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Reducing hops without extra power: Impact of deployment height on low-power multihop wireless network

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Abstract
Many low-power wireless network system deployments are planned on a two-dimensional plane, while in reality, we live in a three-dimensional space. Therefore, although it is essential to well consider the impact of height on the overall wireless system performance, this aspect has often been overlooked if not neglected with simplifying assumptions. Our work takes an empirical effort in quantifying the impact of height on a low-power wireless system's performance. Specifically, we use CC2420 radio–based wireless sensor network motes to quantify the impact of device deployment height on the connectivity and energy efficiency of low-power wireless networks. In addition, to validate the newly proposed sub-GHz low-power radios, we also experiment on the performance of CC1200 narrowband low-power radios to show that increasing a small amount of height in the node deployment phase can lead to drastic improvements in radio coverage and packet delivery performance. Such an observation can naturally lead to the reduction of network depth in a multihop wireless network for a given target deployment field; thus, it can potentially improve the energy efficiency of the overall system by suppressing the number of packet relay transmissions. We support our findings and observations through experiments on real embedded devices.

Keywords
Low-power and lossy network, wireless sensor network, multihop, deployment height, transmission range, RPL routing protocol, sub-GHz low-power radio

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Introduction and background

Low-power and lossy wireless networks (LLNs) composed of thousands of low-power networking devices can be used in a variety of applications including smart grid automated metering infrastructures (AMIs),[1] industrial monitoring,[2] and wireless sensor networks (WSNs).[3,4] Low-power radios used in these networks are widely known to provide very limited coverage for a single-transmission hop in order to consume minimal energy on (typically) battery-operated devices, as well as due to regulation reasons. As a result, for long, wireless networking architectures for real wide-scale outdoor application, systems have mostly been centered on the topic of designing effective multihop networks for delivering sensing data to distantly located gateway devices.[5–7] With wireless standards designed in the late

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20th century and early 2000s,[8] combined with radio modules developed at similar periods,[9,10] the multihop paradigm for low-power wireless networks was considered as a practical and viable option for system developers. Since forming single-hop networks, or even networks with shorter hop counts, require higher output power,[11] maintaining a collaborative architecture with many hops was more suitable for resource-limited embedded computing platforms. Specifically, transmitting data at higher power to form single-hop networks meant more power consumption at resource-limited embedded computing platforms, while a low-power network of more nodes combined with a smart radio power-management scheme (e.g. low-power listening[12–14] or other radio duty cycling schemes) would benefit the overall system efficiency. Furthermore, the capability to deploy more nodes ad hoc and expand network coverage was an appealing factor in applying multihop systems.

However, more than a decade has passed since the introduction of the first IEEE 802.15.4 low-power radio.[8] Still, many deployments are cemented with the axiom that wide-scale low-power embedded systems should use multihop protocols. This article raises a concern to this paradigm and asks the question, "With the recent active development in low-power radios, can we improve the performance of the LLN by reducing the number of hops for low-power networks?" Reducing hops in low-power networks can not only improve latency and throughput, but can also help reduce the energy consumed for packet relaying in multihop networks: something that is unavoidable, but crucial for low-power wireless nodes. Of course, this must be achieved while maintaining the flexibility of the multihop scheme (since there can always be some nodes that are unreachable in 1-hop) as well as the low energy consumption of individual devices. The fact that the paradigms of wireless radio designs have migrated to narrowband radios allows for a simpler hardware design and gives us another reason to confirm the possibility of reducing the number of hops in a low-power wireless network.

Given that simply increasing the transmission power will cause more energy usage and may even increase packet losses due to hidden terminal or load imbalance problems,[15] this is not a plausible solution for effectively reducing network depth. Instead, we focus on factors that can be determined in the system design phase. For example, node deployment "height" can be a system design choice that determines the network hops. By simply installing nodes higher from the ground, nodes can enjoy an increased coverage with the same transmission power. Indeed, this phenomenon is well known and is widely applied in various wireless networks. However, for low-power wireless networks, there is only a limited number of studies on *quantifying* the impact of deployment height[16] despite the fact that some measurement studies consider height implicitly for their experiments.[17,18] Given that new devices, such as drones, can act as mobile (aerial) data collectors, well understanding the performance impact of height becomes even more important.

Our experimental results with off-the-shelf low-power 2.4 GHz radios (e.g. CC2420[19]) show that even a slight increase in deployment height of 1 m can expand the coverage by more than three-fold. This improved communication range helps connect a line-topology network of 100 m in only one or two hops, leading to node energy usage reduction. Furthermore, we show that using more recently introduced sub-GHz narrowband radios (e.g. CC1200[20]), an even more dramatic improvement in coverage and energy efficiency can be achieved. Finally, we empirically show that the increased coverage leads to more elements to be added in a multihop routing table, and the use of instantaneous link-quality estimators can harm the networking performance due to storage limitations on embedded platforms. For this, we suggest using end-to-end path routing metrics when utilizing radios or networks with wide coverage areas.

