Chapter 2
Communication Technologies in IoT Networks

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2.1 Introduction

Internet of Things (IoT) has emerged as one of the promising and prominent areas of the 5G communications. As 5G anticipates interconnecting millions of devices around the globe, IoT will be seen as an integral part of various applications such as smart cities, intelligent transportation services, smart grids and many others. Each application area of IoT promises enhanced quality of experience in everyday life activities. For instance, the motivation behind smart cities is to have control over resources, thereby, promoting healthy economy and sustainable growth. To accomplish a successful operation of an IoT era, a network of IoT requires every device to be connected to its utility gateway directly or indirectly. Therefore, these devices are needed to be equipped with smart sensors that collect their data and forward this data to their network operation center for further processing. Many types of IoT networks including centralized and distributed networks have been proposed. However, communications for an IoT network poses an important challenge for its successful operation. Many communication technologies are proposed that can work in conjunction with an IoT network, however, this chapter focuses in detail about a particular form of technology namely the *cooperative communications*, which when utilized in an IoT network promises, large network gains.

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F. Hussain, *Internet of Things*, SpringerBriefs in Electrical and Computer Engineering, DOI 10.1007/978-3-319-55405-1_2

In this chapter, various types of IoT sensors and the mode of communication between them are discussed. We also discuss cooperative mode of operation in sensor networks and outlines many topologies that can be utilized. Performance analysis of cooperative communication is also presented to supplement the concepts.

2.2 Types of Sensors used in IoT Network

There are plethora of sensor and actuators that can be used to create various forms of IoT networks. Since this chapter mainly deals with sensor networks and their communication techniques, the following non-exhaustive list of sensors can be used to form homogeneous or heterogeneous networks.

- Machine vision/ optical ambient light sensors
- Acceleration/ tilt sensors
- Position and presence sensors
- Motion, velocity and displacement sensors
- Humidity, temperature and moisture sensors
- Leaks and levels sensors
- Electric and magnetic sensors

A more comprehensive detail of sensor can be found in [1, 2] and references therein. The current and common candidates for communication between these sensor nodes are from mobile communications family including global system for mobile communications (GSM), general packet radio system (GPRS), universal mobile telecommunication system (UMTS)/3G, long term evolution (LTE)/ 4G, satellite communications, licensed or unlicensed radio networks and power line communications (PLC) [3]. These sensor nodes, when transmit or receive data, establish radio links and are therefore termed as IoT nodes or devices in addition to commonly known sensor nodes. The chapter will use these terms interchangeably. The upcoming section presents the transmission strategies on the basis of which these IoT devices communicate with their peer nodes and then the chapter focuses on cooperative method of transmitting or broadcasting data to the entire network.

2.3 Transmission Strategy

The smart IoT devices in a sensor network usually have constraint battery life and operate generally at low transmit powers, therefore, these devices cannot transmit wirelessly to a far-off destination gateway having a direct communication link. Instead, the acquired data is transmitted in a multi-hop fashion to a far-off aggregation point using the intermediate devices as relays. This multi-hopping is performed by the IoT devices that are in a close vicinity to one another. Each IoT sensor device, in cooperation with the devices in its vicinity, relays the data received from its preceding IoT device(s) to their successor nodes consuming minimal power. This cooperative transmission of data from one set of IoT devices to the next is known as *cooperative communications*. This cooperative transmission phenomenon along with its relaying mode is discussed in the subsequent sub-section.

2.3.1 Cooperative Communications

Cooperative communications is one of the mature domains of modern communication era. The cooperation between IoT devices helps in sustaining the resources of an IoT network. Some of the advantages of this cooperative relaying of information include the increase in diversity thereby increasing reliability, signal-to-noise ratio (SNR), data rates, and hence the increase in the successful hop count or the maximum distance or hops traversed by the information symbols [4]. All these features of cooperative communications are discussed in detail in the subsequent topics of this chapter.

