 15.13a shows 1-to-all message broadcast in a hexagonal network, and all-to-all communication is given in Fig. 15.13b.

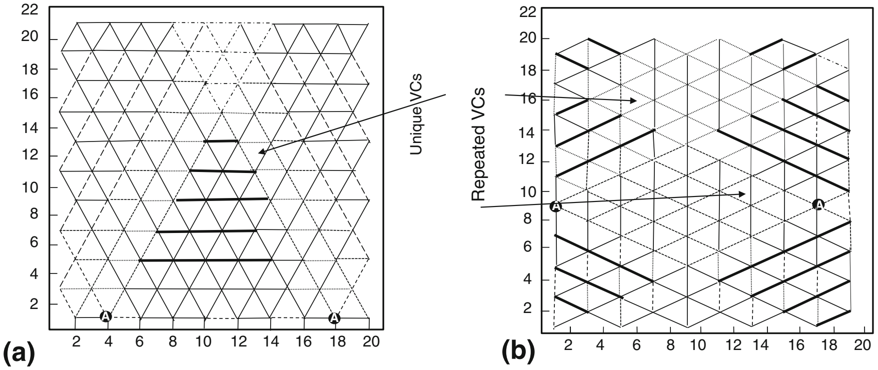


Fig. 15.6 Placement of anchor SNs in 2-D mesh at **a** Bottom corners give all SNs unique VCs. **b** Random location leads to several SNs with identical coordinates

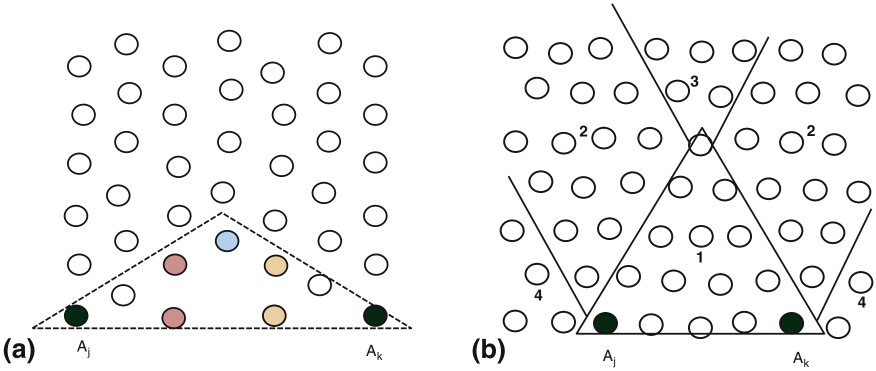


Fig. 15.7 Placement of anchor nodes in triangular topology. **a** 6 hops away following zigzag path. **b** Anchors placed on straight line

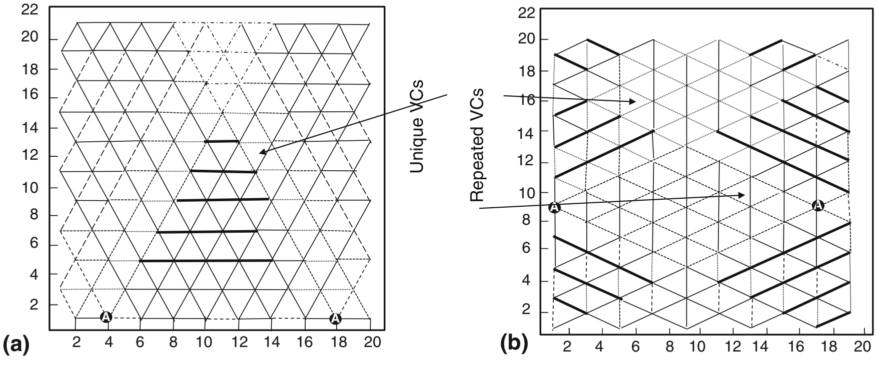
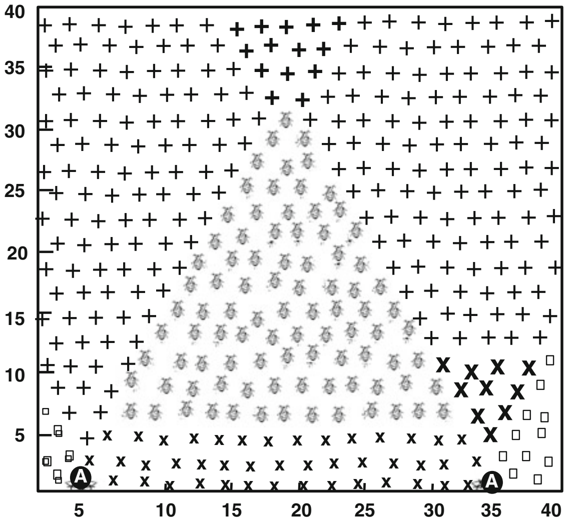


Fig. 15.8 **a** Unique VCs obtained if anchors in a triangular network are placed on straight edge. **b** *Dotted lines* showing region of identical VCs

Fig. 15.9 Identification of SNs region in triangular network using VCs



15.3 Processing in Regular Topologies

Collaborative processing is another challenging area in WSNs and Power-Efficient Gathering in Sensor Information Systems (PEGASIS) [7] of Fig. 9.8 can be applied to regular WSN topologies without much difficulty. This can be done chaining all SNs together so that each SN receives only one message and transmits one till the message reaches the destination or the BS. Figure 15.14 shows examples of 2-D mesh and triangular topologies. Tree formation in a 2-D mesh is given in Fig. 15.15a and broadcasting in 2-D mesh is shown in Fig. 15.15b, c.

Clustering of SNs can be done using SNs 1 hop or 2 hops away from CH and is shown for 2-D mesh, hexagonal, and triangular topologies in Fig. 15.16. Clustering of a large triangular WSN is shown in Fig. 15.17. In a WSN, if it is densely deployed, a set of sensors can be allowed to go to sleep mode while another set monitors the area. 4 sets of sleep–awake cycles in WSN are shown in Fig. 15.18 for three topologies. Figure 15.19 gives 4 sets of sleep–awake cycles in large WSNs with 4 BSs. The CH can define schedule for each SN so that collision from adjacent SNs can be eliminated. Figure 15.20 illustrates one such TDMA schedule in clustered WSNs.

