Chapter 2
Topology, Routing, and Modeling Tools

In this chapter we discuss basic topology and routing concepts in WSNs, as well as mathematical modeling tools such as Voronoi diagrams and Delaunay triangulations that are used in setting up a framework for coverage, localization, and routing in WSNs.

2.1 Topology and Routing Protocols in WSNs

2.1.1 Topology in WSNs

The topology of a WSN refers to how the nodes are arranged within the network. Although wireless sensor networks consist of sensors that are miniaturized, pervasive, and coordinated, the general principles of topology of WSNs are the same as for any other network. The most common topologies are star, mesh and star-mesh hybrids topologies (see Fig. 2.1). Brief details of each of these topologies follow.

Star Topology In this topology the nodes are organized in the form of a star with the base station as the hub of the star. Sensor nodes broadcast data through the base station, and cannot directly exchange messages between each other. This topology offers low power usage as compared to other wireless sensor topologies. However, the base station cannot communicate with a node that is out of range. The fact that this topology depends on a single node to manage the network exposes it to a single-point-of-failure weakness, which negatively impacts the overall reliability of the network, i.e., the network is not very robust to failures of individual nodes.

R.R. Selmic et al., *Wireless Sensor Networks*,
DOI 10.1007/978-3-319-46769-6_2

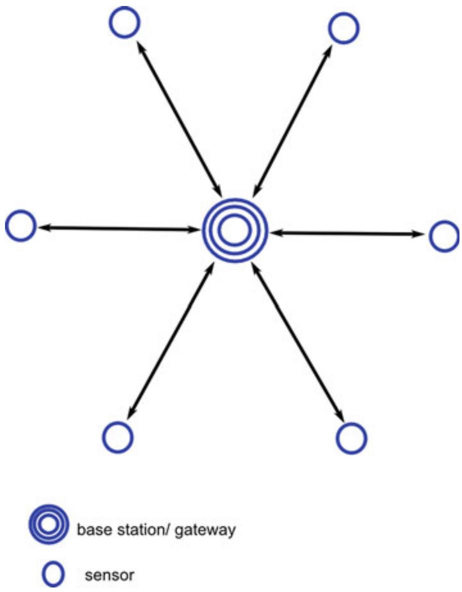


Fig. 2.1 Star topology: all nodes directly connect with the base station and thus communicate with the rest of network

Mesh Topology A WSN with a mesh topology (see Fig. 2.2) has sensor nodes that communicate data through each other. This means that, if a sensor node wishes to send data to an out-of-range node, it can use another node as an intermediate communication resource. One advantage of this topology is that if a sensor node fails, communication is possible with other nodes that are within the communication range. A major disadvantage is that this topology uses more power due to redundant data transmission.

Star-Mesh Hybrid Topology A WSN with a star-mesh topology has attributes of both the star and mesh topologies. On one hand, this topology takes advantage of the low power consumption present in the star topology, while on the other, it takes advantage of the data redundancy present in the mesh topology to ensure data reaches its destination. In the implementation of this topology, nodes at the edge of the network are usually low-energy nodes, while nodes at the heart of the mesh have higher power (and could in some cases be plugged into the electrical mains), since they typically forward messages between large numbers of nodes and serve as a gateway nodes (Fig. 2.3).

2.1.2 Routing Protocols in WSNs

A routing protocol outlines how data is broadcasted through the network. Most routing protocols can be classified as data centric, hierarchical, location based, or QoS aware [1]. Brief details of each of these types of protocols follow.