From the past few years, cooperative relaying methods are under consideration of the researchers while developing transmission strategies for inter-device communications. The initial cooperative relaying strategy considered the source destination pair connected via relays in a two-hop manner as shown in Fig. 2.1. However, dense IoT networks with a variety of devices scattered in an area require multi-hop communications for successful data delivery. In cooperative relaying methods, a symbol is transmitted in each time slot. Hence, in conventional strategies, having a single relay between a source-destination pair, the information rate couldn't achieve its maximum limits. These rates were improved by exploiting the channel fading effects and broadcast nature of the wireless channels through diversity.

Multipath fading affects all the wireless channels, causing the variability of received signal level with time and location. In addition to diversity techniques such as temporal, frequency and spatial diversity, a novel idea of achieving diversity is by

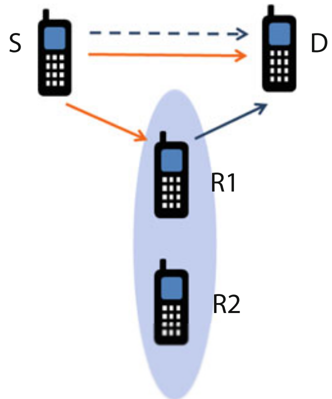


Fig. 2.1 The phenomenon of cooperative relaying. The source node S, uses the help of relays R1 and R2 to deliver the data to the destination node, D. The direct link between S and D may or may not exist. The same information transmitted by relays add the diversity and array gain at the destination, making an overall reliable communication

cooperatively transmitting the information from IoT relaying devices. This improves the chances of correctly receiving the data and minimizes the effect of multipath fading.

The relaying is largely categorized into two types based upon processing of received data. The two major types of relaying are amplify-and-forward (AF) and decode-and-forward (DF).

- Amplify-and-Forward (AF) Relaying: According to AF relaying, the information received at the intermediate IoT device will not be decoded and only the amplified version of the received signal along with noise will be relayed to the successor IoT device(s) of the next hop.
- Decode-and-Forward (DF) Relaying: In DF relaying, the information is relayed to the next set of devices by a preceding IoT device if and only if the data has been correctly decoded by the device. Otherwise, this device will not take part in the cooperative relaying of data towards the destination.

Mostly, the nodes use the DF relaying scheme because of their operation in low SNR regimes, thereby, making an array of devices or hops that remained successful in cooperatively relaying the data.

With all the above inherent advantages of cooperative communication in IoTs, the major issue that this transmission strategy faces is the receive and transmit timing synchronization between the individual IoT devices and the modeling of data propagation. The next sub-section will present the transmission modeling of these cooperative IoT networks by taking into account some possible device arrangements.

2.3.2 *Modeling of Cooperative IoT Network*

Forwarding or relaying of data packets forming wireless multi-hop communications not only finds its application in sensor and cellular networks but also in mobile computing and wireless computer networks. One such promising technique that also finds its application in the IoT domain is opportunistic large array (OLA) that works on the principle of DF relaying. In OLA, each IoT device decodes the received data and immediately cooperatively relays it to the next set of devices without having any coordination with the devices nearby. This information transverses from hop to hop given that in each hop at least one of the devices decodes the information received from the IoT devices of the previous hop. The set of devices that receives the information at the same time instant forms a hop. In this fashion, the data particularly reaches its destination in an inherent energy efficient manner [4].

There is a possibility that because of the opportunistic nature of communications, none of the devices in a particular hop decodes the information thereby resulting in a killing state. The conditional probability that a node decodes the message, given the message was transmitted before, remains the same for each hop in a given topology, and has paved path for modeling these types of networks by using Markov chains. The decision of successful decoding the data is made on the basis of received SNR being greater than a predefined threshold τ. The range analysis with respect to required SNR margin for the IoT network can be performed by considering the geometry of the nodes, types of channel models and channel impairments.