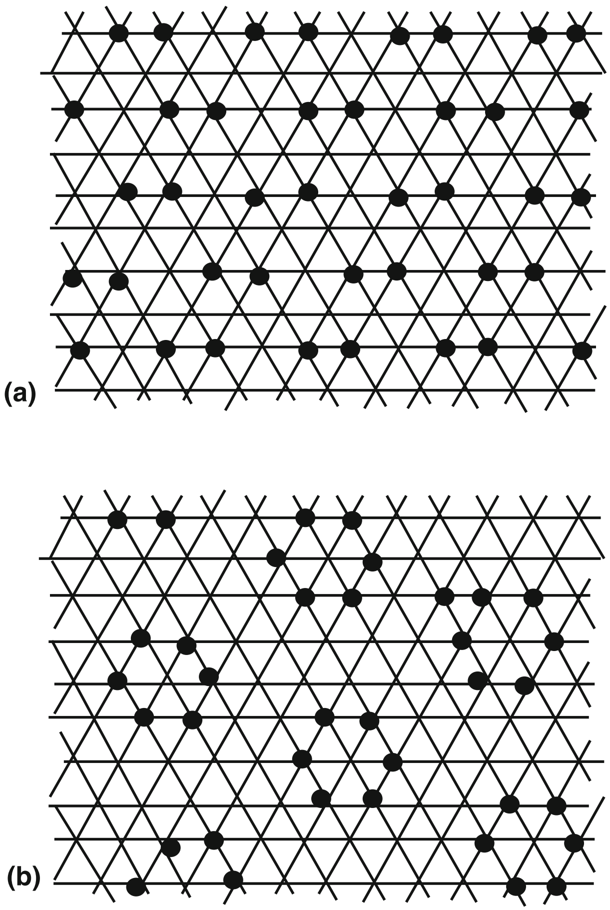
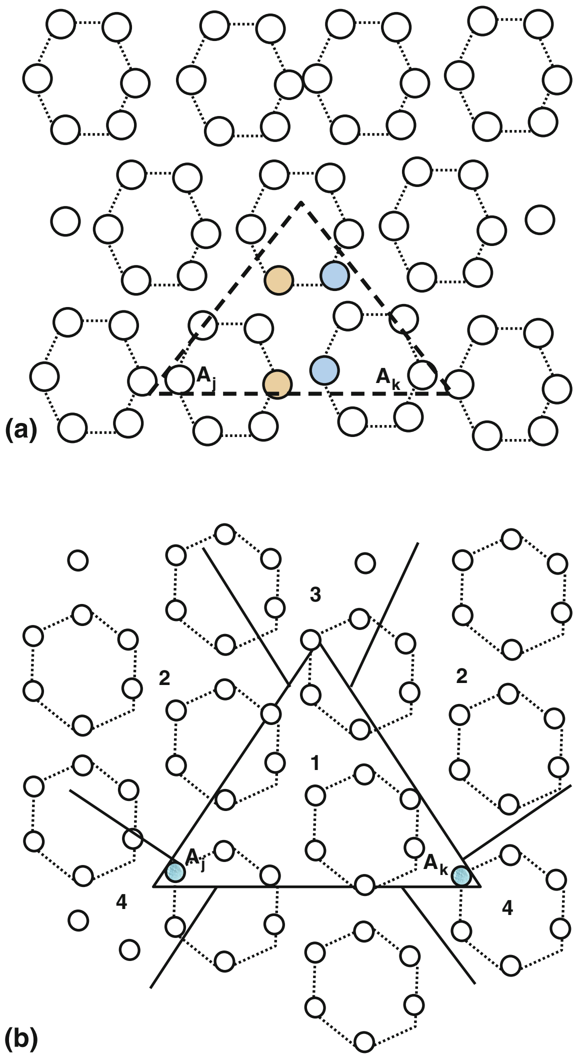


Fig. 15.10 Dominating set in triangular topology. **a** Density 1/3. **b** Density 6/19 [5]

15.4 Mobile Opportunistic Concept for Regular WSN Topologies

Most commonly, SNs forward their data to BS in multi-hop fashion so as to conserve energy. This increases delay in reaching BS while consumes energy in every transmission and reception. Another class of WSN concept is to use opportunistic network (MON) concept where randomly moving mobile relay nodes (RNs) pick up data from SN once within its communication range and RN eventually delivers data to BS. As mobile RNs are randomly moving and WSN has no control over the mobility of RNs, the connectivity between RN and SN as well as between RN and BS are intermittent (Fig. 15.21).

Fig. 15.11 SNs deployed in hexagonal grid. **a** *Dotted region* shows SNs with identical VCs due to anchors placed on *zigzag line*. **b** Different regions when anchors are placed on *straight line*



If T is the intercontact time, then the estimated time to deliver data to BS is $E(T) = N$. As the size on the WSN $N \rightarrow \infty$, then $P(T > n) \sim \text{constant}/n^{1/2}$, for large n where n is the number of SNs, a RN can contact in one transmission. Delivery times required in 2-D mesh of different sizes are given in Fig. 15.22. The RNs used for ferries have completely predictable routes through the geographic area. One example is an ideal spiral search process in a WSN [8] where, unlike *address–centric* routing in which the source node searches for a route to the destination node, the BS looks for a particular data object stored in an unknown subset of SNs. Such spiral is intended for *data-centric* routing as the routing problem is actually a query problem—the routing algorithm must search for the route to a SN with the

Fig. 15.12 Hexagonal network. **a** Identification of SNs region using VCs [4]. **b** Spanning tree for maximum distance of 3 to BS [6]