Fig. 2.2 Mesh topology: nodes do not have to directly connect to the base station, as they can communicate with it via other nodes

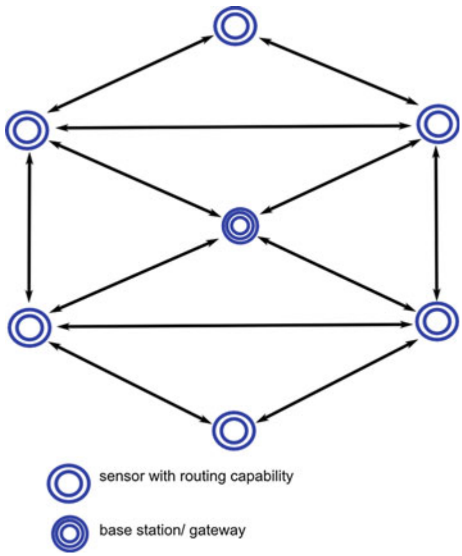
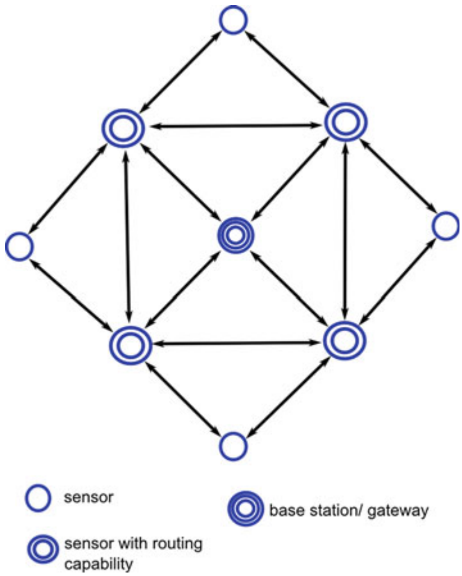


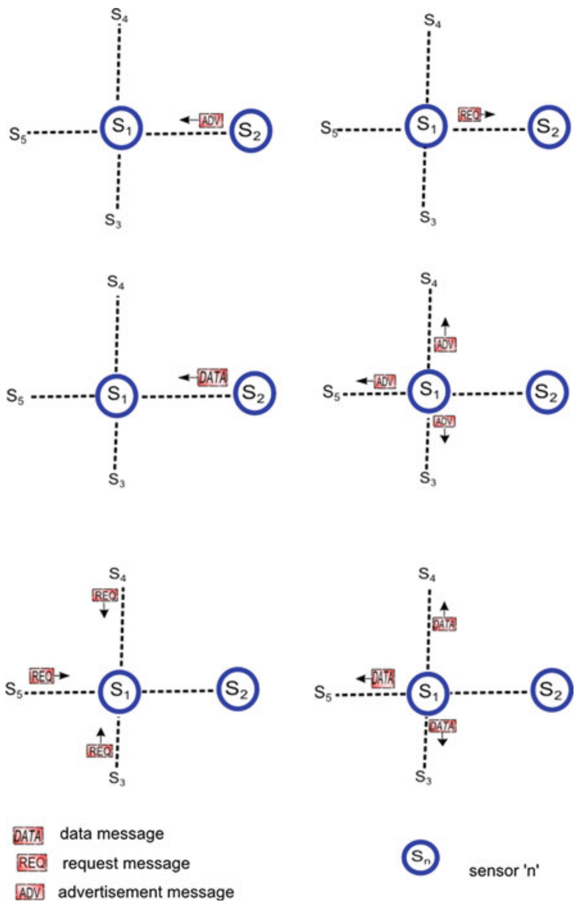
Fig. 2.3 Star-mesh topology: sensors with routing capabilities are connected in a mesh, such that regular sensors can communicate with the base station



Data Centric Protocols In large-scale WSN applications, the large number of randomly deployed nodes makes it infeasible to query sensors using their individual identifiers. One approach to addressing this problem is by sending queries to particular regions (set or cluster of sensor nodes) [1], such that data from sensors in that region is sent in response to the query. The challenge with this approach though is that data from a number of sensors in a given region contains a lot of redundancies, since sensors in any given neighborhood are likely to be sensing the same event (sensor data is highly correlated). Data centric protocols exploit attribute-based naming to aggregate data based on the data properties to eliminate redundancies as the data is sent through the network. This approach achieves significant energy savings in WSNs. Examples of data centric protocols include, Sensor Protocols for Information via Negotiation (SPIN), flooding and gossiping, directed diffusion and rumor routing [1].

Figure 2.4 illustrates the mechanism of operation of the SPIN protocol. First, a sensor advertises its data using the advertisement (ADV) message. Interested neighbors then use the request (REQ) message to request data. Following the request, data is then sent to the interested neighbors. The querying process continues recursively through the network.