The propagation of data through an IoT network at physical layer can be modeled by first considering the fixed arrangement of devices along the grid for simplicity. This grid geometry can be one-dimensional (1D) grid geometry and two-dimensional (2D) geometry. In the next subsections, we discuss these topologies and provide performance analysis as to how an IoT network consisting of devices can use cooperative communications to deliver data to a distance destination.

2.3.2.1 1D Linear Arrangement of Nodes in a Network

For modeling of 1D IoT network as explained earlier, the fixed M number of devices can be arranged in a linear grid manner in each hop as shown in Fig. 2.2. Any IoT device in a given level can decode and forward the received message without error given that the received SNR from the previous level or hop is greater than or equal to a threshold. The filled black circles represent the DF devices in each hop. These DF devices from each hop cooperatively transmit the message over the orthogonal channels that can be formed by using orthogonal space-time block codes (OSTBCS). Considering the channel between the nodes to be flat faded Rayleigh, the resultant aggregated power, Y, at a jth node in any hop has a hypo-exponential distribution [5] given as:

$$p_Y(y) = \sum_{k=1}^{K} C_k \lambda_k exp(-\lambda_k y), \tag{2.1}$$

where,

$$C_k = \prod\nolimits_{\varsigma \neq j} \frac{\lambda_\varsigma}{\lambda_\varsigma - \lambda_k},$$

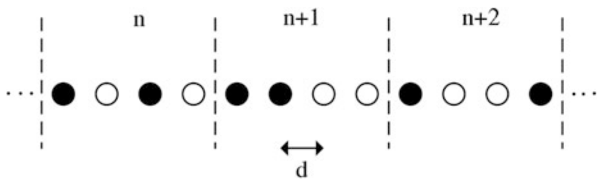


Fig. 2.2 1D arrangement of nodes in a network

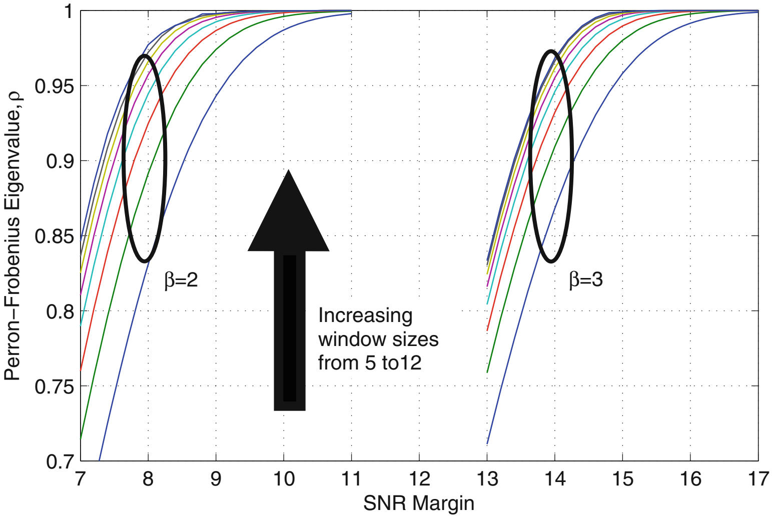


Fig. 2.3 one-hop success probability ρ, which shows the probability that at least one node has decoded and the process of transmission continues

where λ_k is the parameter of exponential distribution, which takes into account the path loss.The probability of successfully decoding a message by a node of the nth hop can then be calculated by integrating the above expression from τ to ∞. This success probability of one node can be used to define the success of a hop and in turn the coverage of the network. In Fig. 2.3, the one-hop success probability, ρ, is shown for different values of required SNR margin, γ. Hence, with the increase in ρ, the probability of successfully decoding a data by different nodes of a hop increases as shown in Fig. 2.3. Also, with the increase in the number of nodes in a hop M, the one-hop success probability, ρ, improves for a given value of SNR margin. The figure also shows that with the increase in the path-loss exponent, β, a higher SNR margin is required for achieving specific success probability.