The remainder of this article is structured as follows. In section "Multihop networks and hop reduction," we introduce the advantages and disadvantages of the multihop networking paradigm and introduce single-hop network as a potential solution for many of the challenges that multihop networks face. We present the main contribution of this work, which includes the quantification of low-power network performance for different deployment heights in section "Experimental validation." Finally, we summarize our work in section "Conclusion."

Multihop networks and hop reduction

In this section, we introduce the multihop networking paradigm widely used today and introduce its fundamental limitations. We then discuss about the benefits and opportunities that single-hop connectivity can bring to low-power wireless networks.

Multihop networks for low-power wireless networks

In designing low-power network applications, one of the most important high-level design goals is minimizing the energy usage of low-power nodes. This has been one of the most important focuses of the whole WSN research over the past decade. Given that many of these systems target to deploy in wide geographical regions, most systems focus on utilizing low-power radios at low transmission powers via multihop connections. This design allows nodes to minimize energy usage for constructing and maintaining the multihop architecture. With only a small amount of traffic, this was a reasonable design decision as the amount of packets to relay will be small and distributed widely over different nodes. However, with increasing number of packets and hops, nodes not only need more complicated MAC/routing/transport algorithms,[5,6,13,21–24] but also face more packets to relay, leading to increased energy usage for serving other nodes; sometimes even exceeding the energy spent for its own packet transmissions.

On a different perspective, a decade ago, multihop was a reasonable choice given the resource and hardware limitations. Widely used low-power radios such as the Chipcon/TI CC2420 IEEE 802.15.4 radio[19] utilized the direct-sequence spread spectrum (DSSS) mechanism as a way to allow greater resistance to external interference. However, such radios had several drawbacks. First, the fact that data are sent over a wideband signal complicates the design at the receiver end, allowing for only a limited receiving sensitivity. Second, the wideband nature of the signal itself caused (potentially) more chances for data collisions. In the industrial, scientific and medical (ISM) bands, where most low-power wireless network operate in, this problem becomes even more prominent since the low-power signals may not be effectively captured at the radios using different standards in their Clear Channel Assessment (CCA) phases. The diverging trend in low-power networking applications along with improvements in hardware over the last decade leads to the need to rethink the low-power network architecture.

Achieving and benefiting from less hops

Wireless networks such as cellular, Bluetooth, and (most) WiFi networks rely on a single-hop connection from a client node to the access point (e.g. base station and master node). Such a network topology allows for a simple management of client devices but also holds the potential to minimize power usage at client nodes by eliminating the packet relay overheads. Prior to the introduction of multihop networks, or even when multihop networks were used, single-hop networks have been the base model for most wireless architectures. However, in order to maintain a stable single-hop network, reliable connectivity to the access point is essential and achieving this could potentially require significant transmission power at resource-limited nodes. Nevertheless, if possible, single-hop networks can free nodes from the packet forwarding burden, multihop network constructing overhead (e.g. routing overhead packets) and minimize the idle listening.

While attractive, constructing a single-hop network with today's low-power radios is still challenging. Even with the new radios which have improved listening sensitivity and higher transmission powers (e.g. CC1200[20]), it is unclear how well, quantitatively in real-world deployments, they will perform. Furthermore, in a real deployment with complex environment, there will always be some nodes that are out of reach of the access point.

For existing radios, we make hypotheses that (1) the deployment height, (2) transmission power, and (3) different radio frequency (RF) band usage can impact the connectivity. First, increasing deployment height can allow outgoing (and/or incoming) RF signals to enjoy a wider range of reflection as it follows the two-ray ground reflection model. Due to reflection and absorption at the reflected points, a low-height transceiver can face significant signal power loss, leading to a significantly reduced communication range.[25] Therefore, and also due to the fact that the deployment height is something that can be relatively easily configured in many outdoor deployments, our work mainly focuses on the impact of increased height on low-power wireless nodes' communications. Furthermore, with the introduction of novel data collection platforms at aerial dimensions, such as drones, understanding how the deployment height factor impacts the data collection performance becomes even more important. The transmission power can be a controversial parameter given various regulations and energy budgets of low-power modules. As for the RF bands, it is well known that a lower frequency will travel longer distances. For this reason, many new radios operate on the sub-GHz range. For example, although the original IEEE 802.15.4 standard[8] specified 2.4 GHz only, the amendment IEEE 802.15.4g[26] added several other lower sub-GHz frequency bands to support for low-data-rate, wireless, smart metering utility networks. Regarding this factor, we will later discuss the impact of utilizing recently introduced radios such as the TI CC1200 radios.[20] Overall, by well utilizing these three design factors, we can open possibilities to reduce hop count and improve low-power multihop system efficiency.

