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Network Initialization in Low-Power Wireless Networks: A Comprehensive Study

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The increasing growth of low-power wireless networks in real-world implementations has intensified the need to develop well-organized key network building blocks. Neighbor discovery, link quality measurement and data collection are among the fundamental building blocks of network initialization process. Over the past decade, network initialization has attracted significant attention from the research community of low-power wireless networks. Accordingly, the general concern of this paper is to survey neighbor discovery, link evaluation and collection tree construction protocols, as well as, research challenges in these research areas. Furthermore, we explore the impacts of these protocols on the functionality of different layers in the network protocol stack. In order to provide a clear view of the state-of-the-art neighbor discovery approaches, this paper also presents a classification of the existing neighbor discovery protocols. Finally, some of the important open issues in developing network initialization protocols are discussed to present new directions for further research.

Keywords: low-power wireless networks; sensor networks; network initialization; neighbor discovery; link quality; collection tree

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1. INTRODUCTION

In large-scale low-power wireless networks (e.g. wireless sensor networks), nodes are randomly deployed in a large area without any communication infrastructure. In order to initiate the network operation, nodes must configure themselves and construct the network topology after their deployment. Moreover, due to the multi-hop communication pattern of these networks, all the nodes should establish multi-hop paths toward the common network collection point (i.e. root node in the network tree) to provide a data collection service for the underlying applications. Therefore, neighbor discovery and collection tree construction are the indispensable parts of network initialization in wireless networks [1, 2].

Although neighbor discovery and collection tree protocols provide simple services, the power constraints of low-power nodes and unpredictable behavior of wireless links introduce a lot of challenges in designing these protocols [3].

Since low-power wireless links are highly dynamic, nodes should be aware of data transmission quality of the links toward individual neighboring nodes to maintain correct network operation. Extensive empirical studies of the behavior of wireless communications have shown that link quality variations significantly influence the performance of neighbor discovery, localization, topology control, routing and medium access control (MAC) protocols [4]. However, the time-varying properties of low-power wireless links have been usually neglected in the existing communication protocols. Specifically, it is usually assumed that perfect communication (i.e. ideal packet reception rate (PRR)) can be achieved inside a specific communication range [5]. Nevertheless, due to the unpredictable behavior of low-power links, neighbor discovery and collection tree protocols may expose a complex behavior under real-world settings (e.g. network partition and routing oscillations) [6]. Since the inefficiency of these protocols can directly influence the performance of higher layer protocols, it is necessary to identify and consider all the effects of link layer issues during the network initialization phase. Accordingly, neighbor discovery and collection tree protocols should benefit from the link quality estimation techniques to maintain the overall network performance at a preferred level. Still, the accuracy of neighborhood assessment highly depends on the probe packet size, traffic rate and environmental conditions.

Despite the static nature of low-power nodes in most of the applications, network connectivity may change frequently due to the restricted power supply, time-varying properties of wireless links, node failures, multipath effect and noise floor [7]. Therefore, in addition to the network initialization phase, neighbor discovery, link estimation and collection tree construction processes must be performed as an ongoing process in the course of network operation to identify network topology changes and update the neighborhood information of the nodes with minimum interruption in the network operation [8, 9]. Since these continuous processes require frequent network scans, channel scan frequency and beaconing rate of the nodes play an important role in providing an energy-efficient and timely response against the network dynamics.

While the network initialization is a non-trivial task in wireless networks, the existing network initialization approaches have not been surveyed in detail so far. There is only one relevant survey by Galluzzi and Herman [10] that reviewed the discovery problem in wireless sensor networks without considering other critical network building blocks at the initialization phase (i.e. neighborhood assessment and collection tree formation). They briefly introduced sensor node platforms and presented some background concepts of distributed computing with a focus on the wakeup problem in neighbor discovery. However, their work cannot provide a clear classification of the previous efforts which have been done on the initialization phase of low-power wireless networks. Moreover, it does not present any information regarding the impacts of wireless propagation on the efficiency and accuracy of network initialization. Due to the lack of comprehensive studies of the initialization of low-power networks, it is difficult for researchers to obtain a coherent view of the initialization problem and find open research issues.

The aim of this study is to provide a clear view of the state-of-the-art network initialization approaches and analyze the reported observations from the previous studies. These analyses can provide useful information for the network designers to make the existing protocols as efficient as these approaches can be or develop entirely new mechanisms according to the main features of low-power wireless networks. In addition, through identifying the effects of network initialization on the performance of different layers of the network protocol stack, importance of the network initialization phase is highlighted.

The rest of this paper is organized as follows. Section 2 analyzes the main characteristics of low-power radio links and demonstrates the importance of understanding link layer issues for designing efficient network protocols. Section 3 provides an overview of the initialization of low-power wireless networks. The main challenges in supporting efficient network setup in low-power wireless networks are studied in Section 4. Section 5 investigates the key design issues in developing network initialization protocols. Section 6 clarifies the impacts of network initialization approaches on the performance of different protocols. A comprehensive taxonomy on the existing neighbor discovery techniques is presented in Section 7. Section 8 introduces some directions for further research. Finally, Section 9 concludes the paper.

2. AN OVERVIEW OF THE LOW-POWER WIRELESS LINKS

Various observations have motivated the research community of wireless networks to focus on the characterization of low-power radio propagation [4, 5]. The main purpose of these research studies is to find the best solutions to overcome the distractive properties of wireless communications. Link layer information can be used to provide the QoS requirements of different applications. For example, routing metrics can be derived using the transmission quality of wireless links to select the best forwarder nodes at each hop, which can reduce the probability of packet loss and the required number of retransmissions at the MAC layer to recover the lost frames. Moreover, utilizing this information for path construction reduces the cost of data transmission throughout the network, while it also improves the end-to-end network throughput and data delivery ratio [11, 12].

Over the past decade, several empirical studies of the characteristics of low-power wireless links have been carried out using various radio chips (e.g. CC1000 and CC2420) [5, 13, 14]. Based on these observations, non-ideal characteristics of low-power wireless links (e.g. interference, irregular radio range, asymmetric communications, dynamic and unpredictable behavior) propose new issues that should be addressed in designing reliable and efficient communication protocols [15, 16]. Due to the high sensitivity of low-power radio signals to the noise, interference and multipath effect, packet delivery ratio of low-power wireless links fluctuates frequently during the network operation [17]. In order to reduce the effects of link variations on the functionality of network protocols, link quality measurement is an essential part for protocol design [4, 18]. In this context, protocol designers should have a detailed knowledge about the properties of low-power radios and wireless communications to design efficient network protocols that consider the real-world characteristics of wireless links and low-power radios.

Different studies with various network and environmental settings (e.g. packet size, traffic load, indoor and outdoor environments) have demonstrated that low-power wireless links can be classified in three individual regions: connected region, transitional region and clear region [19, 20]. As it can be seen

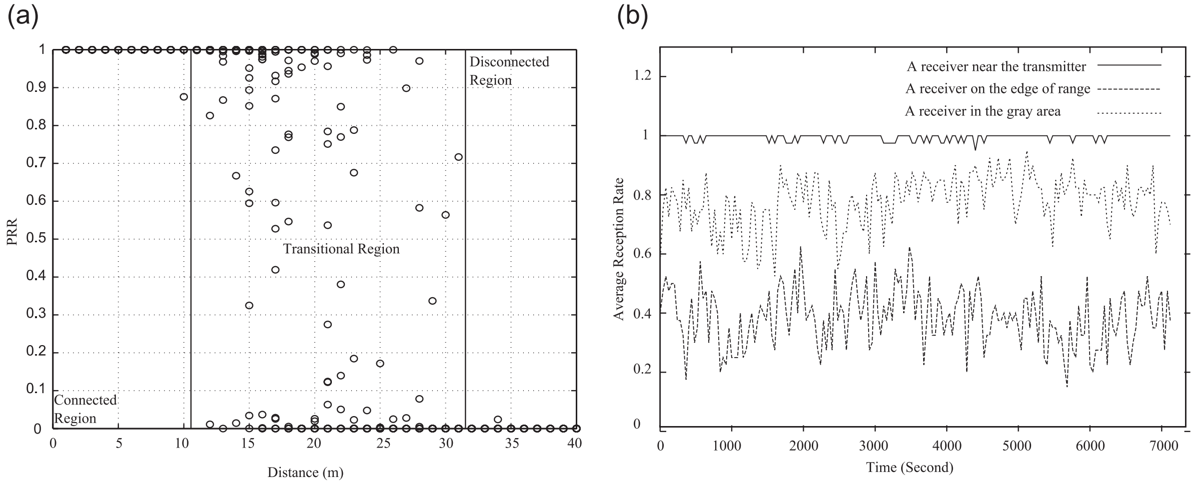


FIGURE 1. (**a**) PRR variations against distance [104]. (**b**) PRR fluctuations over time in different regions [105].

from Fig. 1a, all the nodes inside the connected region have good connectivity and a high PRR. However, the size of this region (i.e. connected region) is highly correlated with the transmission power. In contrast, clear region includes poor-quality links, which cannot be used for data transmission. Between these two regions (i.e. in the transitional region), the average data reception rate declines evenly, but different links in this region represent high variations in their transmission quality.

Figure 1b demonstrates PRR variations over time in the connected region (i.e. a receiver near the transmitter), transitional region (i.e. gray area) and clear region (i.e. a receiver on the edge of transmission range). According to this figure, wireless links in the connected region have small or no variation over time; while the transmission quality of the links in both of the transitional and clear region shows considerable variations. Environmental characteristics, multipath fading of radio signals, shadowing effect of the human activities, transmission power variations, noise floor variations and interference are the main causes of temporal variations in link quality [21–23].