The performance of the cooperative IoT network versus non-cooperative is depicted in Fig. 2.4 in terms of coverage or the normalized distance an information block transverses for a given quality-of-service (QoS), η. The h_d is the hop count or the percentage of nodes that decodes the data, β is the path-loss exponent, γ is the required SNR margin, and M is the number of nodes in each hop of a cooperative network having fixed boundaries. More importantly, the figure shows that the performance of cooperative case is better than the non-cooperative case for a given SNR margin. The general trend that can be observed is that, with the increase in the number of nodes per hop, M, hop-count h_d increases and so the coverage also increases. Therefore, a large number of IoT devices in a hop can be used for better performance of the overall network.

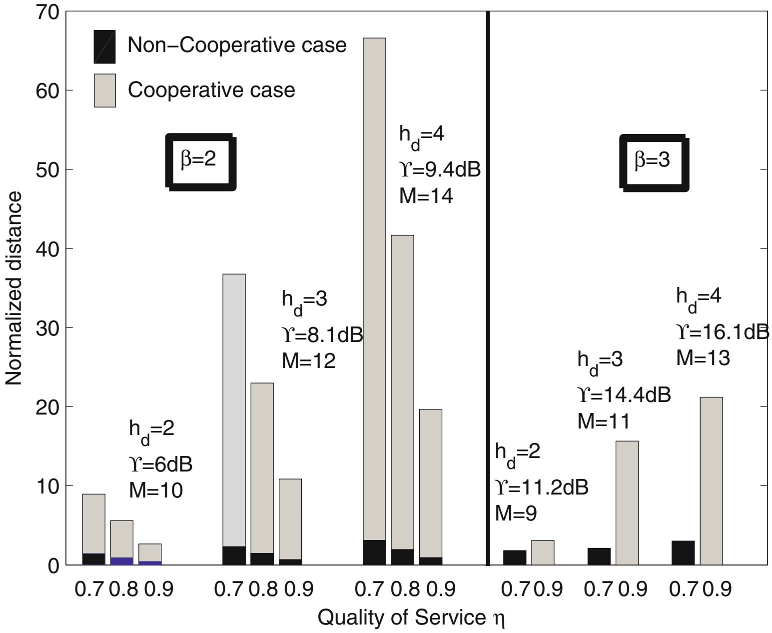


Fig. 2.4 Normalized distance for various cooperative vs. non-cooperative cases

The sensor devices/nodes in a linear cooperative IoT network can also be arranged in a cluster-based co-located manner and its pros over distributed geometry are discussed below.

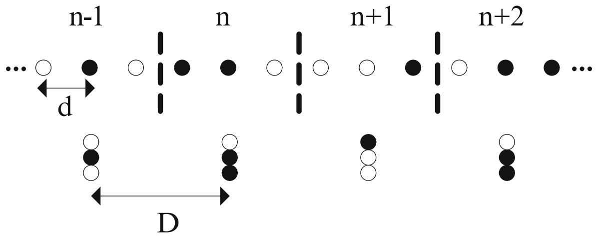
2.3.2.2 Distributed Versus Cluster-Based Linear IoT Networks

In addition to one-dimensional (1D) arrangement of devices that consists of equally spaced nodes along a line, there is another topology in which the nodes in a hop are placed in a co-located fashion by forming groups along a line as shown in Fig. 2.5.