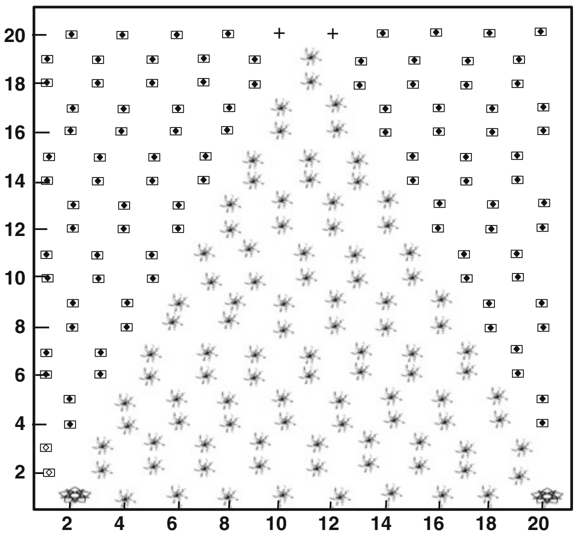
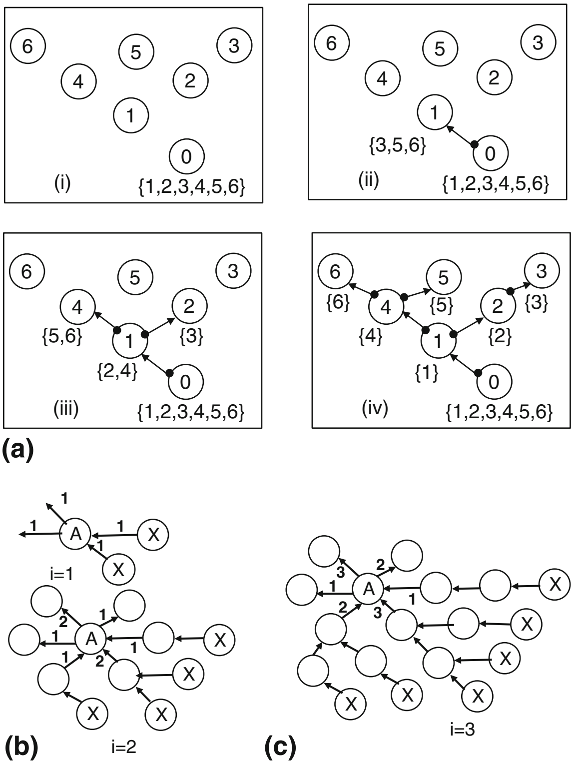


Fig. 15.13 Hexagonal network. **a** Three stages of the one-to-all communication. **b**, **c** 3 steps of all-to-all communication



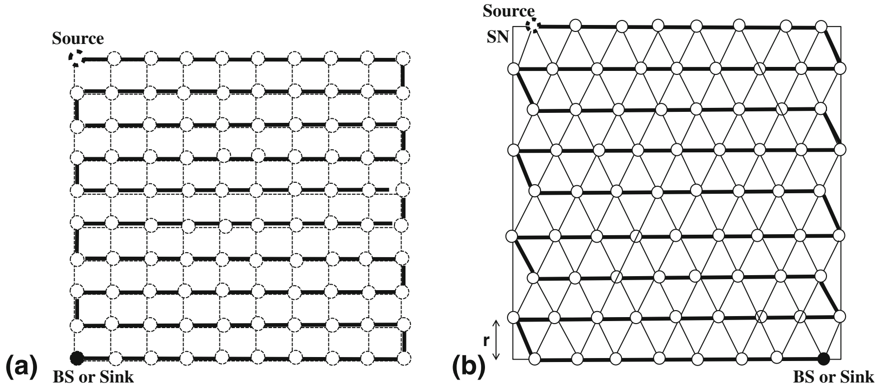


Fig. 15.14 PEGASIS algorithm applied to **a** 2-D mesh WSN. **b** triangular WSN

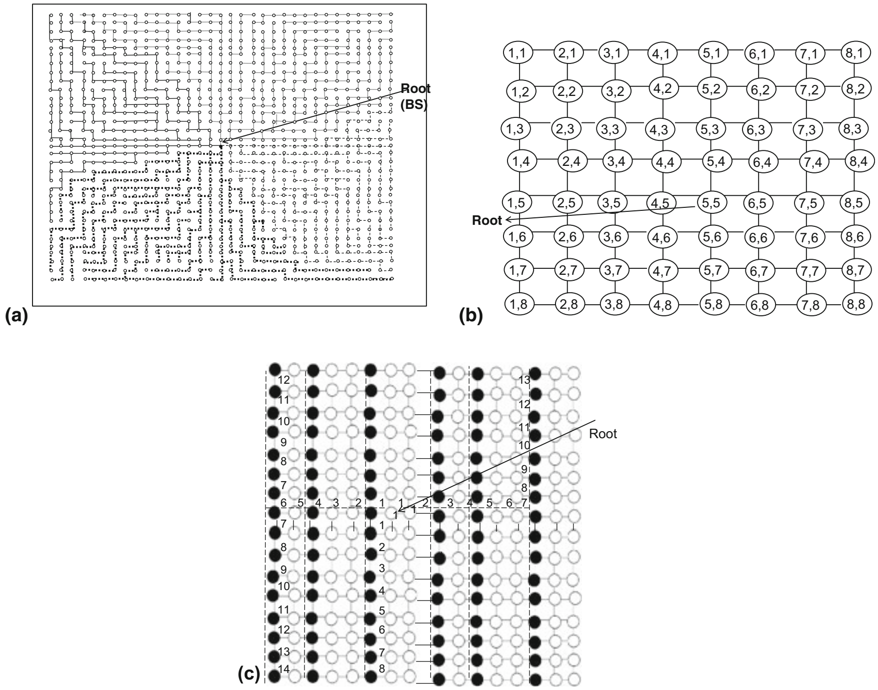


Fig. 15.15 **a** A typical routing tree in 2-D mesh. **b** Broadcasting in 2-D mesh. **c** Minimum SN rebroadcasting marked dark