Besides, the irregular radio range of low-power nodes is another important spatial property of wireless links. In this context, empirical studies have confirmed that the communication coverage of low-power nodes is highly variable in different directions, which results in unpredictable and asymmetric communication quality. This phenomenon is known as the radio irregularity and it can be caused by several factors such as variations in the transmission power, antenna gain, background noise and signal path loss [24]. Radio irregularity is studied in [25] through measuring the variations of received signal strength indicator (RSSI) and PRR over a wireless link with the changes in the angular direction of a receiver node. The achieved results from this study show that the radio range of low-power nodes is highly variable in different directions and it causes a high percentage of asymmetric links and radio interference. Extensive studies of the wireless link behavior show that the links located in the connected and disconnected regions are usually symmetric while most of the links in the transitional region are asymmetric [21, 26]. Figure 2a and b depict the variations of the RSSI values in different directions between two nodes, which are located 10 and 20 feet away from each other respectively. According to this figure, the RSSI value varies continuously by changing the angular direction of the receiver node. This observation confirms the anisotropic property of link quality in low-power wireless networks, which directly influences the functionality of different protocols (e.g. neighbor discovery, collection tree, MAC, routing, topology control and localization protocols) [25]. For example, radio irregularity can disturb the channel reservation operation of the MAC protocols that rely on the carrier sense multiple access/collision avoidance (CSMA/CA) mechanism and decrease the data frame delivery ratio at the MAC layer. Furthermore, as radio irregularity increases the percentage of asymmetric links, it may adversely affect the operation of neighbor discovery and routing protocols. For example, during the neighbor discovery process, node *A* may receive a beacon message from node *B*. Accordingly, node *A* will select node *B* as its neighboring node, while due to the link asymmetry, node *B* cannot hear any packet from node *A* and data transmission from node *A* to node *B* is subject to fail. In addition, path establishment without considering the temporal and spatial variations of link quality may result in unstable paths. As successful data delivery over low-quality paths requires a large number of retransmissions at each hop, network performance will be reduced in terms of throughput, delay, data delivery ratio and lifetime. Radio irregularity also elevates the localization errors and it makes topology maintenance troublesome. In this context, utilizing link layer information in designing topology control protocols can help to select high-quality and long-lived links in order to avoid frequent

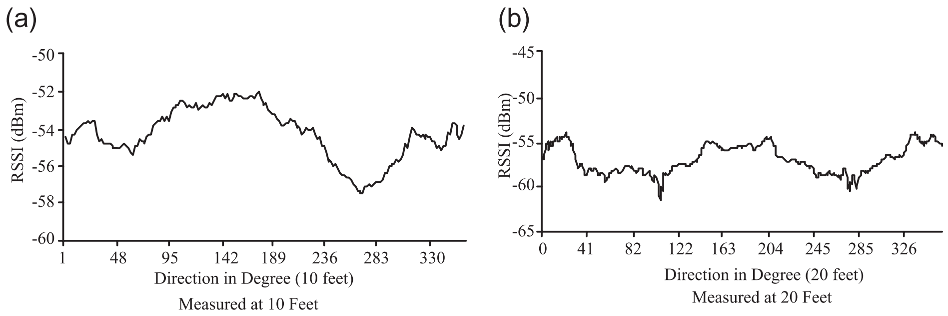


FIGURE 2. (a) Variations of the RSSI in different directions, when the distance between the sender and receiver is 10 feet. **(b)** Variations of the RSSI in different directions when the distance between the sender and receiver is 20 feet.

topological changes. Accordingly, as neighbor discovery and collection tree construction are the fundamental parts of different network protocols, it is vital to consider wireless link characteristics in designing these techniques.

A wide range of link quality assessment techniques have been developed for wireless networks [4]. The existing protocols utilize the provided valuable link quality information by the different layers of network protocol stack to perform link quality estimation process. For instance, physical layer can provide bit level information during the reception of individual packets. Therefore, using physical layer information for link quality measurement can help to avoid spending time on the poor and borderline links. Furthermore, link layer can provide some information regarding the packet delivery statistics. Using the information provided by the link layer, the link estimation method can measure the bidirectional link quality for delivering data packets to the receiver nodes and receiving their acknowledgments at the sender nodes according to the network traffic [27]. As demonstrated in Fig. 3, the existing link quality measurement mechanisms can be generally classified in hardware-based, software-based and hybrid approaches based on the utilized information sources for assessing the data delivery performance of wireless links.

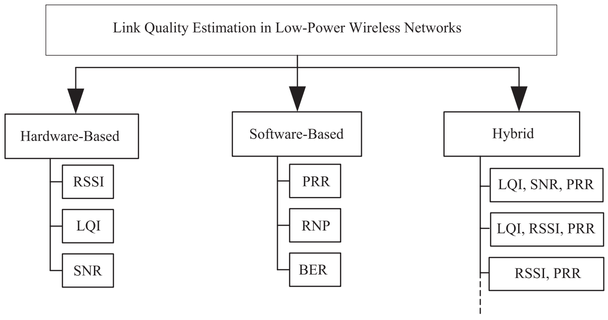


FIGURE 3. Taxonomy of the existing link quality estimation techniques for low-power wireless networks.

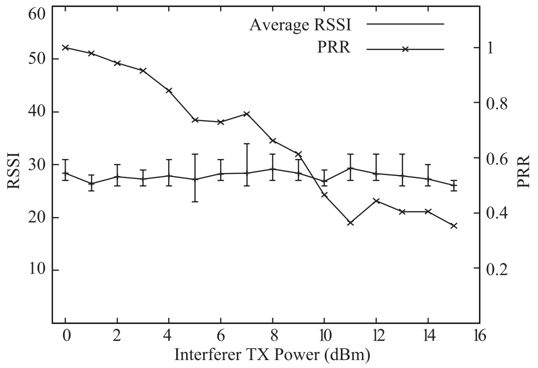


FIGURE 4. RSSI variations cause by the transmission power of an interfering node [70].

2.1. Hardware-based link quality estimation

This category includes several link quality indicators (LQI), such as RSSI, LQI and signal-to-noise ratio (SNR), which can be obtained from the radio transceiver. These metrics can provide a fast estimation about high-quality links (i.e. connected region) and prevent link estimation methods from spending time on measuring the quality of marginal or poor quality links [28]. In the following subsections, the capability of individual hardware-based LQIs are investigated.

2.1.1. RSSI-based link quality estimation

RSSI is a signal-based LQI that represents the observed signal strength at the receiver node during the preamble reception. The valid range of RSSI values depends on the transceiver type. Therefore, the observed RSSI values can be translated into a specific range, according to the specifications of different wireless cards. Since RSSI values are computed based on the preamble bytes, this indicator does not reflect the average received signal strength during the reception of a whole packet. As a result, the RSSI metric cannot capture the effects of wireless interference during the reception of payload data. Figure 4 demonstrates the effects of wireless interference on the RSSI fluctuations with three nodes (e.g. a sender node, a receiver node and an interferer node). During this experiment, the interferer

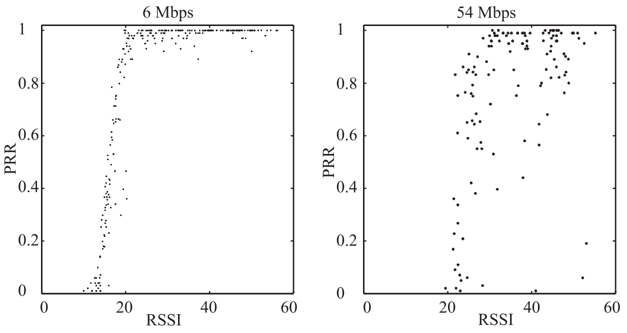


FIGURE 5. Correlation between RSSI and PRR in concurrent transmissions scenario under different traffic rates [70].

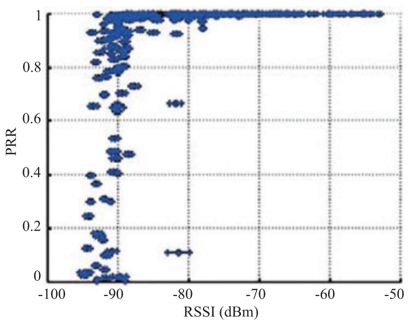


FIGURE 6. Correlation between PRR and RSSI at power level 0 dBm [30].

node continuously broadcasts data packets in the course of data transmission between the sender and receiver. According to this figure, while the RSSI values for different interference levels are almost constant, PRR decreases dramatically as the wireless interference level increases. Given that the RSSI values are recorded during the preamble reception, if the wireless interference occurs during the reception of payload data, the RSSI value still remains constant. Moreover, if the reception of a preamble fails due to wireless interference, the RSSI value cannot be recorded. Furthermore, as the preamble bytes are transmitted at a lower data rate, if the remaining bytes of the packet are transmitted at a higher data rate, no correlation is expected between the RSSI values and PRR. This is due to the fact that high data transmission rates are more prone to noise and wireless interference than low data transmission rates. Therefore, a low level of wireless interference may result in a high bit error rate (BER). The effects of network traffic rate on the relationship between RSSI metric and PRR have been shown through Fig. 5. As expected, for lower traffic rates there is a correlation between RSSI values and PRR, but under high traffic rate conditions, the RSSI values are not correlated with the measured PRR. These observations confirm that RSSI values cannot reflect the exact value of experienced interference level during data transmission. Another drawback of the RSSI metric is that the RSSI value indicates the received signal strength from the transmitter, plus external noise and experienced interference from simultaneous transmissions. Since interfering transmissions can elevate the RSSI values, using this indicator in the presence of interfering transmissions causes inaccurate measurements. The extensive evaluations on a testbed of TelosB motes in [29] confirm that utilizing RSSI as a stand-alone metric is insufficient to classify the whole link quality spectrum in a low-power wireless network. As can be seen from Fig. 6, RSSI-based link quality estimator represents similar packet delivery performance for all the links with the RSSI values more than −87 dBm, which is close to the sensitivity threshold of CC2420 radio (i.e. −90 dBm). However, below this threshold (i.e. lower than −87 dBm) PRR varies significantly between 0 and 100% [30]. Therefore, if the measured RSSI values are above the sensitivity threshold, the considered links should be classified as high-quality links (i.e. links in the connected region) with a constant PRR over time (around 99%) [5, 31]. In contrast, those links with RSSI values below the sensitivity threshold should be categorized as medium or low-quality links (i.e. links in the transitional or disconnected region).

2.1.2. *LQI-based link quality estimation*

Newly designed radios based on the IEEE 802.15.4 standard (e.g. CC2420 radio) can provide the LQI index directly from the radio module. The LQI index in these radios is computed based on the first eight symbols of the successfully received packets. However, the retrieved index by this metric depends on its implementation. For instance, in CC2420 radio, LQI indicates the chip error rate.

According to Fig. 7a, as the RSSI value increases, the LQI index is also elevated. This means that when the observed RSSI values on the wireless links are above the sensitivity threshold, the LQI metric can classify the examined links as high-quality links (e.g. links with 100% PRR). However, due to the high LQI variations of intermediate-quality links over short periods of time, it cannot accurately classify intermediate-quality links. For instance, in Fig. 7b the LQI index of a link with 0.2 PRR is similar to the calculated LQI of a link with 0.8 PRR.

As it can be seen in Fig. 8a, the transmission quality of stable links is almost constant over long periods and a single LQI reading is enough to classify these links. Nevertheless, the high variations of intermediate-quality links over short periods of time (Fig. 8b) require averaging a large number of LQI readings (e.g. at least 40 and up to 120 packets) [30, 32]. However, calculating the average value of a large number of LQI readings is in contrast with the agility of link quality estimation methods. Based on these observations, LQI can identify high-quality links, but it is incapable of providing accurate estimations regarding the intermediate-quality links.