The major difference between the distributed and co-located topology is that there exists a disparate path loss between the nodes of two hops in case of distributed nodes arrangement. Whereas in case of co-located arrangement, all the nodes of one hop will have same path loss with the nodes of other hop. This same path-loss for the co-located case will result in same exponentially distributed received powers from the nodes of previous hop, i.e. having same λ_k, giving rise to Gamma distribution having PDF as given in (2.2) [6].

$$p_Y(y) = \frac{1}{(|\mathbb{N}n| - 1)!}\tilde{\lambda}^{|\mathbb{N}_n|} y^{(|\mathbb{N}_n|-1)} exp(-\tilde{\lambda} y). \tag{2.2}$$

Fig. 2.5 Equi-distant distributed and co-located topologies in line IoT network



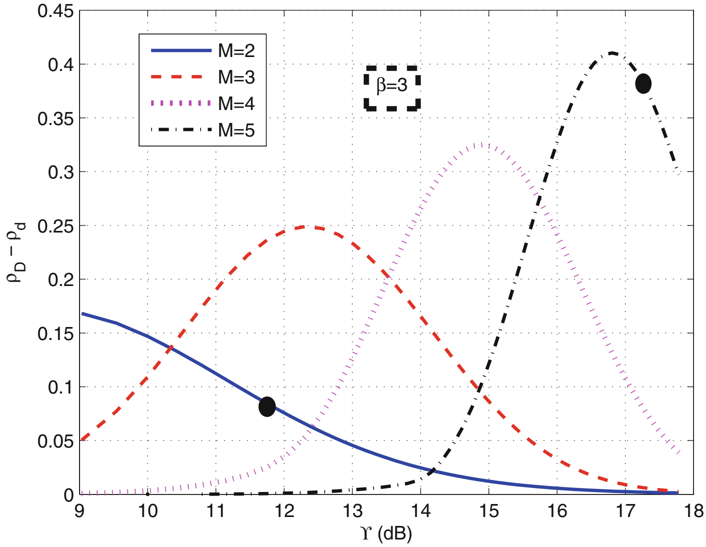


Fig. 2.6 Eigenvalue differences between two topologies; $\beta = 3$

where, $\mathbb{N}_n$ is the set of DF nodes and $|\mathbb{N}_n|$ is the cardinality or length of the DF set. The same path-loss between the node of the two hops accounts for better received power at the jth node of nth hop, and hence results in better one step success probability as shown in Fig. 2.6 for a path-loss exponent of $\beta = 3$.

In Fig. 2.6, the difference between the one-hop success probability of distributed, ρ_d, and co-located, ρ_D, is displayed for different values of SNR margin, γ, and M. The positive difference, i.e., $\rho_D - \rho_d$ shows that the performance of co-located IoT network is better than the distributed IoT linear network, in terms of one-hop success probability, ρ. These results can be extended to a two-dimensional (2D) grid IoT nodes topology, which are presented in the next section of this chapter.

2.3.2.3 2D IoT Network

IoT nodes can either be arranged on the intersection points of a grid and can also be placed randomly along a strip considering strict boundaries in the 2D space. The modeling of the 2D grid-strip is performed in exactly the same manner as of 1D network. But, in case of stochastic node positions along a strip, the distribution of random distance comes into account while examining the performance in terms of energy efficiency and possible obtainable coverage range. The modeling and performance of both of these networks are discussed in the upcoming sub-sections.

2D Grid-Strip IoT Network

The cooperative relaying through these types of networks can take place efficiently on orthogonal channels by employing deterministic orthogonal space-time block codes (OSTBCs) [7, 8]. This implies that the DF nodes of a hop act as virtual multiple-input multiple-output (MIMO) antennas that cooperatively transmit the data block towards the next hop nodes by using OSTBCs. These OSTBCs help in achieving the diversity, reliability, and coverage requirements. This 2D grid-strip geometry having four nodes in each hop is shown in Fig. 2.7.

While using OSTBCs, each node transmits the block of data symbols that makes the one column of OSTBC, whereas, the rows of the OSTBC correspond to multiple time slots. The signal vector received in P time slots at the kth node of nth hop will be [9];

$$\mathbf{y}_{(n)}^{(k)} = P_t \mathscr{G} \left(\mathbf{h}^{(k)} \circ I\,(n-1) \right) + \mathbf{z}, \tag{2.3}$$

where $\mathbf{y}_{(n+1)}^{(k)} \in \mathbb{C}^{P \times 1}$, i.e., $\mathbf{y}_{(n)}^{(k)} = \left[y_1^{(k)} \; y_2^{(k)} \; \cdots \; y_T^{(k)} \right]^T$ is the received signal vector at the kth node of the nth hop and P_t is the transmitted power.