Fig. 2.4 Mechanism of SPIN protocol: a node having data advertises this data, and then sends it to interested neighboring nodes if they send requests in response to the advertisement



In the *flooding protocol*, each sensor broadcasts a received packet to all its neighbors until the packet reaches the destination. To avoid infinite looping, the packet propagation process may be interrupted if the packet exceeds a certain predetermined number of hops. Gossiping seeks to improve on the flooding protocol's extensive usage of resources, e.g., energy, due to the large number of messages moving around, by only advertising a received packet to a randomly selected neighbor.

In *directed diffusion*, the base station broadcasts data requests that are recursively sent through the network [2]. On receiving the requests, sensors nodes recursively set up gradients to the requesting nodes, until the gradients propagate back to the base station. A gradient is essentially a link to the requesting node, and defines the data rate, duration and expiration time associated with the request among other variables [1, 2]. In the final step, the best path is selected before data transfer begins.

Rumor routing improves upon directed diffusion by only routing queries to nodes that have sensed a particular event, as opposed to recursive propagation of requests to a wide range of nodes. To achieve this, the rumor routing uses agents, which are packets that convey information about events occurring at different locations of the network.

Hierarchical Protocols In this routing paradigm, illustrated in Fig. 2.5, the WSN is partitioned into clusters whose heads mainly perform tasks of processing (e.g., aggregation) and information forwarding, while the other nodes perform the sensing tasks within clusters. Hierarchical protocols have the advantage of being scalable due to the multi-tiered design while attaining high-energy efficiencies. Examples of hierarchical protocols include low-energy adaptive clustering hierarchy (LEACH), power-efficient gathering in sensor information systems (PEGASIS) and threshold sensitive energy efficient sensor network protocol (TEEN) [1], among others. A brief description of some of the main WSN hierarchical protocols follows.

In the *LEACH protocol*, the role of a cluster head rotates between sensor nodes to prevent a scenario in which the energy reserves of a few nodes may be drained at a much higher rate than the rest of the nodes. With a certain probability (which depends on the amount of energy left at the node), nodes elect themselves to be cluster heads. These cluster heads broadcast their status throughout the network, with the rest of the nodes assigning themselves to certain clusters depending on which cluster head's location is on a path requiring the least communication energy. The cluster head creates a schedule for the sensors in its cluster (e.g., when to turn radio on or off), aggregates data received from nodes within the cluster and also transmits the aggregated data to the base station.

PEGASIS protocol improves on the performance of LEACH by having nodes communicate only with their immediate neighbors, with a single designated node transmitting the data to the base station in each round. To minimize the average amount of energy spent by each node per round, the task of transmitting data to the base station is taken up by different nodes in turns.

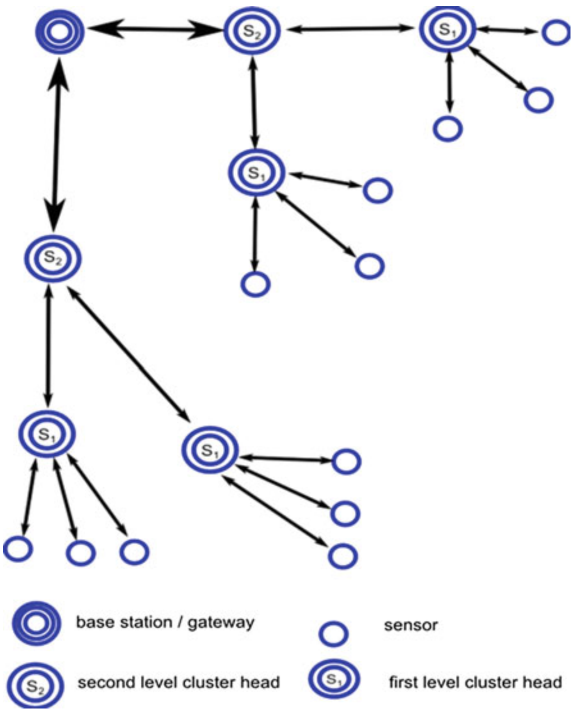


Fig. 2.5 A hierarchical clustering example: sensor nodes are clustered around first-level cluster heads, which in turn communicate to the base station via second-level cluster heads