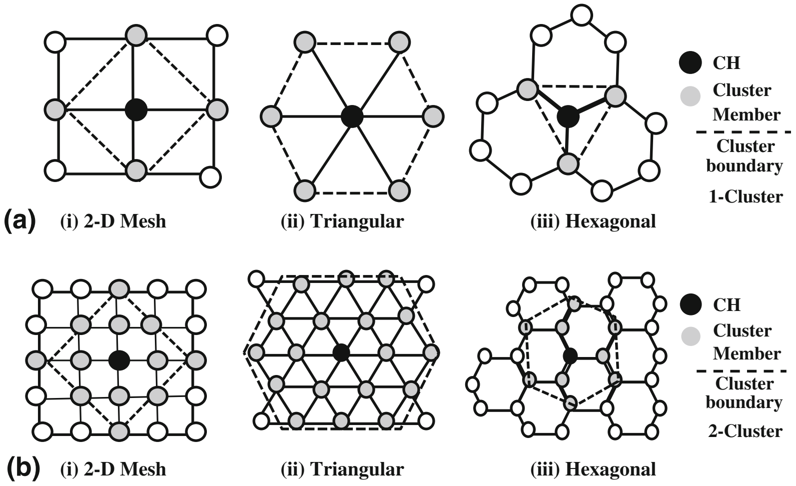
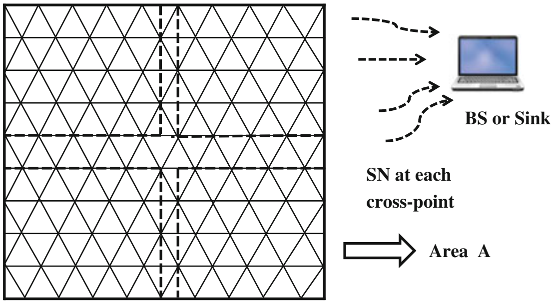


Fig. 15.16 Clustering of WSNs. **a** 1 hop. **b** 2 hops

Fig. 15.17 Clustering of a large triangular WSN



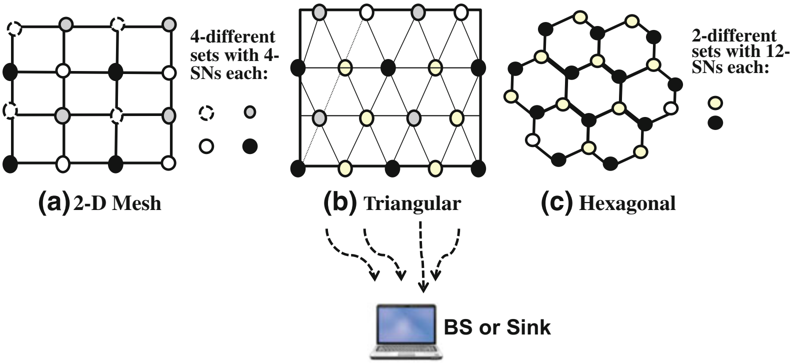


Fig. 15.18 4 sets of sleep–awake cycles in WSNs. **a** 2-D mesh. **b** Triangular. **c** Hexagonal

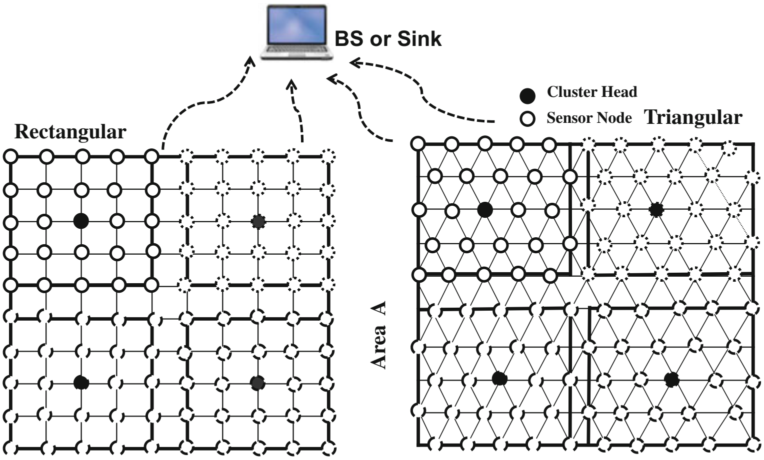


Fig. 15.19 4 sets of sleep–awake cycles in large WSNs with 4 BSs

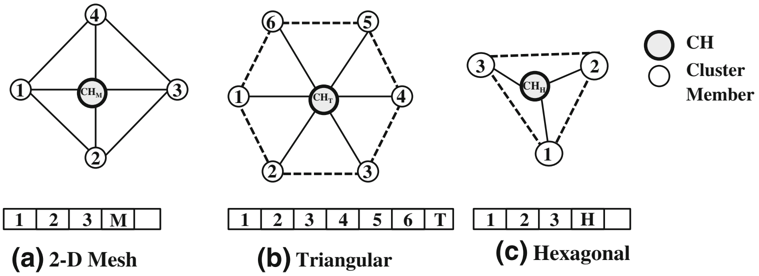
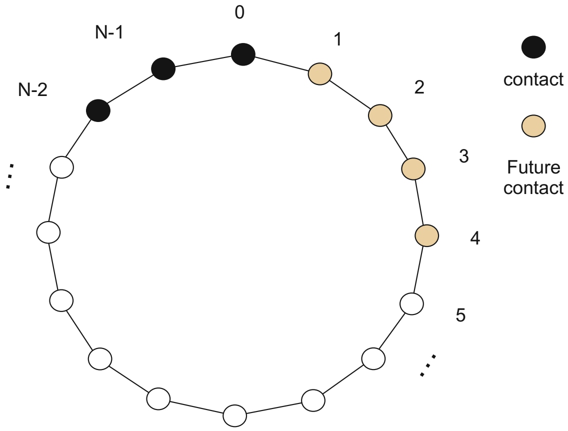