The receiver node applies the decoding of the space-time matrix for retrieving the information symbols back. The coverage trend in terms of number of hops

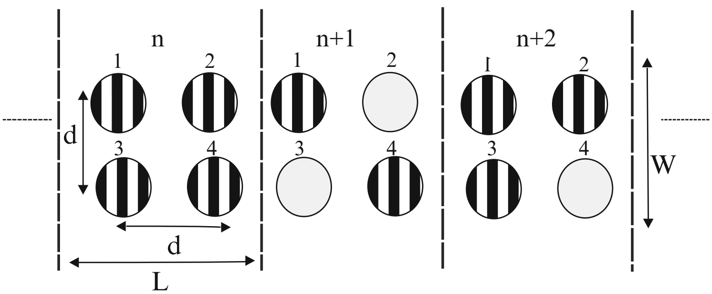


Fig. 2.7 2D grid strip network layout

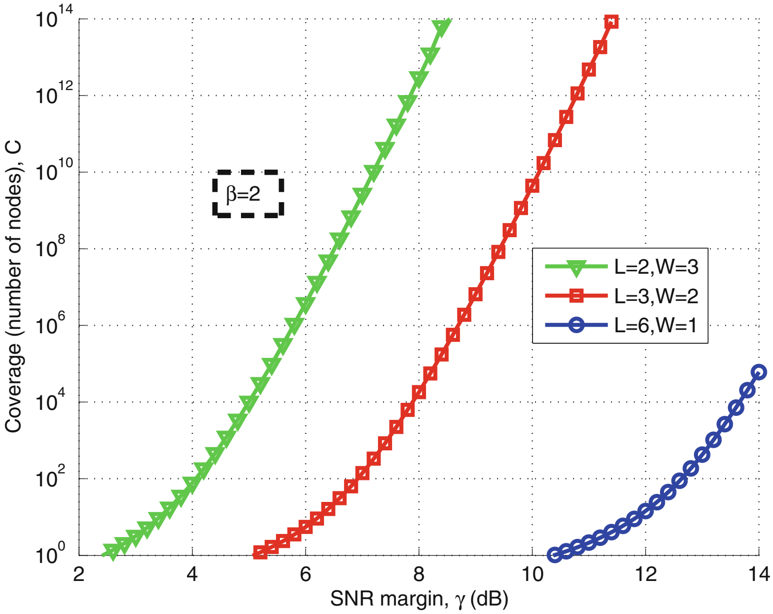


Fig. 2.8 SNR margin vs. maximum coverage for $M = 6$

transversed versus the SNR margin in Fig. 2.8 shows that the 2D topology achieves better performance in terms of one-hop success probability and maximum number of transversed hops as compared to 1D. Here, L and W represent the number of nodes arranged horizontally and vertically in a hop, respectively, where the total number of nodes in a hop is $M = L \times W$. The case where $L > W$ results in smaller coverage as compared to the one in which $L < W$. This is due to the reason that if more nodes are arranged on the horizontal axis then it will result in increased path-loss to the next hop nodes, and hence a degraded performance is achieved.

Stochastic 2D IoT Network

In more practical IoT networks, the node geometry in each hop is considered completely random, i.e., a fixed number of nodes are scattered within a box-shaped hop using a Poisson point process (PPP) as shown in Fig. 2.9. These networks cannot be modeled as a generalization of 1D or 2D grid topologies because of random distance between nodes. This varying distance between the nodes of the two consecutive hops is shown to follow a Weibull distribution [10].