TEEN protocol is an energy-efficient WSN routing protocol that is designed for time-critical WSN applications in which changes in the sensed variable require immediate reaction. Nodes continuously perform the sensing functions, with the messages broadcast from the base station including threshold values that are used as basis for triggering sensors to forward data that has been sensed. TEEN is not suitable for applications that require data to be continuously relayed, since sensors will never transmit if thresholds are not exceeded.

Location Based Protocols These protocols use information about sensor location to route data in an energy-efficient way [1]. The distance between two sensor locations is calculated and its energy requirement estimated. Location based protocols include minimum energy communication network (MECN), geographic adaptive fidelity (GAF) and geographic and energy aware routing (GEAR) [1].

MECN is applicable to both WSNs and mobile ad hoc networks, and uses GPS to keep track of node locations. The protocol uses node-positioning information to identify paths in the network that minimize the energy required for data transfer. The protocol is built on the concept of a relay region for each node, which defines a set of neighboring nodes via which transmission is cheaper (in energy terms) than direct transmission between a given node and the destination.

GAF was designed for mobile ad hoc networks, but can also be used with WSNs. GAF uses location information to turn off or turn on certain nodes for energy

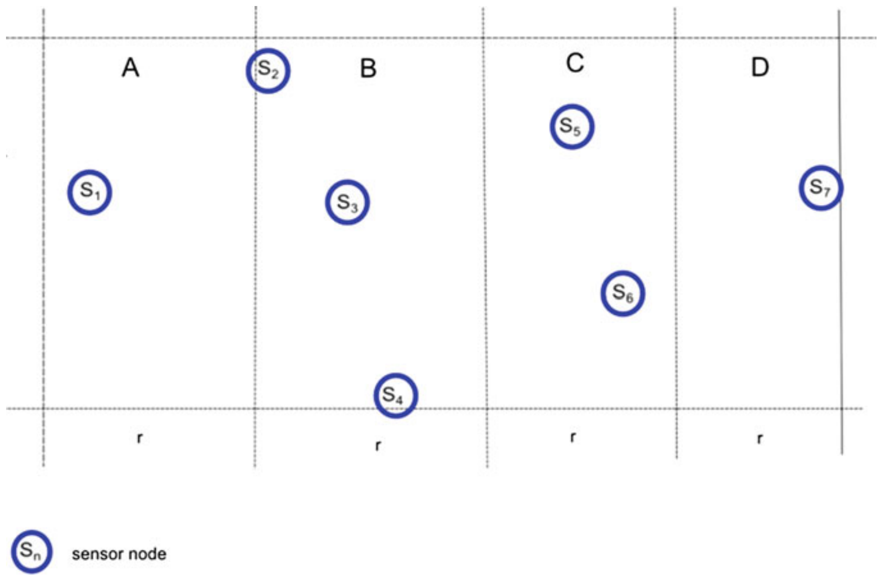


Fig. 2.6 Virtual grid in a GAF protocol: sensors in the same grid can alternate between active and passive states for load balancing and energy conservation

conservation purposes, in such a way not to compromise the routing tasks. Figure 2.6 shows a simple illustration of the function of the GAF protocol. Each node uses its GPS location to associate itself with a point on the virtual grid. Nodes belonging to the same grid are regarded as redundant and alternate between active and dormant states in a bid to save energy. In Fig. 2.6 sensors 2, 3, and 4 are all in the same grid. Similarly sensors 5, and 6 are also located in the same grid. Sensor 1 can reach any of sensors 2, 3, or 4 in region B, and any of them can reach either of sensor 5 and 6 in region C. Therefore, to save energy, only one sensor in region B and C will be active at any given moment while the others are dormant. The sensors will alternate states to balance the load between all sensors in the associated region.