Experimental validation

In this section, we present our experiment results showing that height has a dramatic impact, much more than expected. This is the first work to experimentally validate and quantify this disparity in the low-power wireless networking domain.

Increasing transmission range and connectivity with height

We first empirically show that the deployment height of nodes can have dramatic impact on the connectivity of a low-power wireless network. As mentioned, similar facts are widely used in other wireless networking

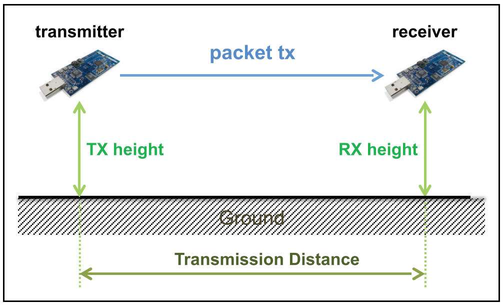

Figure 1. Single-hop experiment setup to measure the impact of deployment height on transmission range and connectivity.

domains such as cellular and WiFi, but this work is one of the first to quantify and confirm whether the impact of height also holds for low-power wireless network deployments. For this validation, we install a single receiver at a fixed location and vary its installation height from 0 (ground) to 4 m. (We use receiver heights 0, 0.5, 1, 1.5, 2, and 4 m, but show plots for subset of these based on significance to make the figures more readable and distinguishable.) The transmitter, which transmits periodic packets at 10 Hz, is configured at different relative distances (from 0 to 100 m) and height from 0 (ground) to 1.5 m. Figure 1 depicts our experiment setup. We use the TI CC2420 radio on TelosB[27] mote for both the transmitter and the receiver in this experiment to validate that height will introduce positive impact even for already widely used low-power radios. In Figures 2 and 3, we plot the received signal strength indicator (RSSI) of packets observed at the receiver along with the packet reception ratio (PRR) for 1000 packet transmissions, respectively. From Figures 2 and 3, we can notice that given the low-power nature of the CC2420 radios, the deployment height shows a dramatic impact, even if the nodes are raised only slightly. For example, focus on the square and triangle plots in Figure 3, which represents the case for the receiver being configured at 0 and 1 m. For all varying transmitter heights, from Figure 3(a) to (d), we can observe that a single meter of deployment height impacts the coverage area by more than three-fold in most cases. The RSSI plots in Figure 2 also agree that a small increase in height can dramatically impact the system's connectivity range, thus making it easier to reduce the number of hops with longer link connectivity in the network.