Fig. 15.20 TDMA schedule in clustered WSNs

Fig. 15.21 Random walk on Torus



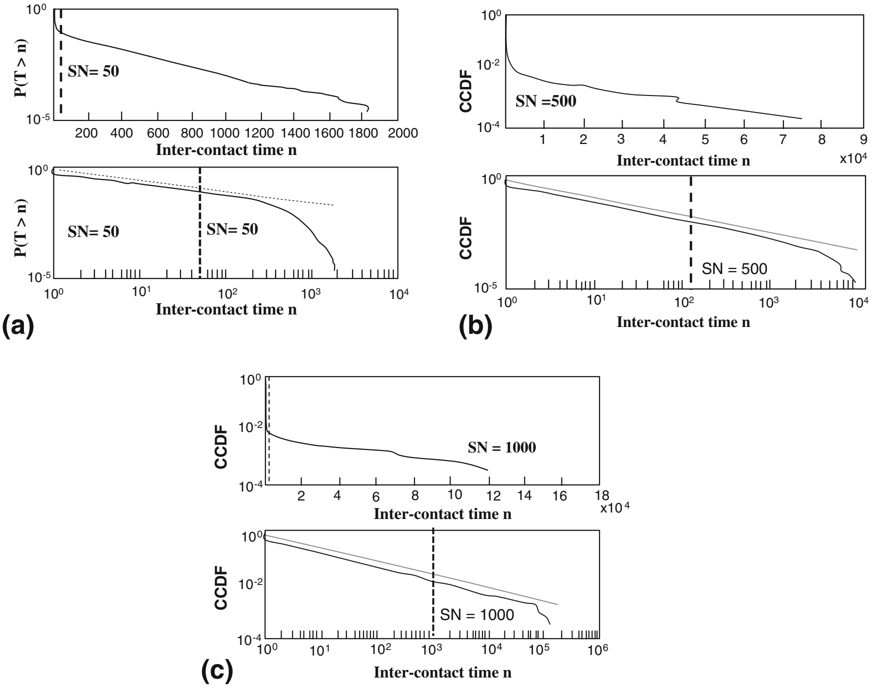


Fig. 15.22 Random walk on Torus with # SNs equal to **a** 50. **b** 500. **c** 1000

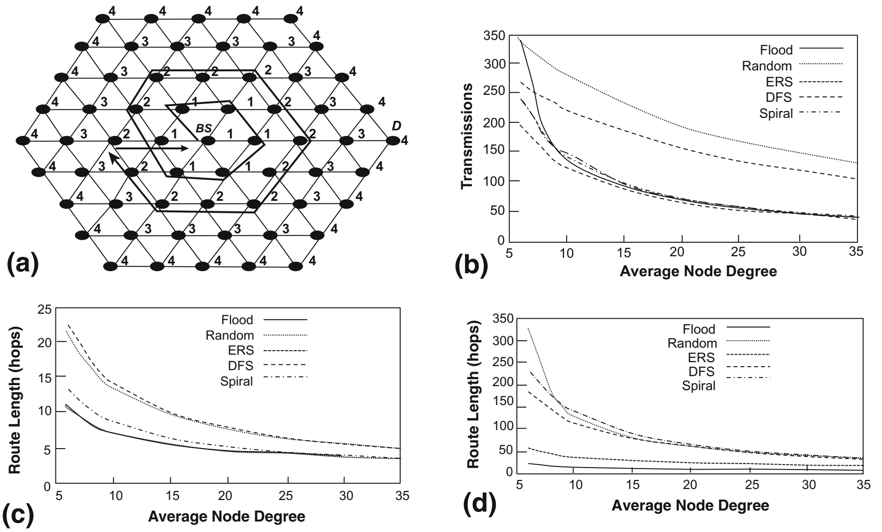


Fig. 15.23 **a** Spiral search process in a triangular WSN. **b** Route discovery cost versus network density. **c** Route length versus network density. **d** Search time versus network density

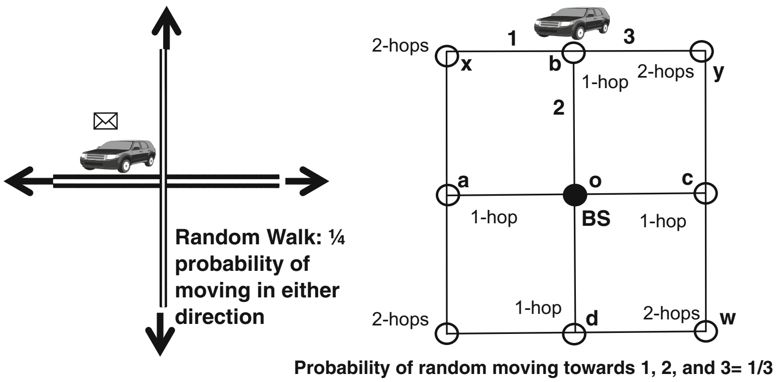


Fig. 15.24 Probability of random mobility in 2-D mesh

desired data and then data can be transmitted along the discovered route to the BS. Spiral reduces the communication overhead and the energy consumption for both route discovery and subsequent communication. One such spiral search in a triangular WSN is shown in Fig. 15.23a and the corresponding performance is shown in Fig. 15.23b, c. Spiral's total cost for 40 packets communication is only 72% to flooding, 81% of ERS (Expanding Ring Search), 74% of random walk, and 73% of DFS (Depth-First Search). In flood-based algorithms, the data query has to be flooded into entire WSN. The SNs with desired data transfer data using discovered the routes.