The *GEAR* protocol uses sensor location information to improve on the energy usage of the generalized directed diffusion process by sending queries to only a few selected regions of the network (instead of the whole network). This kind of selective querying is especially useful in sensor network applications where the aim is to collect data on location basis (e.g., the temperature at a certain point at a certain time).

QoS Aware Protocols The previously described categories of WSN routing protocols could also be considered to be QoS-aware, since they seek to optimize variables such as energy consumption, a fundamental factor in determining the QoS obtained from a WSN. As such, the definition of a QoS-aware protocol is not well streamlined in WSN literature, and we briefly discuss the routing protocols which touch on QoS elements such as end-to-end delays and prioritization of packets in the network.

SPEED (*not an acronym*) is a routing protocol that ensures that every packet in the network attains a certain speed during a transfer [1]. The protocol utilizes a form of data acknowledgement mechanism that enables a node to estimate the delay to a given neighbor, which in turn helps to determine which route meets the required transmission speeds. The protocol also offers a form of congestion control during a network overload.

SAR (*sequential assignment routing*) uses the priority of a given packet, network energy and QoS considerations along a link while making routing decisions. Each node is associated with a tree (rooted at the node), which defines a set of paths from the node in question. The paths generally avoid low-energy nodes and are periodically recomputed. The multi-path approach used by SAR makes it fault tolerant, with the best of the tabulated paths being used for routing. For large WSNs, the protocol faces significant overhead in maintaining state and all the tables at the different sensors.

Energy-aware QoS routing protocol is another routing protocol that seeks to minimize energy consumption and end-to-end delays. The protocol classifies traffic as best effort or real-time (real-time data being mainly data from imaging sensors), with real-time data seeing higher priority during times of heterogeneous traffic. The overall performance of the protocol depends on the setting of the bandwidth ratio, a parameter that determines the bandwidth share between different traffic types during congestion.

Other WSN protocols that have been classified as QoS-aware include maximum lifetime energy routing, maximum lifetime data gathering and minimum cost forwarding among others [1].

2.2 Modeling Tools

2.2.1 Voronoi Diagrams

A Voronoi diagram, such as the one shown in Fig. 2.7, is one of the most useful structures in computational geometry. It is named after Georgy Voronoi, a Russian mathematician who generalized and formally defined the n-dimension case in [21]. The origin of Voronoi diagram dates back to Descartes [9] in the 17th century. The first computational algorithm for constructing Voronoi diagram is presented by Shamos and Hoey [19], who investigate in problems regarding to the proximity of a finite set of distinct points in Euclidean space, such as finding a minimum spanning tree, identifying the smallest circle enclosing the set of points, locating the nearest and farthest neighbors. Ever since, a lot of researchers have devoted to this field. A dual diagram that [23] can be constructed from Voronoi diagram is called Delaunay tessellation or Delaunay triangulation, which is named after Boris Delaunay [8]. A complete overview on the Voronoi diagrams can be found in [18].

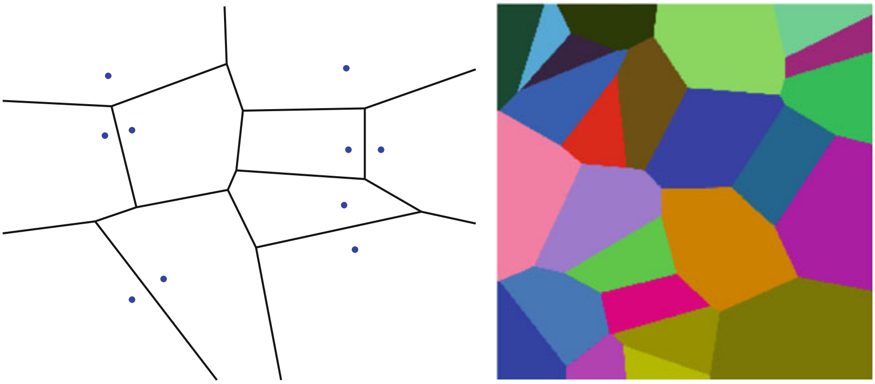
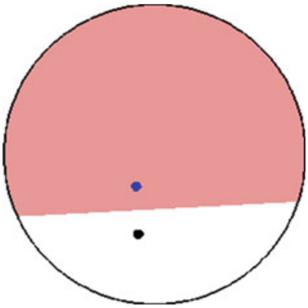


Fig. 2.7 Two examples of Voronoi diagrams created with randomly deployed points

Fig. 2.8 The bisector of two sites divides the plane into two half-planes



Voronoi diagram is a form of decomposition of metric space with respect to the Euclidean distances (other metrics can also be used) to specific set of points in the space. We consider only the situation when there are finite points in the space. Voronoi diagram with infinite number of points are called infinite Voronoi diagrams and are described in [18].