2.1.3. *SNR-based link quality estimation*

This metric indicates the ratio of the received signal to the noise power (the noise power includes the environmental and

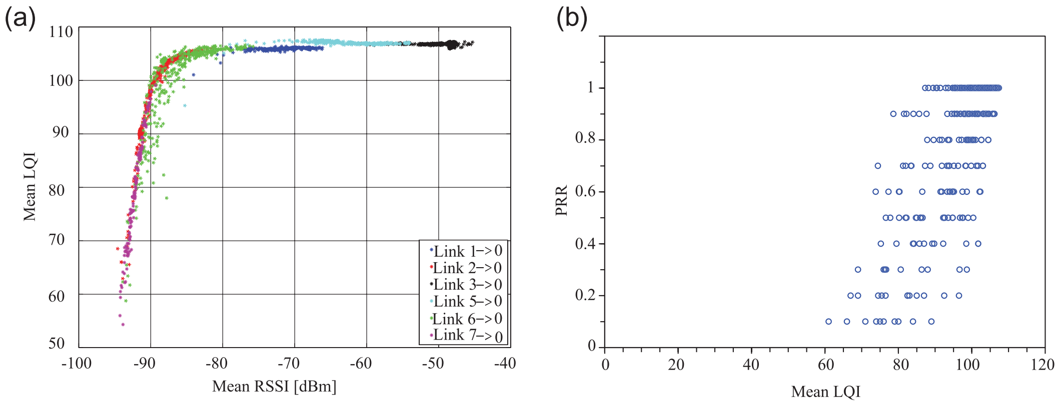
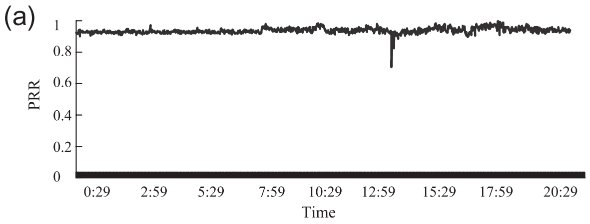
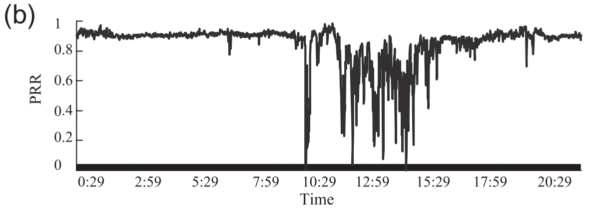


FIGURE 7. (**a**) Correlation between LQI and RSSI [29]. (**b**) Correlation between PRR and LQI [39].



A Stable Link



An Unstable Link

FIGURE 8. Variations of PRR over stable and unstable links [53].

hardware noise). Accordingly, SNR can provide better estimates of the link quality than the RSSI because the RSSI value indicates the sum of received signal power plus noise floor. Similar to the other hardware-based metrics, SNR can only differentiate between high-quality links and other links [33]. As it is shown in Fig. 9, if the calculated SNR for a link is above 20 dB, it can be classified as a high-quality link. However, links with the SNR values between 5 and 10 dB cannot be easily distinguished. Different empirical studies show that the relation between SNR and PRR highly depends on the node hardware and environmental factors such as temperature [34].

2.2. Software-based link quality estimation

PRR, required number of packet (RNP) transmissions and BER metrics can be categorized as the software-based LQIs. The following subsections are dedicated to describe different aspects of these metrics.

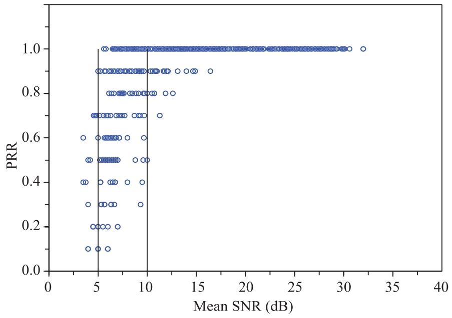


FIGURE 9. Correlation between PRR and SNR [39].

2.2.1. *PRR-based link quality estimation*

PRR identifies the ratio of the received packets at a receiver to the number of transmitted packets by the sender node during a predefined time window. Accuracy of this metric highly depends on the size of the selected time window for link monitoring, network traffic rate and probe packet size. With respect to the high variations of intermediate-quality links, accurate link estimations can be achieved by measuring the PRR metric over a large time window. Also, due to the low variations of high-quality links, utilizing a small time window would be sufficient to yield accurate estimations.

Measuring the PRR of intermediate-quality links over a large time window can provide more accurate results; however, transmitting a large number of control packets for link measurement will reduce the agility and responsiveness of the link quality estimators against link fluctuations. Therefore, the time window adjustment should exploit a trade-off between the accuracy and agility of the link quality estimator so that it can provide a sufficient number of packet exchanges to obtain accurate link estimations in the shortest possible interval. In order to provide a stable network performance against short-term link quality variations, some protocols utilize filter-based link quality estimators (e.g. moving average, exponentially weighted

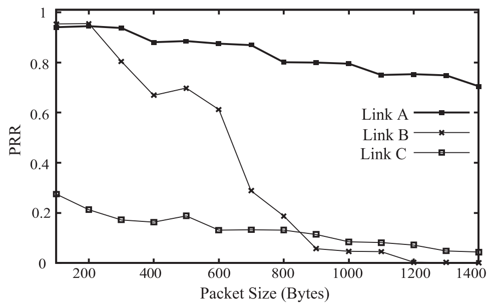


FIGURE 10. PRR variations against different packet sizes [70].

moving average and time-weighted moving average) to smooth the estimated link quality values [35, 36]. These link quality estimators use a historical control factor to control the effects of previous link quality estimations on the new estimations. Meanwhile, the utilized historical factor has a high impact on the performance of these estimators. For instance, they can provide more stable network performance as the historical factor increases. However, this factor should be properly adjusted to provide stability with a reasonable responsiveness.

In addition to the time window size, the accuracy of the PRR-based link estimator also depends on the probe packet size [37]. There is a lower probability that small-size data packets be affected by external noise and wireless interference. Thus, using small probe packets cannot result in accurate estimations. Figure 10 shows the effects of probe packet size on the PRR of three randomly selected links in a wireless testbed. According to this figure, the data transmission quality of the selected links is highly affected by the changes in the packet size.

2.2.2. *RNP-based link quality estimation*

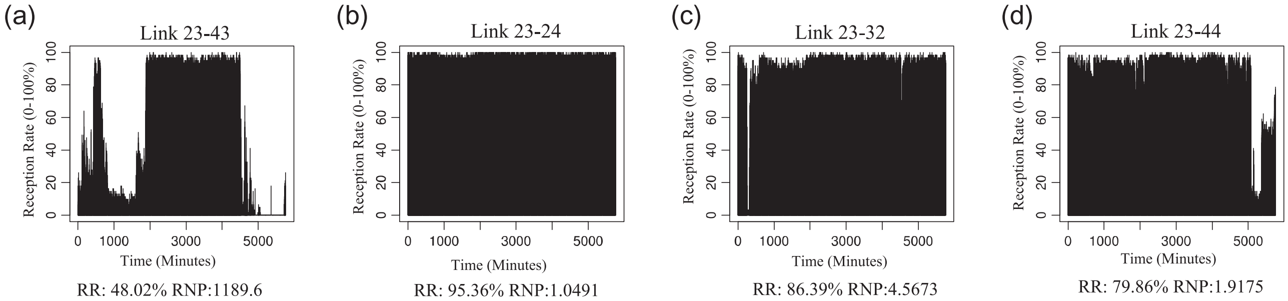
RNP metric estimates the RNP transmissions or retransmissions to achieve a successful packet reception. The sender node can realize the number of successfully transmitted packets through counting the number of received acknowledgment packets. Therefore, RNP-based link quality estimation technique requires an automatic repeat request mechanism at the links layer to enable the network nodes to repeat packet transmission until a successfully reception [4, 38].

Empirical studies of the temporal properties of wireless links in a test-bed of Mica motes showed that the RNP metric provides better link quality estimations than the PRR-based mechanism [21]. This is due to the fact that RNP considers the underlying packet loss distribution and RNP retransmissions to provide reliable estimations. In fact, if a successful data delivery over a link is achieved after one or more retransmissions, the PRR metric will report the same data transmission quality for that link. Whereas, RNP can reflect the inefficiency of low-quality links, which require a large number of retransmissions before successful reception of individual packets. To confirm this issue, the authors in [21] measured the ability of the PRR and RNP methods to characterize good-, intermediate- and bad-quality links over several hours. The measurements are demonstrated in Fig. 11. According to Fig. 11a and b, the PRR- and RNP-based methods measure the data transmission quality of a low-quality link with an average reception rate of 48.02% and a very high-quality link with an average reception rate of 95.36% in the same manner. However, as it is shown in Fig. 11c and d utilizing the PRR-based method to indicate the data transmission performance of intermediate-quality links (i.e. with average reception rates of 86.39 and 79.86%) overestimates the actual quality of those links for data transmission. Based on these figures, although the link between node 23 and node 32 has better PRR than the link between node 23 and node 44, by using the RNP-based link quality estimation method, the second link (i.e. links 23–44) provides more efficient communication than the first one (i.e. links 23–32). The rationale behind this behavior is that short intervals of packet loss increase the RNP metric, while during these periods the average PRR may remain constantly high.

As measuring RNP metric relies on the number of received acknowledgment packets, link asymmetry imposes some problems in supporting reliable link characterization. For instance, if a node has an asymmetric link toward one of its neighboring nodes, sometimes it requires to perform a lot of retransmissions due to the low quality of its backward link, while the data transmission quality of its forward link is quite good. In this case, performing neighbor discovery in conjunction with an RNP-based link quality estimator can help to identify asymmetric links.

2.2.3. *BER-based link quality estimation*

BER determines the ratio of corrupted bits to the total number of received bits. In order to obtain information from corrupted packets, the CRC functionality must be disabled. Furthermore, if the length bit of a packet is corrupted or several bits of a packet shifted by some bit positions, the BER will be measured wrongly. In the first case, the receiver tries to interpret a wrong number of payload bits. Although in the second case, it is possible that all the bits have been correctly received, but due to the shift of some bits the received packet is incorrectly marked corrupted. Therefore, a lot of pre-processing operations should be done on a large amount of data in order to calculate this metric. Similar to the hardware-based estimators, this metric is computed based on correctly or corrupted received packets. Therefore, loss of packets which may include a large number of erroneous bits or unsuccessful packet reception due to the interference during transmission of the preamble and header parts causes inaccurate BER values. Moreover, this metric also behaves like PRR under different traffic rates. Therefore, the measured BER values under low traffic rates cannot reflect the data transmission quality of links under high traffic rate scenarios.