To quantify the coverage, the Weibull analysis is extended to obtain the expression for outage and coverage of this cooperative network with stochastic node positions in [10]. The success probability for stochastic network also increases with the increase in the number of nodes per hop, M. In Fig. 2.10, the contour plot of

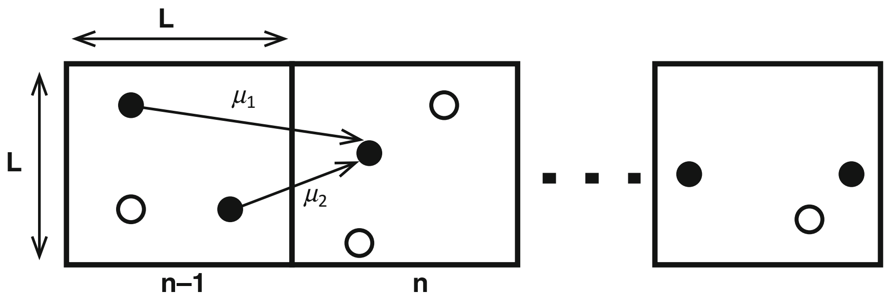


Fig. 2.9 Fixed boundary strip network with randomly placed nodes; $M = 3$

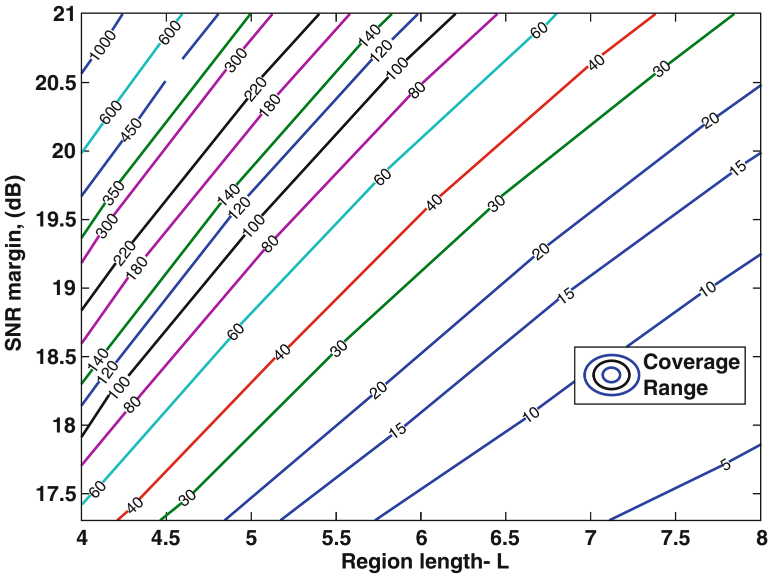


Fig. 2.10 Coverage range for various values of region lengths, L and SNR margin γ; $\eta = 0.8$, $M = 2$

coverage range (CR) against different values of SNR margin, γ, and region length, L, of a hop is shown. For two nodes per hop, i.e. $M = 2$, and a required quality-of-service (QoS) $\eta = 0.8$, the figure shows that with data propagates to larger distances. The reason of less coverage in case of higher region length is that the path-loss is likely to increase with the increase in the area of a hop or its region length L.

For this stochastic geometry, the orthogonal transmission takes place by employing near-orthogonal STBC as used in [11, 12]. These opportunistic networks can be made more energy efficient by having a limited number of nodes to participate in each hop. In this manner, the energy-efficiency of these networks increase, which is an important parameter for an IoT network where the devices generally have low energy values [13].