A MON basically elongates lifetime of WSNs as compared to traditional WSN. It provides constant throughput when number of SN approaches infinity and requires smaller number of SNs and practically no maintenance. The associated disadvantage is potentially long message delay due to intermittent connectivity as mobility of RNs is not controllable. If you have several RNs, you do not know which one SN should give a copy of data. This can be addressed satisfactorily if you know the mobility pattern of RNs. This may be a difficult proposition as SN may know in which direction RN is currently moving. The probability of randomly selecting a path depends on number of paths at a given SN (Fig. 15.24a, b). So, to select an appropriate RN, just use moving direction to determine the bias of each RN and select RN that is moving toward the BS. Thus, by slightly increasing the bias level of the message, forward data to RN with better bias toward the location of the BS. If there is a provision, SN could send many copies of the same data to multiple RNs (Fig. 15.25a). Select RNs such a way that will help to reduce the latency to BS. You could consider complex movement of the data (RN) relative to location of the BS. Latency of a single copy message forwarding algorithms as a biased random walking of message (RN) is shown in Fig. 11.25b, c.

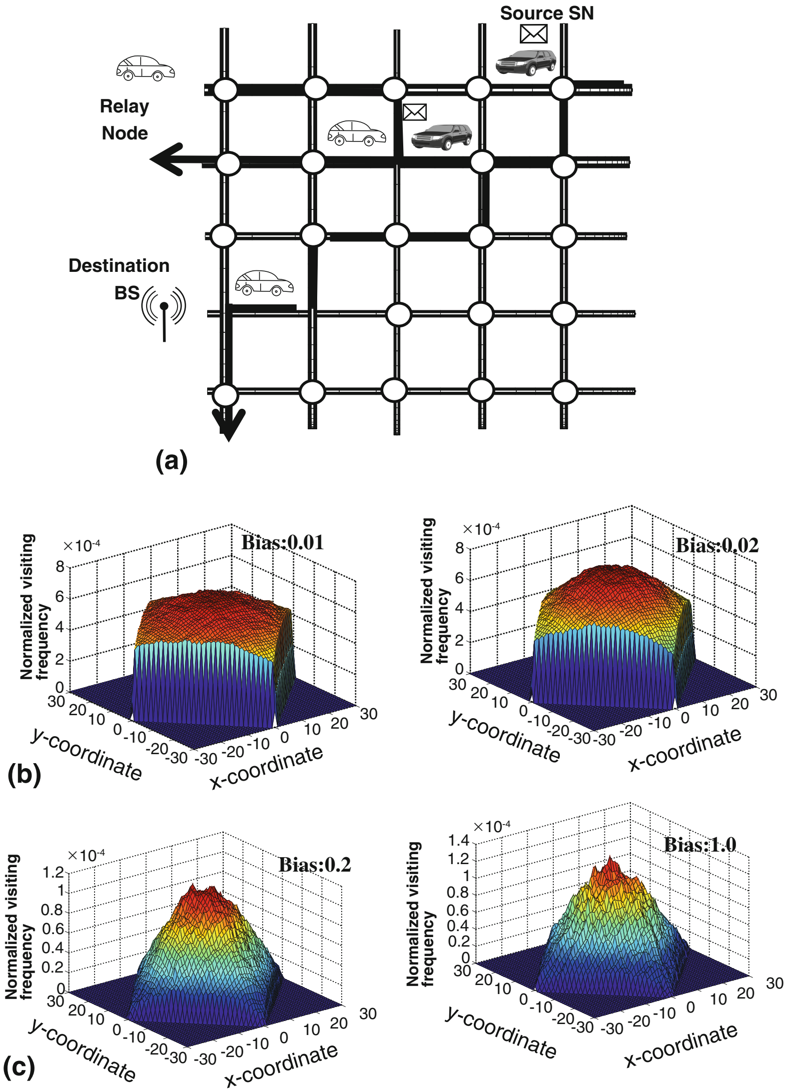


Fig. 15.25 **a** Random mobility in 2-D mesh. **b**, **c** Mobility with different bias to BS

So, there is a need to model a general random walking model that could possess both random walk and random waypoint walk which is difficult to do. So, an approximated formula of average message delivery time as a function of message bias level is feasible as there is a close relationship between mobility and bias. If RNs are independently moving randomly and delivering single copy to the BS via RNs, then that would lead to an optimal relay strategy. So, a basic scheme is to select a random destination point. Define a bias level between zero and one; once

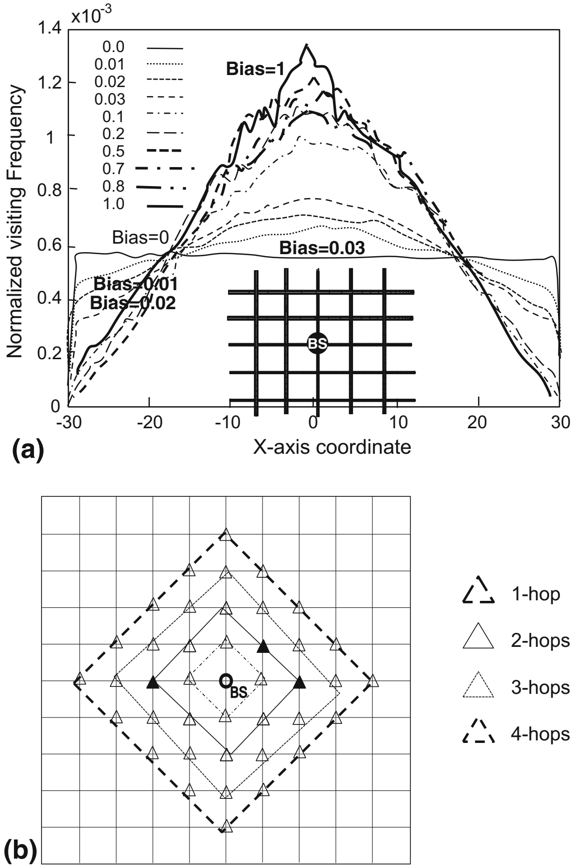


Fig. 15.26 2-D mesh. **a** Normalized visiting frequency on *x*-axis. **b** 1-, 2-, 3-, and 4-hop neighbors [9]