RR: 48.02% RNP:1189.6

RR: 95.36% RNP:1.0491

RR: 86.39% RNP:4.5673

RR: 79.86% RNP:1.9175

FIGURE 11. PRR over time [21].

2.3. Hybrid link quality estimation

While each of the software-based and hardware-based link quality estimation methods can individually provide valuable information regarding the link characteristics, each method has its own advantages and disadvantages. Recent studies of the link quality characterization confirm that the combination of link quality estimation methods can cover the disadvantages of individual metrics and improve the performance of higher layer protocols [39, 40]. In fact, the main motivation behind designing hybrid link estimators is that each class of link estimation methods (i.e. software and hardware-based) can detect a particular link behavior. For instance, hardware-based link quality estimation can provide fast link qualification and present some immediate information on the channel quality during the reception of a packet. Since these methods can classify the wireless links according to the packet decoding quality, they can improve the agility of link quality estimation process through avoiding the time required to measure the poor and borderline links. However, as hardware-based link quality metrics are only measured based on the first symbols of the successfully received packets, and they do not consider the underlying packet loss distribution, these techniques usually overestimate the data transmission quality of wireless links in the presence of excessive packet losses. In contrast, software-based link quality estimation techniques measure the quality of links according to the successful and unsuccessful transmitted packets during a predefined time window. Therefore, they can provide more detailed information on the link quality variations [27, 41]. These differences have been shown in Fig. 12. As it can be seen, there is a period that the PRR over a link drops from 0.9 to 0.6, but the LQI did not change. This is because during this time the receiver could not receive all of the transmitted packets, but the received packets have been correctly decoded.

Hybrid link quality estimators are usually defined as a weighted function of software- and hardware-based link quality estimation metrics. The weight of each metric must be set according to the environmental conditions and performance demands of the underlying application. Different information sources (e.g. number of MAC layer retransmissions, PRR, RSSI values and LQI) can be used to provide the required information of hybrid link quality estimation metrics.

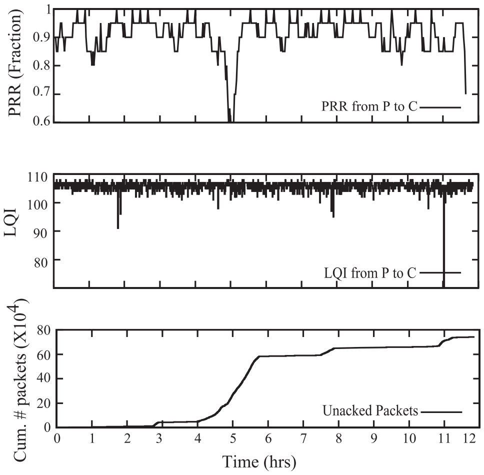


FIGURE 12. Difference between link quality characterization through software and hardware-based link quality estimations [27].

3. INITIALIZING LOW-POWER WIRELESS NETWORKS

Neighbor discovery in wireless networks is basically defined as identifying all the nodes in the communication range of a given node that can communicate with them directly. Upon a network deployment, all the nodes have to detect their neighboring nodes as soon as possible to construct the network topology. At the end of this stage, all the nodes have preliminary information about their surrounding neighborhood. This knowledge is required for performing distributed algorithms such as medium access mechanisms [42, 43], collection tree formation [9, 44], routing [45–47] and localization support [48]. When the network topology is established, nodes should start to construct the network data collection tree which allows data delivery from multiple source nodes toward one or more data collection points. Upon the construction of the network routing topology, upper layer protocols can start their normal operation to fulfill the application demands. Due to the link dynamics, neighbor discovery and collection tree protocols should periodically update neighborhood and routing information in the course of network operation (i.e. continuous neighbor discovery) to maintain the desired network performance. Furthermore, through continuous neighbor discovery, the hidden nodes, which have not been identified during the network initialization due to the unreliability and asymmetric nature of wireless links can be recognized and joined to the network structure.

In order to provide an efficient network setup with respect to the resource limitations of low-power wireless networks and high dynamics of wireless links, different parameters must be considered in designing network initialization protocols. Accordingly, the key performance parameters are described as follows:

Node deployment and topology construction delay: Based on the achieved results from real-world deployments, installation of low-power nodes even in easily accessible areas may take several days or weeks [49, 50]. Accordingly, the deployment process increases the whole delay of network topology formation. Although the neighbor discovery delay can be reduced by enforcing each installed node to start the discovery process upon its installation, any attempt for neighbor discovery during the network deployment phase cannot provide complete information regarding the surrounding area of individual nodes. To avoid the unnecessary energy utilization during the deployment process, neighbor discovery mechanisms should reduce the period of idle listening and decrease the frequency of transmitting beacon messages before all the nodes are installed. However, this technique may increase the delay of network topology formation.

Energy efficiency: During the neighbor discovery phase, network nodes should increase their listening period to learn about the connectivity structure of their vicinity, while they should also raise their beaconing rate to elevate the probability of being discovered by the other nodes. However, these benefits can be achieved with the cost of more energy consumption. Moreover, although energy efficiency can be achieved through reducing the listening period of network nodes and decreasing channel probing frequency, it will increase the neighbor discovery delay. To overcome these issues, network nodes should aggressively participate in the neighbor discovery process at the network startup. If there is no activity or there is no significant change in the network connectivity, they can reduce their communications. Therefore, neighbor discovery should provide a trade-off between energy consumption and neighbor discovery latency.

The data collection algorithm should construct an optimal network routing topology to allow energy-efficient data collection and delivery from source nodes toward the network data collection point. To this aim, the constructed collection tree should be able to transmit the collected data to the collection point with minimum number of transmissions even in the presence of link quality variations or network connectivity changes.

Link quality awareness: Empirical studies of the link characterization have shown that PRR of more than half of the links in a low-power wireless network is highly variable from 10 to 90% over time and space [19, 51]. These studies confirmed that link quality is not exactly related to the distance from the sender. Accordingly, even if two receivers are located at the same distance from a sender, these receivers may experience different PRRs from a same sender node. Moreover, as illustrated in Fig. 1b wireless links with intermediate PRR values exploit high variations in their packet delivery performance over time. These observations demonstrate the effectiveness of link quality estimation methods to improve performance of network protocols. To this aim, data collection tree protocols can benefit from the provided link layer information by the employed link estimation techniques at the network initialization stage to construct a stable network data collection tree. By performing link quality estimation concurrent with neighbor discovery process, network nodes will be able to assess the data transmission quality of their incoming and outgoing links through utilized probe packets for neighbor discovery [49, 52]. Moreover, as rapid link quality fluctuations may result in frequent network connectivity changes and successive packet losses, all the nodes should update their neighborhood information periodically to avoid long periods of topology disconnections and packet loss.

Responsiveness to the link quality variations: In order to maintain stable network performance, the constructed data collection tree should adapt to the network connectivity changes without any interruption in the network operation. To this aim, neighbor discovery and link quality estimation protocols should provide complete neighborhood information at individual nodes under different environmental conditions. Furthermore, link quality estimators must be able to detect long-term link quality fluctuations and update the neighborhood information of network nodes. In this context, the link probing period (e.g. estimation time window), the frequency of link quality estimations and the utilized link monitoring technique play an important role to provide reliable response against link quality variations with minimum energy utilization.

Robustness: Collection tree protocols should be tolerant against the short-term variations of wireless links. Since route reconstruction is a costly and time-consuming process, the routing topology should remain stable in the presence of short-term link quality variations. However, if the employed link estimation mechanism finds link variations over a long time period (e.g. 10 min), it should stimulate higher layer protocols to react against the latest link quality estimations with minimum latency. Accordingly, constancy can be achieved through long-term estimations. Some of the existing link quality estimation techniques use filter-based methods such as exponential weighted moving average with a large smoothing factor to provide long-term link quality estimations [38]. Although, using long-term estimations can improve the robustness of link quality estimators, this mechanism significantly reduces the agility of link quality estimators to react against link quality variations. For instance, if a link quality estimator measures the quality of wireless links frequently to provide a fast response against link quality fluctuations, it may consider short-term link quality variations in its estimations. However, in order to support a stable network performance, these short-term link quality variations can be ignored. Accordingly, an efficient link quality measurement technique should make a trade-off between robustness and responsiveness against link quality variations. Lin *et al.* [53] proposed the competence metric which is a long-term link quality estimation technique. This paper suggested a combination of this metric with a short-term link estimation method such as ETX [11] to provide quick response against link quality changes, while supporting stable network performance through a long-term link quality characterization. Performance analysis of this approach shows that the combination of long-term and short-term link quality measurement techniques can result in selecting those wireless links that provide high data transmission quality in long-term and short-term periods.

Accuracy: One of the important goals in designing network initialization protocols is to maximize the possible number of neighboring nodes that individual nodes can discover during the network setup phase. Therefore, at the network initialization phase, all the nodes should intensively take place in the discovery process in order to maximize the probability of being discovered by the other nodes and elevate their chance to identify maximum possible number of neighboring nodes. Furthermore, deploying a link quality assessment technique during the network initialization phase can help to reflect the real behavior of wireless links and increase the accuracy of neighbor discovery. The accuracy of information provided by an employed link quality estimator is highly related to the utilized technique in the link quality estimation mechanisms for monitoring the link quality variations and conveying useful information on the quality of data transmission over different links. For instance, small-size beacon packets can be utilized to reduce the imposed signaling overhead by link measurement techniques. Most of the existing protocols (e.g. CentRoute [54], Beacon Vector Routing [55], S4 [56], Optimized Link State Routing [57], MintRoute and MultihopLQI) assume slow link quality changes over time. Accordingly, they rely on infrequent transmissions of small beacon packets to provide reliable data delivery [5, 19]. Since the data delivery performance of the wireless links are highly related to the size of data packets, using small-size beacon packets cannot yield accurate link quality estimations. Furthermore, as the traffic rate in the real-world deployment is variable during the network operation, infrequent beacon transmissions cannot reflect the impact of data rate variations on the transmission quality of wireless links. Therefore, selecting the best probe packet size and beaconing rate requires a trade-off between the accuracy and energy efficiency of the employed link assessment mechanism.

Practicability: Network initialization protocols should be easily employed and executed in resource-constrained networks without requiring additional mechanisms or hardware supports (i.e. specific radio chip features). In fact, if the initialization protocols are designed through certain algorithms, they may require an entirely new network protocol stack to set up the network. Thus, initialization protocols should preferably be simple enough to be compatible with existing protocol stacks. Furthermore, these mechanisms should be executed with minimum errors and network resource utilization.