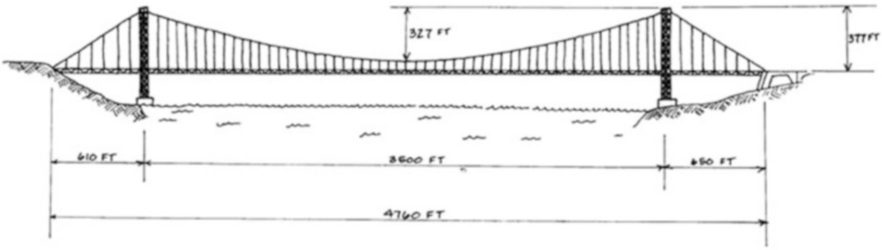


Fig. 2.11 Structural health monitoring of bridges using 1D IoT network

2.3.3 Applications of 1D and 2D Models in IoT Networks

Linear ad-hoc networks or 1D IoT networks find a variety of applications in practical scenarios. Typical examples include structural health monitoring of buildings where the nodes are located in hallways or walls in a linear fashion, however, may not be equally spaced. One-dimensional sensor networks along bridges provide another application area as shown in Fig. 2.11. In this case, a sensor node can transmit its information via cooperative mechanism to a distant central facility. Similar application include fault recognition in transmission lines for future smart grid systems where sensors are installed on transmission lines for their healthy activity. Another important area of application is vehicular ad hoc networks (VANETS), where a spatially random distribution of vehicles is formed along a road with sensors embedded in each of the vehicle.

Strip-shaped networks usually arranged as 2D IoT networks also provide an interesting paradigm of a "plastic communication cable", which is made out of a non-conducting material with embedded radios. Such cables can be used in applications involving high electric fields such as air industry where light materials are required to be mounted on the air vehicles. Similarly, 2D vehicular network where many vehicles are running along a highway constitutes an important application area for 2D cooperative IoT networks.

2.4 Other Candidate Technologies for IoT Networks

Although the focus of this chapter is mainly on a special form of communication technology, i.e., cooperative communications, for an IoT network, however, there are many other techniques which are under consideration or being used in an IoT network which include; millimeter wave (mmWave) technology with or without energy harvesting and interference cancellation. Similarly, many other techniques include spectrum sensing, orthogonal/non-orthogonal multiple access, opportunistic cognitive radio with STBC/distributed beamforming.The existing physical (PHY) layer protocols relevant to IoT are IEEE 802.15.4, IEEE 802.15.6, Bluetooth

Low Energy (BLE), long term evolution-advance (LTE-A), IPV6 over low power wireless personal area networks (6LowPAN), and near field communication (NFC). The main objective of designing communication protocols at lower layers is to achieve high diversity gains, maximize energy and spectral efficiency, and reduce the complexity. Two main approaches in this regard are [14]: techniques for energy-efficient and reliable transceiver design and techniques for low complexity data fusion rules. In addition to (STBC), beamforming technique is employed by considering the distributed nature of sensor/IoT networks where the phase mismatching might affect the performance. In order to make the IoT network more efficient and resilient against collision and retransmission issues, it is required to design estimation/detection techniques having better performance so as to minimize the network overhead [15].

In addition to making the network more energy efficient and reliable by cooperatively transmitting the information, the transmission strategy in [16] also addresses the hidden node issue of wireless sensor networks. To solve the issue of performance degradation due to hidden node problem, various conventional orthogonal and non-orthogonal multiple access (NOMA) techniques are used [17]. As these techniques do not provide a viable solution, therefore, cognitive radio spectrum sensing algorithms can be employed to further mitigate this problem [18].

Moreover, the millimeter wave technology (e.g. E-band) in combination with massive multiple-input multiple-output (MIMO), beamforming and multiple access techniques such as NOMA can ensure significant provide in bandwidth and performance [19] of upcoming IoT networks.

2.5 Summary

This chapter has provided an overview of the types of sensors that can be used in various forms of IoT networks. Further, the transmission strategies through these IoT networks, specially cooperative transmissions, have been discussed in detail, by considering some possible sensor node geometries. Comparative results for coverage of each topology have been provided with an in-depth analysis. It can be concluded that cooperative mechanism provides an elegant and simple strategy to obtain reliability in future IoT networks, which is an integral demand of 5G communications. Towards the end, the chapter is concluded by mentioning some of the other candidates of communication techniques used in IoT networks in addition to cooperative communications.

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