Let S be a set of distinct points $p_1, p_2, \ldots, p_n$ in the Euclidean space, where $n < \infty$ and $I_n = \{1, 2, \ldots, n\}$. To distinguish points p_i' that $p_i' \in S$ and point p_i that $p_i \in S$, we define point p_i as Voronoi site p_i [3], or site p_i for short. In case of 2-dimensional Euclidean space, each of the generated Voronoi polygons will contain only one site $p_i \in S, i \in I_n$. Meanwhile, any site $p_i' \notin S$ that is inside a give polygon $V(p_i)$ is closer to the corresponding site $p_i \in S$ than to other sites in S. Voronoi diagram divides the plane into regions such that each point of a single region has the same closest site, Fig. 2.8. The formal mathematical definition of a planar ordinary Voronoi diagram is stated in [18]. Suppose the Cartesian coordinates of site p_i are labeled as a pair

$p_i = (x_i, y_i)$ where $p_i \neq p_j$ for $i \neq j$, $i, j \in I_n$. Then, the Euclidean distance between point p and site p_i is

$$d(p, p_i) = \sqrt{(x - x_i)^2 + (y - y_i)^2}. \tag{2.1}$$

and the Voronoi diagrams is given by the following definition:

Definition 2.1 Let $S = \{p_1, p_2, \ldots, p_n\} \subset \Re^2$, we call the region given by

$$V(p_i) = \{p | \|p - p_i\| < \|p - p_j\| \quad \text{for } i \neq j\}. \tag{2.2}$$

the Voronoi polygon of p_i. The set $V = \{V(p_1), V(p_2), \ldots, V(p_n)\}$ is called as the *planar ordinary Voronoi diagram* generated by sites S. Each site p_i is called the *generator site* of the corresponding Voronoi polygon $V(p_i)$, Fig. 2.9. The boundaries of Voronoi polygon, which is defines as *Voronoi edges*, consist of line segments, half lines or infinite lines. The end points of Voronoi edges are called Voronoi vertices.

Based on Definition 2.1, the bisector of any pairwise site i and site j $(i \neq j)$ divides the Euclidian space into two half spaces, $H(p_i p_j)$ and $H(p_j p_i)$ as shown in Fig. 2.8.

The Voronoi polygon $V(p_i)$ can be formed as an intersection area of half spaces, which is considered in the following definition.

Definition 2.2 The Voronoi polygon $V(p_i)$ can be formed as

$$V(p_i) = H(p_i p_1) \cap H(p_i p_2) \cap \cdots \cap H(p_i p_n). \tag{2.3}$$

Suppose there are four sites in Euclidian space. Figure 2.10 shows the process to form the Voronoi polygon $V(p_1)$ based on Definition 2. 2.

Voronoi polygons of other sites can also be formed in the same fashion and the computation complexity is $O(n^2 \log n)$. Shamos [20] have shown that a lower bound for the computation of Voronoi diagrams is $O(n \log n)$, where x-coordinates of all sites have to be strictly increased. Some algorithms such as divide and conquer