4. CHALLENGES IN DESIGNING NETWORK INITIALIZATION PROTOCOLS

Minimizing network energy consumption is one of the primary concerns in designing network initialization protocols for low-power wireless networks. For instance, in wireless sensor networks, all the nodes are battery powered and they are usually deployed in large areas. When a node runs out of battery, it is a costly and time-consuming process to replace its battery. Accordingly, the failed node disappears for a long time and this phenomenon has a significant effect on the functionality of different protocols that use the support of this node to accomplish their tasks. In those wireless networks without any serious concern about the energy consumption, usually neighbor discovery would not be performed as a separated phase. In these networks, upper layer protocols (e.g. AODV [58] and DSR [59]) use a simple broadcast technique during the network operation to enable the nodes to identify the whole set of their neighboring nodes [60]. However, each node should assume that its neighboring nodes can be only in either listen or transmit states at each time. This means that the neighboring nodes of a given node are always in the listen state unless they are in the transmission state. While this constant listening can eliminate the need for explicit neighbor discovery, it cannot provide energy-efficient communications. Despite the recent advances in radio frequency circuits design, the radio transceiver is still the major source of energy consumption in a low-power wireless node. Although the energy consumption in receive and transmit modes are different, the energy consumption of the receive mode is almost the same as that of idle listening mode. Similar to microcontrollers, radio chips also support low-power sleep mode in which the energy consumption is almost negligible. In order to conserve energy, radio should be set into the sleep mode whenever it is not intended to transmit or receive. Accordingly, all of the designed MAC protocols for low-power networks use a periodic sleep/listen mechanism to provide energy-efficient communications [61–63]. Therefore, since nodes can receive a message during their active periods, two nodes can discover each other whenever both of them are active. However, during the network initialization phase, all the nodes have to participate intensively in the discovery phase to increase the chance of being discovered by the other nodes and identify a large set of neighboring nodes.

In addition, as at the initialization stage network nodes do not have any information regarding the duty cycle of their surrounding nodes, the neighbor discovery problem becomes more challenging. Hence, the main issue in developing neighbor discovery protocols for low-power wireless networks is that the radio should operate at low-duty cycles, while the neighbor discovery algorithm must ensure the reliability and agility of the discovery process under different conditions. Therefore, the employed scheduling algorithms in power constrained networks (i.e. periodic sleep/listen mechanisms) introduce a lot of challenges in providing accurate network initialization.

Since supporting global synchronization in large-scale low-power wireless networks is a non-trivial task, neighbor discovery algorithms should provide asynchronous node operation. In asynchronous neighbor discovery algorithms, each node can start the neighbor discovery process at a different time. In this situation, there is a high probability that network nodes miss each other's transmissions due to non-overlapping listen intervals.

The special characteristics of radio communications (e.g. wireless interference, heterogeneous transmission power levels, irregular radio propagation and link asymmetry) cause more problems in designing neighbor discovery and link quality measurement techniques [64]. For instance, neighbor discovery algorithms should be able to cope with the packet collisions caused due to the broadcast nature of wireless channel to provide accurate information. However, supporting collision-free operations without enough knowledge regarding the neighboring nodes of each node is difficult. In addition, according to Fig. 13 changing the receiver direction can result in various PRRs from a sender node [6]. This observation confirms that anisotropic link quality also influences the accuracy of the neighbor discovery and link estimation protocols. Besides, link asymmetry which is the result of hardware variations and irregular radio propagation would cause more challenges in supporting accurate network initialization. For instance, in Fig. 14 node *A* can discover node *B*, *C* and *D* as its neighbors by receiving beacon packets from these nodes. Since the link between node *A* and *B* is asymmetric, whenever node *A* chooses node *B* as its next-hop neighboring node to forward its data packets, node *B* cannot hear the transmitted packets by node *A*. In this case, node *A* can receive the transmitted packets from node *B*, while node *B* cannot receive any packet form node *A*.

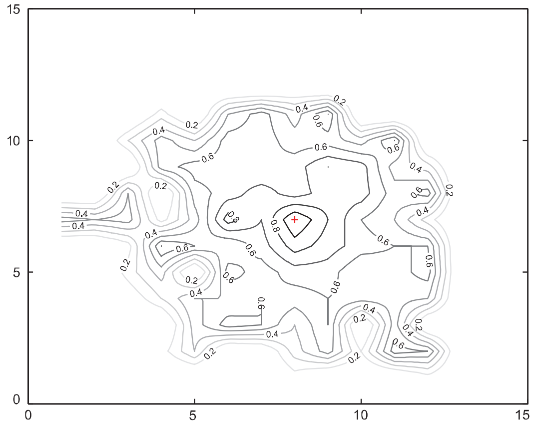


FIGURE 13. PRR from a central node at different directions [6].

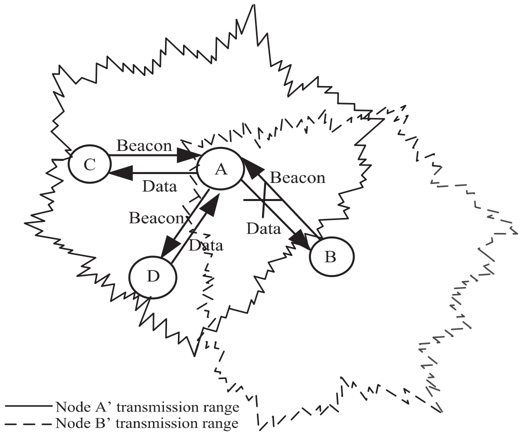


FIGURE 14. Impact of the radio irregularity on the neighbor discovery.

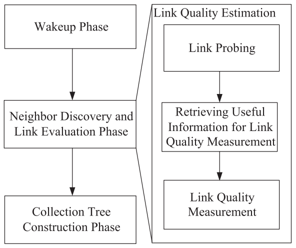


FIGURE 15. Different phases of a typical network initialization protocol.

5. IMPLEMENTING NETWORK INITIALIZATION PROTOCOLS IN LOW-POWER WIRELESS NETWORKS

In order to configure network nodes and construct an efficient network infrastructure within an acceptable period, several phases should be considered in designing network initialization protocols. These steps are described in the following sections and are outlined in Fig. 15.

5.1. Wakeup phase

In order to identify all of the possible network connections, network nodes should transmit beacon packets or listen to the channel during the discovery process. Therefore, any attempt for neighbor discovery before full network deployment results in energy waste. An alternative solution to provide energy-efficient network initialization is to trigger neighbor discovery process after full network deployment [49]. Therefore, when all the nodes are deployed, the discovery phase should be stimulated through programming a given node (e.g. the data collection point) to flood a wakeup message to the networks. This message usually includes the start time of neighbor discovery, number of probe packets for connectivity evaluation and channel probing interval. Since the accuracy of neighbor discovery is related to these information, the wakeup message should be delivered to all the nodes with high reliability within a specific time.

5.2. Neighbor discovery and link evaluation phase

At the start of the neighbor discovery phase, all the nodes become active and start to broadcast beacon packets and listen to the channel to receive incoming beacon packets. In order to reduce signaling overhead of the link quality estimation process, initial link quality measurement can be combined with neighbor discovery through using the transmitted probe packets for link quality measurements.

Link quality measurement process is usually a combination of three procedures to provide efficient and accurate link quality information. Link probing is the first task that should be performed to assess the quality of data forwarding through individual nodes. The rationale behind considering this process is to generate traffic over the links and monitor link behavior over a predefined measurement period. There are three kinds of link probing techniques employed by the existing link quality measurement mechanisms: (1) active link probing, (2) passive link probing and (3) hybrid link probing.

In active link probing, each node probes the identified links toward its neighboring nodes through a broadcast [11] or a unicast [37] mechanism with a certain data rate. In the broadcast-based link probing, network nodes broadcast a certain number of probe packets to their neighboring nodes within a predefined period (i.e. estimation time window) without using acknowledgment and retransmission mechanisms. Since the number of broadcast probe packets is constant at all the nodes, each node can easily calculate the packet delivery ratio over the links toward its neighboring nodes by dividing the number of successfully received probe packets by the total number of transmitted packets. In the unicast-based link probing approach, the network nodes utilize a unicast mechanism to send the probe packets. The main advantage of unicast-based approach is that it can provide more accurate results on the quality of individual links than the broadcast-based mechanism [37, 65]. However, communication overhead of the unicast-based approach is directly related to the frequency of link probing and network density.

It has been proposed that passive link probing overcomes with the limitations of active monitoring through utilizing the network traffic to indicate the link quality [37, 66]. Accordingly, this mechanism can provide accurate results without causing additional communication overhead. Several empirical studies show that link quality estimation through application traffic is more accurate than the active link probing approach [67, 68]. As passive link monitoring uses the network traffic to estimate the link quality, this mechanism is not applicable during network initialization. However, it can be used during the network operation to update the transmission quality of wireless links [66]. In the passive link monitoring approach, all the nodes, including those nodes that do not participate in data transmission, should listen to the channel and overhear the data packets passing through their neighboring links. As the energy consumption of the receive mode is almost the same as that of idle listening mode, passive link probing cannot yield an energy-efficient link measurement. Moreover, whenever the network traffic is low, this mechanism cannot provide up-to-date information and may result in inaccurate estimations.

To make an efficient trade-off between advantages and disadvantages of active and passive link monitoring mechanisms, hybrid link probing is proposed. This link probing approach adaptively selects the active or passive link probing mechanism according to the network traffic. In the absence of application traffic, this approach exploits active link probing, while in the presence of application traffic it can use the existing traffic as the probe packets [41, 69]. By this combination, hybrid link probing approach can consider the impacts of various packet sizes, network traffic rate and environmental changes on the offered communication quality by different links.

Given the above classification, each link monitoring approach uses a specific traffic generation technique for link quality measurements. Since at the network initialization phase, there is no cross traffic in the network, all the nodes should transmit a predefined number of beacon messages to monitor the transmission quality of links during the neighbor discovery process.

The second task in the link quality measurement process is dedicated to fetch useful information regarding the data transmission quality of the examined links from the transmitted and received probe packets. To this aim, whenever a node receives a beacon message, it should fetch the necessary information (e.g. BER, RSSI and LQI) from the received message in order to calculate the transmission quality of the link over which this packet has been received.

Finally, when all the required information to perform link estimations are collected, the link evaluation process can take place through different mathematical expressions. The link quality metric can utilize only one or a combination of multiple LQIs to measure the transmission quality of wireless links [29, 39, 70].

As the network initialization phase includes a lot of broadcasts within a restricted time interval, the probability of packet collision is extremely high and it may decrease the accuracy of link quality estimations. Accordingly, the number of beacon packets and the beaconing interval of the nodes should be adjusted to reduce the probability of packet collision. Furthermore, link quality estimation should be performed frequently in the course of network operation to provide stable packet delivery performance during the network lifetime.