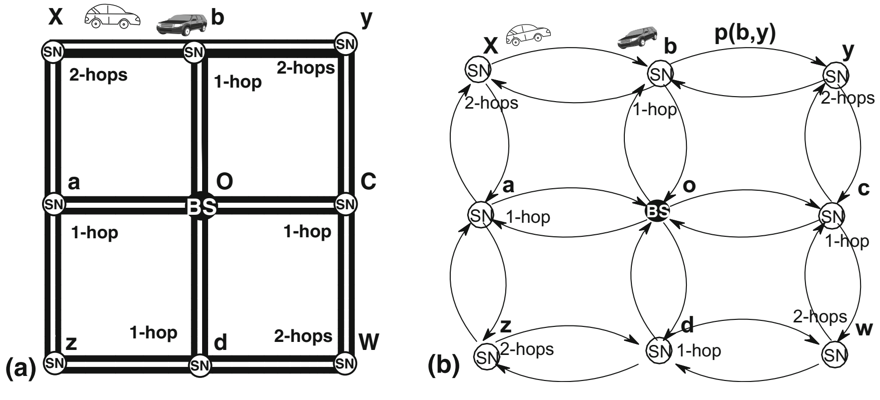


Fig. 15.27 **a** Analyzing relay time in 2-D WSN. **b** Converting to 2-D graph

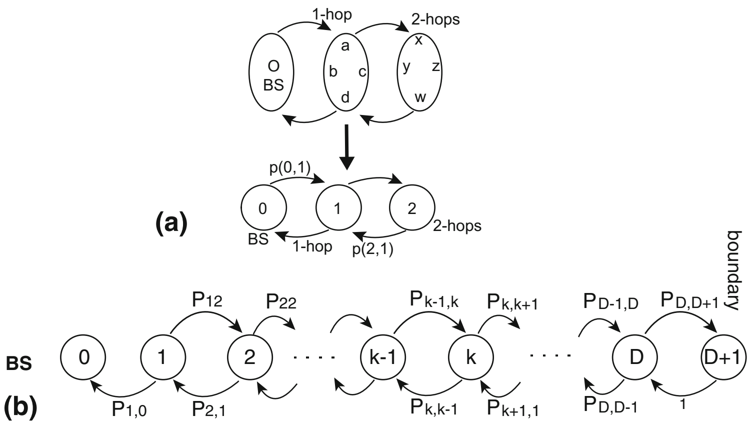


Fig. 15.28 **a** Converting 2-D model to 1-D. **b** Final 1-D Markov model

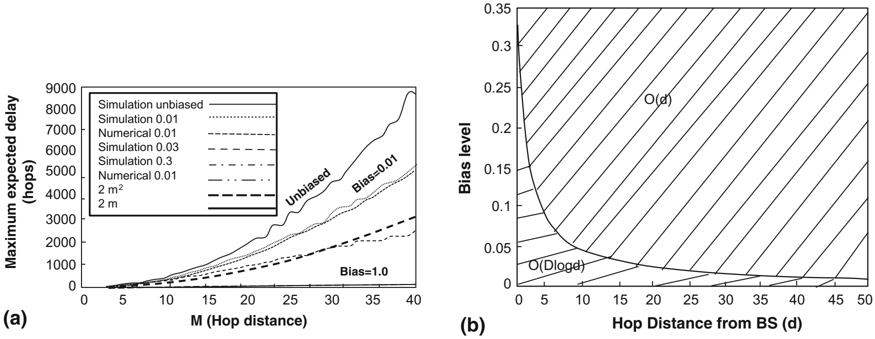


Fig. 15.29 **a** Analytical and simulation results for 2-D mesh. **b** Relationship between bias level and expected latency

the destination is reached, it selects another arbitrary destination (and bias level) and repeats these three steps. Normalized visiting frequency along *x*-axis is shown in Fig. 15.26a and various 1-, 2-, 3-, and 4-hop neighbors in a 2-D mesh from the BS are shown in Fig. 15.26b. If bias level—>0, the schemes become equivalent to a regular random walk; while bias level—>1, the scheme is equivalent to random

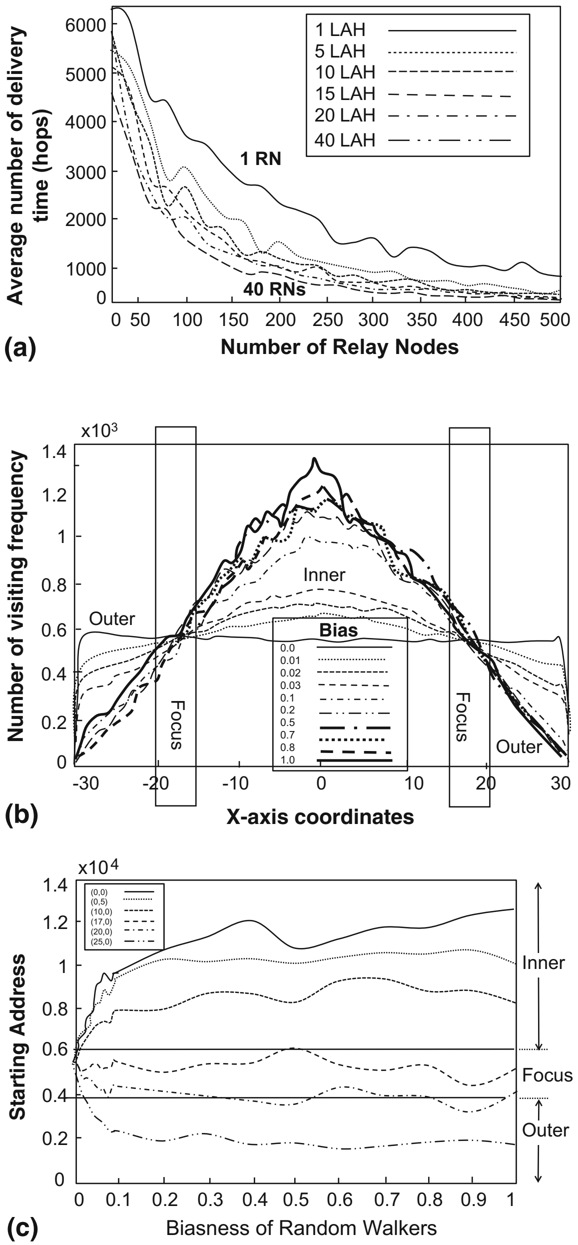


Fig. 15.30 **a** Simulation results with increasing number of RNs in 2-D WSNs. **b** Normalized visiting frequency on *x*-axis when biased changed. **c** Visiting frequency of different biased random walks