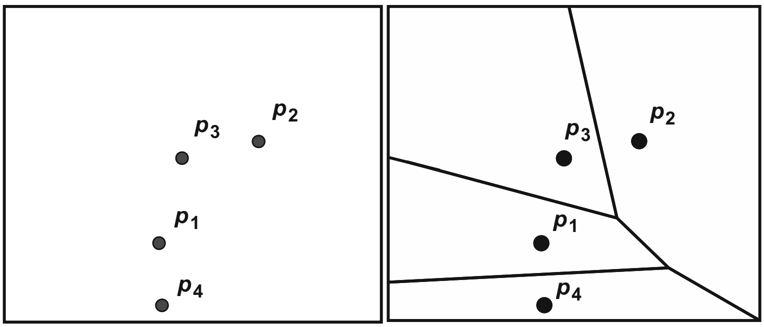


Fig. 2.9 The Voronoi generator site and the corresponding Voronoi polygon

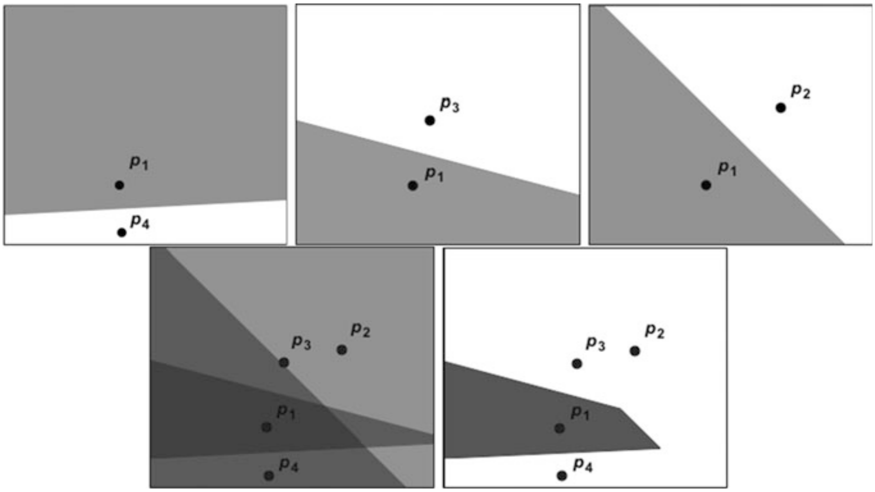


Fig. 2.10 The formation of Voronoi polygon as described in Definition 2.1

based algorithm and sweep line based algorithm can run in $O(n\log n)$ with specific data structure to satisfy the same condition. For example, Fortune's algorithm [10] uses binary search tree to store the structure of sweep line.

Voronoi diagrams and Delaunay triangulations have been widely used in many fields [3, 4, 11, 18] from biology to chemistry, from marketing to astronomy, and many others. In the area of wireless sensor networks, Voronoi diagrams have been extensively used for coverage related problems [14, 15, 22], motion planning problems [16, 24], routing problems [12, 17], localization problems [5], target tracking [7], and others.

2.2.2 Delaunay Triangulations

A triangulation T on a point set P in two-dimensional space (can also be equivalently analyzed in higher-dimensional spaces) is a set of triangles such that [6]:

a. A point p is a vertex of a triangulation triangle if and only if $p \in P$;
b. The intersection of two triangles is either an empty set or an edge of a triangle;
c. The set T is maximal: there does not exist any triangle that can be added to T without violating the previous rules.

A triangulation T is a Delaunay triangulation if and only if the circle circumscribing each triangle does not contain any point of the set P. Figure 2.11 shows Delaunay triangulation for a set of points in two-dimensional space.

Note that Delaunay triangulation is not unique if there are four or more points lying on the same circle. For example, consider a square and its four vertices. There

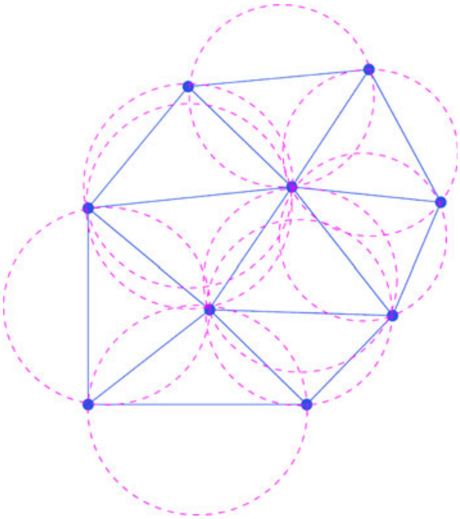


Fig. 2.11 Delaunay triangulation for a set of points in two-dimensional space

are two possible ways to triangulate those four points (draw those triangulations as an exercise). In case of all points lying on the same line, triangulation is not possible.