5.3. Collection tree construction phase

The main purpose of data collection tree protocols is to enable all the nodes to find at least one path toward a single or multiple network data collection points for data transmission [71, 72]. Different metrics (e.g. hop-count and link quality) can be used to construct a spanning tree that includes lowest cost paths [73–76]. Network nodes calculate the cost of data transmission over different paths toward the network data collection point according to the utilized cost function. Construction of the network collection tree is usually triggered by the network data collection point (e.g. sink node in wireless sensor networks) through flooding a control packet. Upon receiving the control packet, the receiver node updates the cost field of the received message according to the data transmission cost of the link from which this message has been received. If it is the first time that the receiver node receives a control packet over a link, it should broadcast the received packet after updating its cost field. Otherwise, if the updated cost is lower than the previously calculated cost, the receiver node rebroadcasts the new cost value. When the network routing structure is established, all the nodes are ready for transmitting their collected data toward the given data collection point. The employed collection tree protocol should periodically update the network connectivity and routing information to provide quick response against network dynamics. Most of the collection tree protocols use a fixed interval for updating the routing information of the nodes [77, 78]. Although increasing the beaconing interval of the nodes results in lower bandwidth and energy utilization, it reduces the responsiveness of the collection tree protocols and link estimation techniques to the link quality variations. Accordingly, to provide a quick response against topological changes with an efficient network resource utilization, an adaptive beaconing approach should be employed to adjust the beaconing rate according to the network condition [9]. For example, under normal conditions (e.g. as long as routing structure works properly and the estimated cost of data transmission over different paths is correct) the beaconing interval can be increased exponentially up to a specified maximum value to reduce the frequency of broadcasting beacon packets. Whenever, a node detects a significant change in the underlying routing topology (e.g. when a node joins or leaves the network, variations in the routing cost of the nodes or long-term link quality variations), the beaconing interval can be reduced to provide a fast response against the network dynamics [9].

6. IMPACTS OF NETWORK INITIALIZATION PROTOCOLS ON THE DIFFERENT LAYERS OF THE PROTOCOL STACK

Based on the empirical observations regarding the temporal and spatial behavior of low-power wireless links, the performance of higher layer protocols can be improved through performing an efficient network initialization which includes neighbor discovery, link quality estimation and collection tree construction processes. Accordingly, this section is dedicated to identify the impacts of network initialization on the performance of higher layer protocols.

6.1. MAC layer

All the developed MAC protocols for low-power wireless networks (e.g. CSMA-based, time-division multiple-access (TDMA) based and hybrid protocols) exploit the available neighborhood information at individual nodes to perform different channel access functionalities (e.g. channel reservation and channel access scheduling) [79, 80]. For instance, MAC protocols can benefit from neighborhood information to measure the channel contention level for a given link during each time slot. In this context, they can use these information to determine the set of nodes that can be activated at the same time, while this selection reduces the number of collisions and results in high channel utilization [81]. Moreover, in contention-based medium access mechanisms, nodes can adjust their contention window size according to their neighborhood size to reduce idle listening and packet collision due to the concurrent transmissions or hidden node terminal problem [82]. The employed channel access scheduling techniques in TDMA-based MAC protocols also determine the channel access schedules for each node based on its two-hop neighborhood information so that concurrent data transmission from several nodes does not cause packet collision [83]. Furthermore, they can utilize the available neighborhood information at individual nodes to provide fair bandwidth utilization and avoid resource starvation problem.

Non-spherical pattern of link quality in low-power wireless networks also causes several problems during the channel reservation through contention-based MAC protocols. Therefore, link quality information can be used for further improvements in the functionality of these protocols. Figure 16a demonstrates the impact of asymmetric links on the channel reservation mechanism through Clear to Send (CTS) and Request to Send (RTS) handshaking. When node *A* receives an RTS message from node *C*, it responds to this message through transmitting a CTS message to node *C*. All the nodes that overhear the transmitted CTS message should postpone their packet transmission until node *C* completes its data transmission to reduce the probability of packet collision. However, due to the link asymmetry, it is possible that node *E* could not hear the transmitted CTS message by node *A*, while node *A* can hear packet transmission from node *E*. Therefore, concurrent packet transmission from node *E* and node *C* will result in collision at node *A*. Moreover, when CSMA is used as the medium access mechanism, the radio irregularity may cause the hidden terminal problem. As it is demonstrated through Fig. 16b, when node *A* transmits a packet to the node *B*, node *C* cannot hear this transmission. Since node *C* senses a clear channel, it starts packet transmission toward node *B*, but this transmission will result in packet collision at

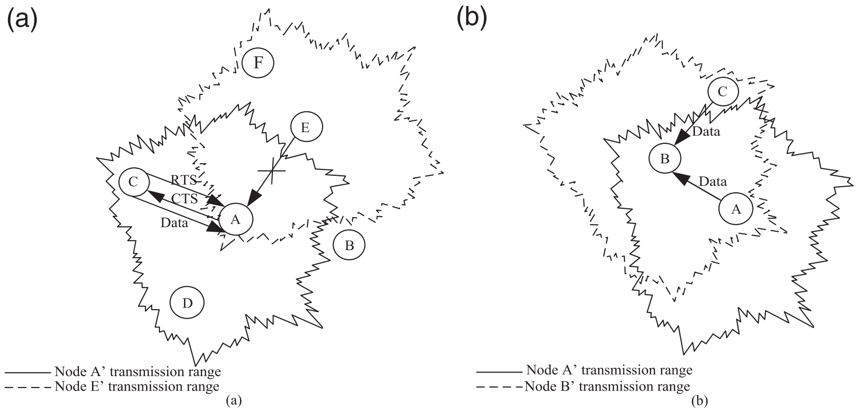


FIGURE 16. (**a**) Impact of radio irregularity on the medium access control layer. (**b**) Radio irregularity and hidden terminal problem.

node *B*. Accordingly, the combination of neighbor discovery with link quality estimation can improve performance of the MAC protocols.

6.2. Network layer

Due to the multihop communication pattern of low-power wireless networks, the main task of network layer is to select a set of optimal forwarder nodes between each node pair [84, 85]. In order to meet the performance requirements of different applications and provide efficient communications, routing protocols should be designed according to the performance demands of the underlying application [86–88]. Most of the early routing protocols in wireless networks rely on minimum hop-count routing [84, 89]. In the minimum hop-count routing approach, each node selects its highest distance neighboring node to minimize the number of hops along the paths. In order to increase the probability of successful data transmission over long hops, network nodes should increase their transmission power, which is in contrast with the energy constraints of low-power wireless networks. However, with a limited transmission power, the probability of packet loss over large distance hops is very high [36, 90]. This situation increases the RNP retransmissions to elevate the packet delivery ratio. Nevertheless, increasing the number of packet retransmissions causes higher energy consumption at individual nodes, more wireless interference and elevated data transmission delay. Although hop-count-based routing can provide minimum transmission delay and network resource utilization in wired networks, due to the special characteristics of radio communications (e.g. interference, fading, temporal and spatial link quality variations) this method is not suitable for low-power wireless networks [75]. According to the vast range of empirical studies of link characterization, a large area of a low-power wireless network belongs to the transitional region (where the PRR varies between 10 and 90%) [51, 91]. Accordingly, most of the wireless links in large-scale low-power wireless networks are asymmetric and unreliable [51]. Several works have shown that link asymmetry has a significant impact on the performance of multihop routing protocols [11, 19]. For instance, during packet transmission over asymmetric links a sender node may not receive any reply message from the receiver node for the delivered packets. In this case, the sender node assumes that the transmitted packet has been lost, and it will retransmit this packet until it receives a reply message. These unnecessary retransmissions waste network resources and decrease network performance in terms of throughput, delay, data delivery ratio and lifetime. Accordingly, by performing link quality measurement along with neighbor discovery process, routing protocols will be enabled to construct stable and high-quality paths to overcome link fluctuations [92–94].

6.3. Transport layer

The main aim of transport layer protocols is to provide end-to-end reliable packet delivery. Furthermore, these protocols can support QoS guarantee based on the performance demands of different applications, orderly transmission and network congestion control [95]. The bandwidth limitations and wireless interference of low-power wireless links can cause network congestion, which may affect the normal packet exchange rate in the network [96, 97]. For example, transmitting a large volume of data packets over low-quality links causes high packet loss ratio and increases the number of packet retransmissions to support the reliability demands of different applications. Accordingly, congestion control is the major concern in developing transport protocols to reduce packet loss rate. Furthermore, as nodes use a shared medium to communicate with each other, some of them may be poorly served due to the high dynamics of radio communications. In fact, link quality variations and the distance between the source and destination nodes cause unfair resource sharing between different application flows. In order to support end-to-end reliable data delivery, transport protocols can benefit from the information provided by the neighbor discovery and link quality estimation mechanisms to control the network traffic rate and mitigate network congestion.

6.4. Application layer

Link quality variations in combination with resource limitations of low-power wireless networks impose several challenges in supporting high-quality data delivery for different application traffic flows with various data transmission rates and performance demands. Since link quality variation is the main cause of unstable network performance, it should be considered a key factor for data rate adjustment. Fairness is another problem that emerges when multiple traffic flows exist in the network simultaneously [98, 99]. As different traffic flows pass over various links with dissimilar link quality, performance of the traffic flows that experience low channel quality may be influenced by the flows that are transmitted through high-quality links. Without considering the fairness issue in developing low-power wireless networks, unfair resource sharing of these networks may highly influence performance demands of network traffic flows. In order to overcome unfair resource sharing, the data transmission rate of the active application flows should be determined according to the quality of utilized paths by individual traffic flows. Furthermore, neighbor discovery and link quality estimation should be considered ongoing processes to identify new nodes that can provide better data transmission quality (in terms of network lifetime and throughput) than the active nodes along the established paths.

7. CLASSIFICATION OF THE EXISTING NEIGHBOR DISCOVERY PROTOCOLS

Generally, neighbor discovery can be performed in a centralized or a distributed manner [100]. In the centralized mechanisms, all the nodes should report their identities to a central node. After that, the central node determines the neighboring nodes of each node and informs all the nodes about their neighboring sets. Since the energy cost of this approach is highly related to the network size, it cannot fulfill the energy efficiency requirements of large-scale low-power wireless networks. In contrast, distributed neighbor discovery approaches allow the nodes to cooperate with each other to perform neighbor discovery. By this technique, the neighbor discovery cost is eventually distributed between all the nodes.