waypoint walk without pausing time. We can represent mixture of different random walkers by selecting different bias levels appropriately [9, 10] by modeling as a Markov chain in the case of unbiased walk ($a = 0$). The time taken by a message in reaching BS is given by

$$\begin{aligned} E\left[N_{d,0}\right] &= \sum_{i=1}^{d} \frac{(2D^2+4D+1)}{2i-2} - \sum_{i=1}^{d} \frac{2i^2}{2i-1} \\ &\approx \left(2D^2+4D+1\right) \log(2d-1) - \frac{1}{2}(d^2+d-2) \\ &= \Theta(D^2 \log d) \end{aligned} \tag{15.5}$$

where $(D + 1)$ is maximum distance of a SN from the BS along shortest path and d is the starting state of the random walk. The expected latency under this model is equivalent to generally known hitting time of a random walk in a grid and given by (n is the number of nodes in the grid):

$$\begin{aligned} &n = |V| = 2D^2 + 2D + 1 \\ &\Theta(D^2 \log D) = \Theta(n \log n). \end{aligned} \tag{15.6}$$

Suppose we have a 2-D mesh like topology, where destination BS is at the center of an area. In a biased random walk, with a bias level $0 \leq \alpha \leq 1$, the expected length of random walk path starting at d hops away from the BS follows the following bound:

$$E_{ax} = \begin{cases} O(D^2 \log d), & \text{for } ax = 0 \\ O(D \log d), & \text{for } 0 < ax < \frac{1}{2x+1} \\ O(\max\{d, D-d\}), & \text{for } ax = \frac{1}{2x+1} \\ O(d), & \text{for } \frac{1}{2x+1} < ax \leq 1, \end{cases} \tag{15.7}$$

where x is the current distance of the node from the BS during the random walk, α_x is the bias level at node, and d is the state from where random walk starts. This leads to relay time in 2-D mesh as shown in Fig. 15.27a and simplified to 1-D graph as Fig. 15.27b. The corresponding Markov model is obtained as shown in Fig. 15.28. This gives results of Fig. 15.29 for one RN. When the number of RNs is increased, the results obtained are summarized in Fig. 15.30. The expected delay of biased random walk reduces quickly as bias level is increased from 0 to 0.1 and the delay becomes almost linear when bias level is 0.3. So, a small bias for far away nodes works effectively in a 2-D mesh WSN.

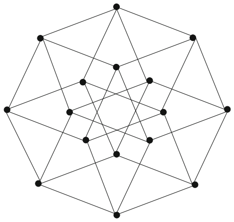
15.5 Conclusions

Regular topologies offer many advantages such as no need for neighbor discovery, easy clustering and CH selection, and underlying TDMA schedule to eliminate any potential collisions. The use of regular topologies ought to be stressed further in civilian applications. Further reduction in energy consumption is possible if relay nodes (RNs) are deployed to collect data from SN in one hop and ultimately deliver to BS. The use of multiple RNs could prove to be very useful.

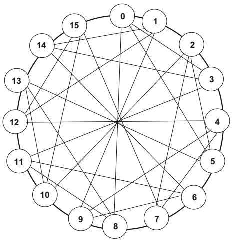
15.6 Questions

Q.15.1. How can you define a cluster in a regular WSN?

Q.15.2. What kind of clustering is possible in the following WSNs?



(i)



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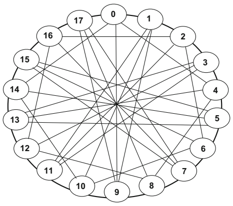
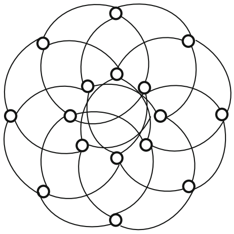
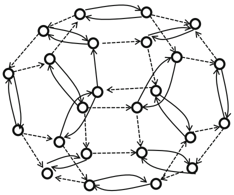


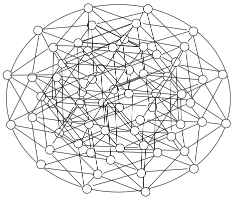
(iii)



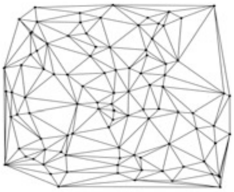
(iv)



(v)



(vi)



(vii)

Q.15.3. Can you use sleep–awake cycles for Problem 15.2?

Q.15.4. Can you determine a TDMA schedule for these examples?

Q.15.5. 4 RN will consume more power than 1 RN. What is the main advantage of using 4 RNs as compared to only 1 RN?

Q.15.6. Can you use RN just to collect data from CHs in place of all SNs? What are the advantages?

Q.15.7. In Q.15.6, can you aggregate data at CH before transferring to a RN? What is its impact?

Q.15.8. In a triangular topology, assume clusters have been defined such that SNs in a cluster are at the most 3 hops away. Can you determine how each cluster looks like?

Q.15.9. In Q.15.8, how do you compare this scheme if aggregation is done for the whole network at BS? What are the advantages and disadvantages of the two approaches?

Q.15.10. Does data gathering from CHs in opportunistic wireless sensor network having 4 RNs depend on the size of the cluster?

Q.15.11. Can you repeat Q.15.8 for hexagonal topology?

Q.15.12. Can you repeat Q.15.8 for rectangular topology for 6 hops away? A RN monitors these CH. Define one way of traversing the WSN so as to minimize visiting time?

Q.15.13. Repeat Q.15.10 when 2 and 4 RNs are used.

Q.15.14. How do you compare data gathering in opportunistic wireless sensor network having 1 RN with a CH-based scheme?

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