Delaunay triangulation and Voronoi diagrams are dual. Two vertices are connected in Delaunay triangulation if and only if they share a common boundary in Voronoi diagram. The Voronoi vertex is the circumcenter of some Delaunay triangle, Fig. 2.12.

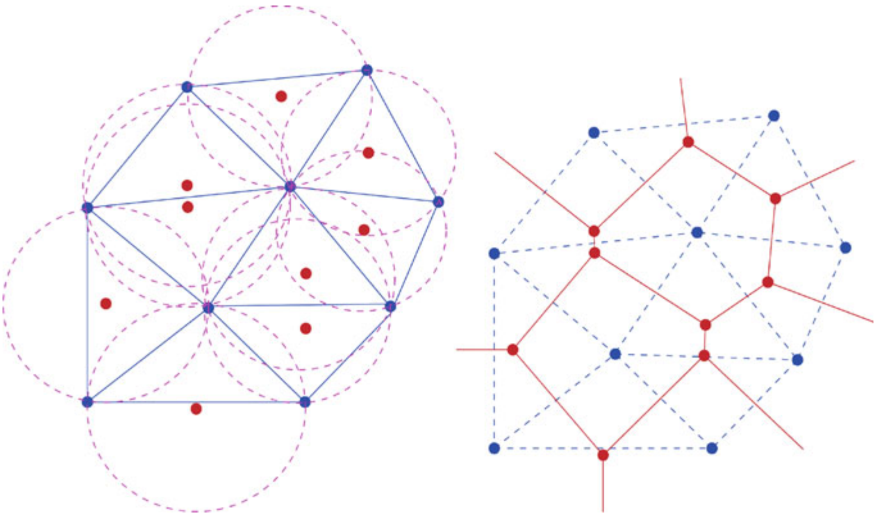


Fig. 2.12 Delaunay triangulation is dual to Voronoi diagram: circumscribing *circles* and their centers (*left*) and Voronoi diagram created from the Delaunay vertices (*right*)

Delaunay triangulation or Voronoi diagram cannot be generated in a fully distributed fashion. For a large circumcircle of three nodes, one needs to check if the circle is empty of other nodes [13], thus requiring centralized information such as location of all other nodes in the network. Construction of Delaunay triangulation of full network would require extensive communication among all nodes, and therefore, is not very practical. Its construction time complexity is $O(n\log n)$ [13].

Questions and Exercises

1. Briefly describe the concept of data aggregation as used in wireless sensor networks. What are its advantages? You may use a drawing and (or) an example of a WSN application of your choice for illustration purposes.
2. One of the categories of routing protocols for WSNs is a group of QoS-aware protocols. How do you understand the term “QoS” as used in WSNs? How do the QoS demands of WSNs differ from those of regular computer networking applications?
3. Describe in detail the mechanism of operation of one QoS-aware routing protocol in WSNs. Can a QoS-aware routing protocol be hierarchical at the same time? Please explain.
4. What is the SPIN protocol’s major weakness? For what kinds of applications would SPIN be unsuitable? With the aid of diagrams if possible, briefly describe the weaknesses and strengths of the flooding and gossiping protocols for WSNs.
5. Given a set of points $A = \{(-2,2),(2,2),(-2,2),(-3,-3)\}$, draw the Voronoi diagrams and Delaunay triangulations. Repeat the same task for the set $B = \{(-2,2),(2,2),(-2,2),(-2,-2)\}$.
6. Explain why Voronoi diagrams and Delaunay triangulations are dual? How is such duality related to their geometrical interpretation?
7. Given N homes in a region, where within the region to place a nuclear power plant such that it is as far away from any home as possible?

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Wireless Sensor Networks
Security, Coverage, and Localization
Selmic, R.R.; Phoha, V.V.; Serwadda, A.
2016, XIV, 215 p. 122 illus., Hardcover
ISBN: 978-3-319-46767-2