As can be seen from Fig. 17, the proposed neighbor discovery protocols can be categorized as synchronous and asynchronous approaches. This section describes some of the existing neighbor discovery mechanisms of each category. Furthermore, Table 1 provides an in-depth comparison of some of the existing neighbor discovery protocols based on the details of their discovery algorithms.

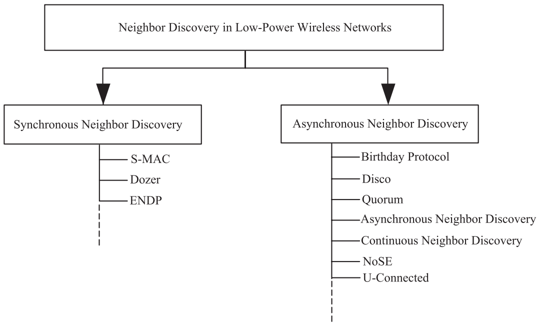


FIGURE 17. Taxonomy of the existing neighbor discovery protocols in low-power wireless networks.

7.1. Synchronous neighbor discovery

In order to perform a synchronous neighbor discovery, all the nodes should be assigned the same neighbor discovery schedule. Therefore, network nodes transmit beacon messages according to a predefined transmission schedule. Furthermore, most of the existing protocols employ a CSMA/CA mechanism to control medium access and reduce the probability of packet collision during beacon transmissions. Moreover, every transmitted beacon message should include the ID and synchronization information of the message originator. Accordingly, upon the reception of a beacon message, the receiver node knows the exact time of the upcoming beacon messages and the active periods of the sender, while it also establishes a new link to its newly discovered neighboring node. In this category, the duration of each state (i.e. sleep, listen and transmit) and the beaconing interval of nodes have a high impact on the number of collisions and neighbor discovery latency. Consequently, the probability of transition between sleep, listen and transmit states can be determined based on the network density to provide reliable and energy-efficient neighbor discovery with minimum delay.

Slotted-based MAC protocols like S-MAC [79] and SCP-MAC [101] provide synchronous neighbor discovery in low-power wireless networks. S-MAC tries to reduce network energy consumption through employing periodic sleep/listen scheduling at network nodes [79]. By this technique, nodes become active when at least one traffic flow exists in the network. Otherwise, they stay in the sleep mode. In S-MAC, all the neighboring nodes synchronize their sleep/listen schedules to reduce the network control overhead. Accordingly, they go to the sleep mode simultaneously and they wakeup again at the same time. In order to synchronize the sleep/listen schedules in the network, all the nodes should broadcast *SYNC* packets to exchange their schedules with their neighboring nodes. Therefore, each node should select a schedule and exchange it with its neighboring nodes before starting its periodic sleep/listen operation. Furthermore, it should also preserve the schedules of its identified neighboring nodes. To this aim, neighbor discovery is one of the important

TABLE 1. Comparison of the existing neighbor discovery protocols in low-power wireless networks.

Protocols	Synchronous	Power saving technique	Neighbor size-aware	Criteria	Time bounded	Network type	Link estimation	Mobility support
S-MAC [79]	Yes	Synchronized sleep/listen	No	Energy efficiency	No	Sensor	No	No
Dozer [102]	Yes	Synchronized sleep/listen	No	Energy efficiency, reliability	No	Sensor	No	No
ENDP [7]	Yes	Synchronized sleep/listen	No	Energy efficiency	No	Sensor	Yes	Yes
Birthday protocol [50]	No	Periodic sleep/listen	Yes	Energy efficiency before and during initialization, delay	Yes	*Ad hoc*	No	No
Disco [103]	No	Periodic sleep/listen	No	Delay, reliability	Yes	Sensor	No	Yes
Quorum [63]	No	Periodic sleep/listen	No	Energy efficiency	No	*Ad hoc*	No	Yes
Asynchronous neighbor discovery [100]	No	Periodic sleep/listen	Yes	Energy efficiency, delay	Yes	Sensor	No	No
NoSE [49]	No	Low power listening	No	Energy efficiency before and during initialization, delay	Yes	Sensor	Yes	No
Continuous neighbor discovery [8]	No	Periodic sleep/listen	Yes	Energy efficiency	Yes	Sensor	No	Yes
U-Connected [60]	No	Low power listening	No	Energy efficiency, delay	Yes	Sensor	No	Yes

operations in S-MAC. In this context, all the nodes exchange *SYNC* packets during the neighbor discovery period to perform synchronization process. During this process, each node first listens to the channel for a fixed interval to hear an *SYNC* packet from its neighboring nodes. If it did not receive any packet during this period, then it selects its own schedule and informs its neighboring nodes about its selected schedule by broadcasting an *SYNC* packet. Otherwise, if it receives an *SYNC* packet from one of its neighboring nodes before broadcasting its schedule, it will follow the announced schedule by its neighboring node. Network nodes on the border of two schedules (i.e. nodes that receive two different schedules from their neighbors) should follow both schedules and wakeup during the listen periods of these two schedules. In addition to the initial neighbor discovery, S-MAC also utilizes periodic neighbor discovery to avoid the case in which two nodes miss each other forever. Accordingly, all the nodes periodically perform neighbor discovery by listening to the channel for the whole synchronization period to hear the *SYNC* packets from their neighboring nodes. Dozer is a data-gathering framework that is designed to support low-power data collection in environmental monitoring applications [102]. This protocol architecture considers a coordinated interaction between MAC, topology control and a tree-based routing protocol to provide a low-power network protocol stack, which is suitable for data gathering in monitoring applications. Dozer supports energy-efficient data transmission from source nodes toward the network data collection point by using a TDMA-based MAC protocol. Since this protocol utilizes a tree-based network structure, all the nodes should be a part of the data-gathering tree to provide the network data collection point with their collected data. Accordingly, each node should try to join to the network tree upon its activation. To this aim, network nodes should start to listen to the channel upon their activation to obtain some information regarding their neighborhood structure. Whenever a node connects to the network-spanning tree, it sends beacon packets at the start of its TDMA schedule to enable its neighboring nodes join the network tree. When a given node scans the whole length of a TDMA round, it analyzes the received beacon messages to select the best parent node. After that, it uses a simple back-off mechanism to set up its connection toward the selected parent node. Upon receiving a connection request packet, the receiver node finalizes the connection setup phase through assigning a time slot within its TDMA schedule and returns this information to the sender node. Energy-efficient neighbor discovery protocol (ENDP) is another neighbor discovery mechanism, which is suitable for synchronized low-duty cycle MAC protocols in mobile wireless sensor network [7]. This protocol tries to reduce the energy overhead of beacon exchanges through utilizing MAC layer beacon packets for distributing node schedule information. Since the beacon packets of MAC layer protocols are periodically transmitted to maintain link synchronization, the neighbor discovery algorithm can reduce the signaling overhead of neighbor discovery and synchronization processes through piggybacking the two-hop neighborhood information of the nodes (including ID and synchronization information) in the payload of the existing MAC beacons. Furthermore, as these beacon messages are exchanged by a synchronized MAC protocol, utilizing these packets can help to avoid unnecessary idle periods and provide energy-efficient communications. At the network initialization phase, ENDP performs an initial network scan to enable the network nodes to identify their neighbors. In order to minimize the network scan duration, initial network scan will be finalized if a neighbor node with high RSSI is found, or a preferred number of neighboring nodes are identified. ENDP determines the preferred number of neighboring nodes according to the network topology and frequency of network dynamics. During the neighbor discovery process, each node exchanges the synchronization information of its parent with which the synchronization is currently maintained. This process replicates among the neighboring nodes of a node, and each node tries to receive a beacon message from a neighboring node that is not synchronized with that node. Upon receiving a beacon message, if the RSSI value of the received beacon is higher than the determined quality for high-quality links, the receiver node adds the sender ID to its neighborhood table. Moreover, each node also caches the received information from the nodes that their received RSSI values are adequate for communication. At the end of the neighbor discovery process, if the number of identified high-quality neighboring nodes is not enough, redundant links can be selected from the cached neighboring information. According to the operation of ENDP, network nodes can sleep and communicate with each other during the neighbor discovery process by using a synchronous beacon exchange mechanism at the MAC layer.

7.2. Asynchronous neighbor discovery

In contrast to the synchronous algorithms, in asynchronous discovery protocols nodes have their own schedules for neighbor discovery and they transmit beacon messages at randomly selected times. In this category, a network node announces itself through periodically broadcasting a beacon message which includes its ID. Furthermore, network nodes should sample the wireless channel frequently to detect the transmitted beacon messages and establish the initial network topology. Whenever a node receives a beacon message, it can establish a new link toward the recently discovered neighboring node.

Birthday protocol [50] is a neighbor discovery algorithm that uses a probabilistic technique to support asynchronous neighbor discovery. The main aim of this protocol is to provide energy-efficient network deployment, while it allows the network nodes to discover their neighboring nodes during the network initialization phase with high probability. In this protocol, each node can transit between the transmit (T), listen (L) or energy-saving (S) states with different probabilities at the start of its own time slot to provide energy-efficient neighbor discovery. Whenever a node is in the transmit state, it advertises itself by broadcasting a beacon message, while during the listen state, a node continuously listens to the channel for incoming beacon messages. If a node receives a beacon message in this stage, it adds the included sender address in the message to its local neighbor table. Furthermore, a node can go to the sleep mode during the energy-saving state to prevent unnecessary energy consumption. Therefore, in this protocol all the nodes operate at Birthday-Listen-and-Transmit (*BLT*) and Birthday-Listen (*BL*) modes. In order to avoid unnecessary listen periods at the start of the neighbor discovery process, network nodes start to discover their surrounding areas in the *BL* mode. In this state, at each time slot, network nodes randomly choose one of the listen or sleep states with a random probability. Upon receiving the first message, the receiver node switches to the *BLT* mode. In the *BLT* mode, at each time slot a node can choose state S, state T or state L with different probabilities to sleep, transmit or receive a beacon message. Afterward, it can switch back to the *BL* mode which can randomly alternate between state S and T to save its energy for further operations. The neighbor discovery process will be terminated, whenever all the nodes return to the *BL* mode. Disco is another asynchronous neighbor discovery protocol, which allows the nodes to operate at low duty cycles, while they can discover each other without any global synchronization [103]. In this protocol, network nodes select a pair of prime numbers such that their inverses are approximately equivalent to the application-defined duty cycle. In addition, each node has a local counter and increments it with a fixed period which is predefined globally. Whenever the value of local counter at a node is dividable by either of the selected prime numbers, the node should change its state to the active mode for one period. During the active periods, each node can transmit beacon packets to introduce itself to its neighbors or listen to the channel for incoming beacon messages. By this mechanism, Disco guarantees that two nodes will have overlapped periods during a restricted period even if they have individual duty cycles. In Disco, the desired discovery latency or nodes duty cycles should be determined according to the requirements of the underlying application. After that, the prime numbers will be determined automatically according to the selected discovery latency or nodes' duty cycle. Figure 18 demonstrates the main operation of this protocol for two nodes. In this figure, C_i and C_j represent the preserved counters at node i and node j, respectively. Node i and node j select prime number 3 and 5, which are relatively prime and

x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
c_i	-	**0**	1	2	**3**	4	5	**6**	7	8	**9**	10	11	**12**	13	14	**15**	16	17	**18**	19	20	**21**	22
c_j	-	-	**0**	1	2	3	4	**5**	6	7	8	9	**10**	11	12	13	14	**15**	16	17	18	19	**20**	21

FIGURE 18. An example of communication schedule under disco [103].

their inverse are approximately equal to the desired duty cycle of node i and node j. Node i and node j start to increment their counters at time $x = 1$ and $x = 2$, respectively. The black boxes in this figure indicate the active times of node i and node j. As it can be seen, at $x = 7$ and $x = 22$ both of the nodes have overlapped active periods. Therefore, these nodes can discover each other during these times. In addition to the discussed protocols, asynchronous neighbor discovery has also been handled through the Quorum protocol [63]. In this protocol, time is divided into the sequence intervals and then all the time intervals grouped to the sets of m^2 adjacent intervals. In this protocol, m is a global parameter, which can be determined according to the desired node duty cycle. Furthermore, in each group the entire m^2 intervals are arranged as a 2D matrix. A node randomly selects one row and one column of the entire intervals in each group and transits to the active state during the represented slots by the selected values. A node in the active state can transmit its beacon packets or listen for incoming beacon packets from its neighbors. By this mechanism, each node pair can be in the active state and discover each other at the time intervals represented in the intersection of their selected rows and columns. Borbash *et al.* [100] proposed another asynchronous neighbor discovery protocol. This protocol includes a distributed algorithm that allows the nodes to start neighbor discovery at different times. In this protocol, each node has its own time slotting and it can operate independently. Furthermore, in each slot a node can enter into the transmit or receive state with probability p_t and p_r, respectively. It is assumed that at the start of the neighbor discovery process most of the nodes are deployed in the listen-only mode, while the rest of the nodes are in the discovery mode. When a node in the discovery mode decides to transmit a beacon message during a time slot, it starts to transmit W copies of beacon message, where W has a fix positive value in the network. When a node in the listen-only mode receives a beacon message, it goes to the discovery mode and stays in this mode for a fixed duration of time slots S. During a receive slot, a node decodes its received message to identify the transmitter of the received message. After that, the receiver node makes an entry for the sender node in its neighbor table. However, due to the high probability of packet collision during beacon transmissions, the neighbor table of a node may not be completed at the end of the discovery period. In order to support energy-efficient operation from the beginning of the node deployment phase (i.e. before and during the network initialization) and provide a preliminary link quality estimation, a network initialization scheme called NoSE has been proposed in [49]. Since a complete network topology information cannot be achieved before full network deployment, in this protocol each installed node only listens to the channel at its wakeup intervals to detect the ongoing communications. When the network has been entirely deployed, a specific programmed node triggers the start of the neighbor discovery process by flooding a wakeup message to the network. In order to prepare all the nodes for initiating neighbor discovery, the wakeup message includes various information such as the beginning of the neighbor discovery process, its duration and further information such as the number of beacon packets and channel polling interval for link quality evaluation. The aim of this wakeup call is to synchronize all the nodes on a common time window to perform neighbor discovery and link estimation process. Accordingly, this synchronization dose not indicate that all the nodes synchronize their active periods for beacon transmission. When all the nodes receive the wakeup message, they start to perform the neighbor discovery and link assessment process within a fixed time window. During this process, all the nodes should exactly broadcast N beacon messages that include their identity. In order to accomplish the neighbor discovery process within a predetermined time, each node divides the discovery duration into N sub-slots and broadcasts a beacon at a randomly selected time during each sub-slot. Furthermore, every node should keep the number of received beacon messages and the maximum RSSI value for every single neighboring node in its neighborhood table for link quality estimation. By the end of the neighbor discovery process, all the nodes will have a list of their available neighboring nodes along with their respective data transmission quality.

The design of continuous neighbor discovery is discussed in [8]. This protocol tries to identify the hidden links that have not been discovered during the network initialization. A hidden connection in a set of connected nodes is identified as a direct communication link that can be identified between two nodes, while these nodes are not aware about this connection. The dashed links in Fig. 19 demonstrate the hidden links in a set of connected nodes. For instance, in this figure, node D has three hidden links toward node C, K and I. In this protocol, the whole task of neighbor discovery is divided between the nodes that have identified some of their immediate neighbor nodes during the network initialization phase. Accordingly, when a node that has been already joined to the network topology discovers a new neighboring node, it broadcasts an *SYNC* message to inform its previously identified neighbors about this new connection. Furthermore, to discover the hidden links from a node that is not connected to the network topology (e.g. node K in Fig. 19),

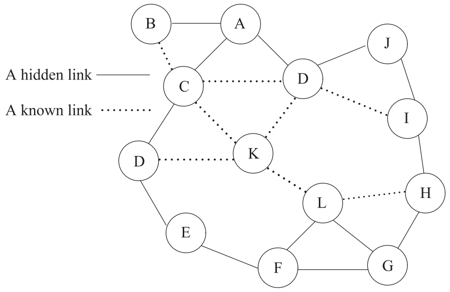


FIGURE 19. A set of connected nodes with hidden links.

the disconnected node should broadcast a *HELLO* packet at its wakeup times and listen to the channel for the incoming *HELLO* messages.

8. FUTURE RESEARCH DIRECTIONS

During the past decade, several research works regarding the initialization of low-power wireless networks have been presented. However, there exist several open research issues which are not properly covered yet. This section introduces some of the important topics in this area which require further investigation.

Scalable, practical and simple implementations for network initialization: According to the resource constraints of low-power wireless networks, it is necessary to exploit simple and scalable solutions to provide accurate network initialization with minimum cost. In this context, it is required to develop low-cost and simple protocols, which consider the main characteristics of low-power wireless links without requiring any particular hardware support or executing complex algorithms. For example, some radio transceivers do not provide LQI metric. Also, as the SNR metric cannot be easily obtained from the radio chip, a specific algorithm should be programmed at the software level. Therefore, it is necessary to design efficient link quality measurement techniques through combining those link quality metrics that can be easily and independently obtained from the employed wireless hardware. In addition, with respect to the deployment of low-power wireless networks in large areas, the number of nodes in an application may be in the order of hundred or thousand nodes. Therefore, network initialization algorithms should be scalable to work with different network sizes.

Compatibility: Most of the existing initialization protocols are designed based on specific assumptions such as a global network synchronization, specific MAC layer mechanisms and a fix network density. However, it is required that network initialization protocols be developed that can be executed without any limitation.

Providing optimal trade-off solutions between energy consumption and delay of neighbor discovery: Although the low-duty cycle operation is required to maximize network lifetime, it increases the delay of packet transmission. Accordingly, a good trade-off is desirable to design energy-efficient neighbor discovery protocols while they also satisfy the delay requirements of different applications.

Improving network collection throughput: Due to the bandwidth constraints of low-power wireless networks, it is necessary to increase network throughput as much as possible. For this reason, it is essential to design routing cost metrics that consider wireless interference and data transmission quality of different links to construct a high-throughput network collection tree.

Robustness of network collection tree protocols: Collection tree protocols should be robust against wireless interference and sudden link quality fluctuations to provide stable network performance under dynamic topologies. For instance, high variations of intermediate-quality links cause routing oscillations and unstable network performance. To this aim, most of the existing collection tree protocols utilize short-term link quality estimations. Since stable and unstable links may maintain a good data transmission quality over short periods, existing short-term link quality estimation techniques cannot accurately reflect the long-term variations of channel quality. Furthermore, as unstable links require frequent link quality measurements, the existing short-term link quality estimation techniques cannot provide low-energy cost operations. Accordingly, new approaches that can help to choose stable links for constructing the network collection tree should be investigated.

Continuous neighbor discovery and link quality estimation: Since topology of low-power wireless networks is highly dynamic, network nodes should update their neighborhood information periodically to improve responsiveness of upper layer protocols against network dynamics. In most of the existing protocols, initial and continuous neighbor discovery are performed in the same way. However, since neighbor discovery and link quality estimation during network operation can be considered the long-term processes, their optimization is necessary to provide efficient network resource utilization and increase network lifetime.

9. CONCLUSION

Neighbor discovery and collection tree construction processes are essential to enable network protocols to perform their functionalities. Over the past decade, network initialization has received a notable attention from the research community of low-power wireless networks. Therefore, there was a need to summarize the ongoing research works on the initialization problem in low-power wireless networks. In this context, we have attempted to survey the fundamental concepts of network initialization.

The importance of understanding link layer behavior for designing network protocols have been shown through analyzing previous empirical studies of the packet delivery performance of low-power wireless links. We identified the effects of link dynamics on the performance of neighbor discovery and data collection protocols. Moreover, it is understood that achieving reliable neighbor discovery and high-throughput data collection capability depends on the efficiency of employed link quality measurement mechanism to provide a detailed link classification. In order to discuss the existing link quality estimation approaches, these protocols have been categorized into the hardware-based, software-based and hybrid techniques. We also examined the correlation between different LQIs as well as their pros and cons to evaluate the transmission quality of wireless links.

We identified the primary performance parameters that should be fulfilled by the design of network initialization protocols. Furthermore, we introduced different steps of the network initialization process which are required to satisfy the discussed performance parameters. Moreover, the main challenges in designing these protocols have been highlighted through different scenarios. In addition, the significance of network initialization has been clarified through discussing its impacts on the performance of different network protocols.

To provide a comprehensive review of the existing neighbor discovery protocols, we classified these approaches into synchronous and asynchronous protocols. The synchronous approaches require global time synchronization to maintain high synchronization level among network nodes. Therefore, due to the issues such as clock drifts, high signaling overhead and significant cost of maintaining global synchronization, these protocols may not be well suited for large-scale wireless networks. In contrast, the second group of neighbor discovery protocols does not require synchronization between nodes. Therefore, individual nodes can start the discovery process at different times. Since in these protocols nodes operate asynchronously, they should wakeup frequently to provide overlapped wakeup schedules. While the second approach does not require particular assumptions or implementation of complex algorithms (e.g. prior knowledge about the number of neighbors or global synchronization), it is less energy-efficient than the first approach.

Based on the analyzes and discussions presented in this paper, we identified some of the open research challenges in designing efficient network initialization protocols. Hence, we highlighted some of the future research directions to encourage new research for further investigation on the initialization of low-power wireless networks.

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