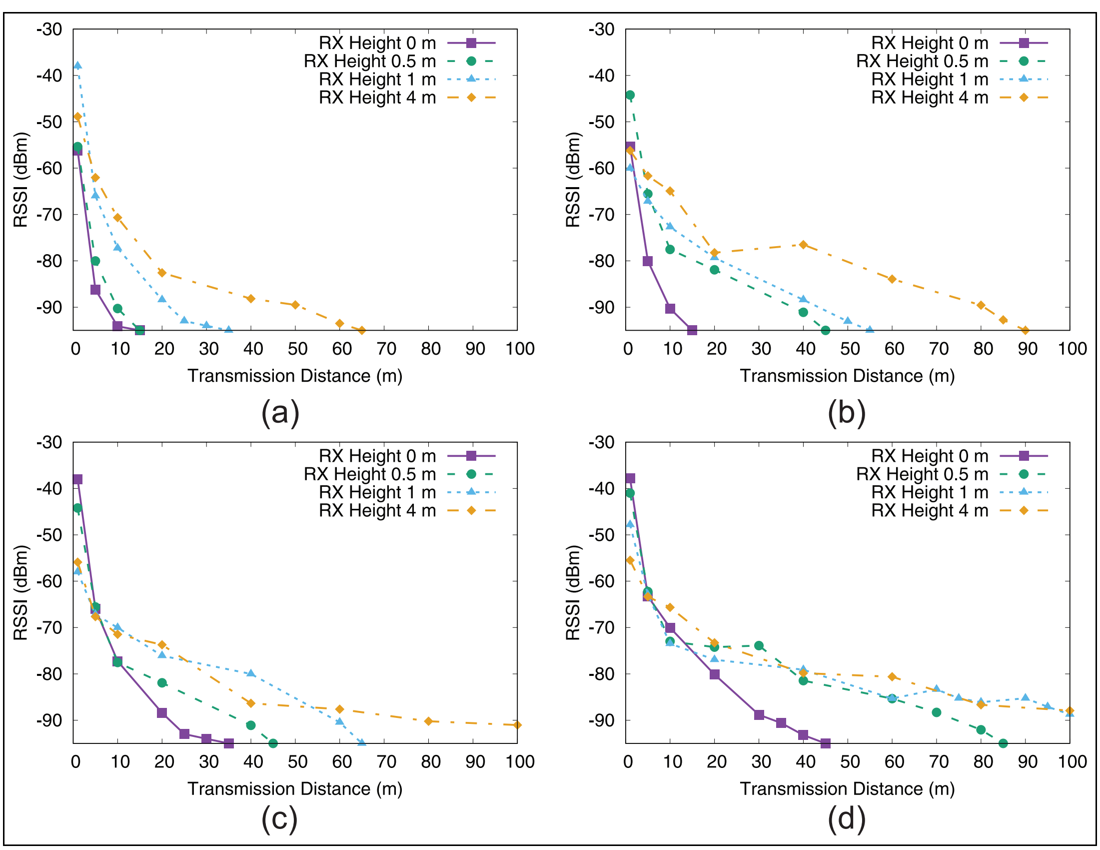

Figure 2. Received signal strength indicator (RSSI) value at the receiver versus transmission distance with varying heights of the transmitter and receiver: (a) TX height 0 m, (b) TX height 0.5 m, (c) TX height 1 m, and (d) TX height 1.5 m.

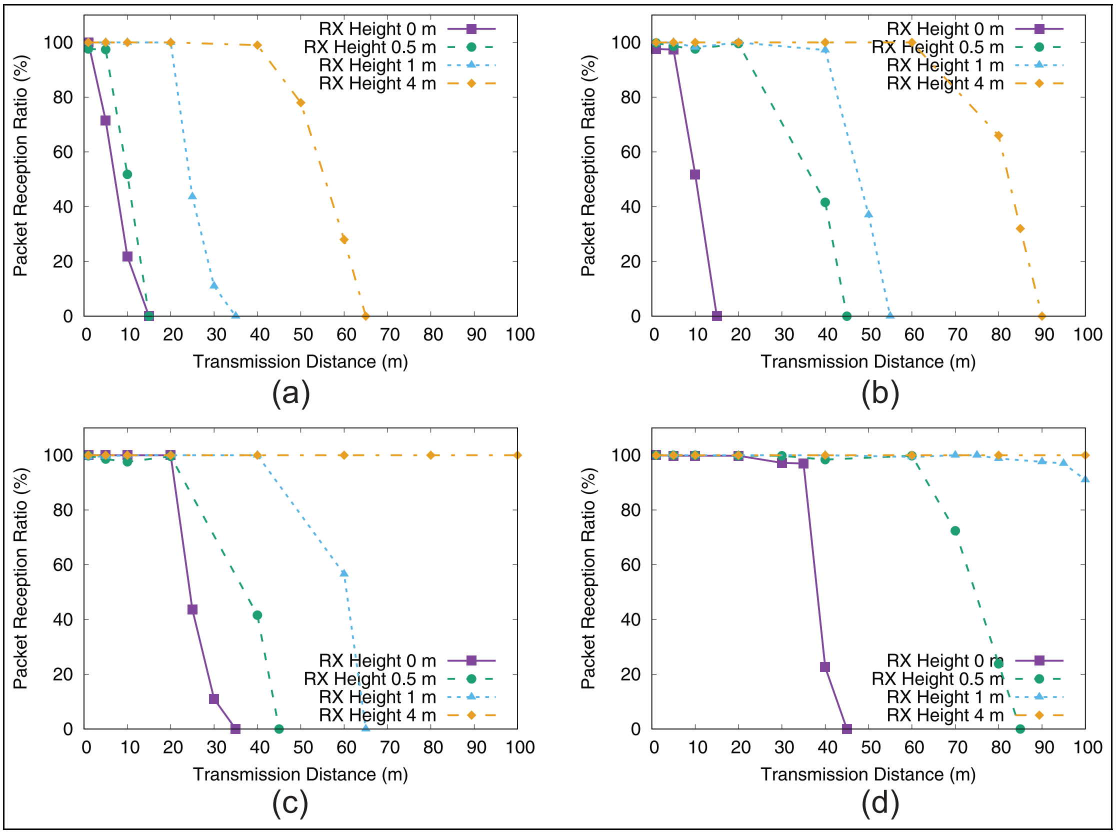

Figure 3. Packet reception ratio (PRR) at the receiver versus transmission distance with varying heights of the transmitter and receiver: (a) TX height 0 m, (b) TX height 0.5 m, (c) TX height 1 m, and (d) TX height 1.5 m.

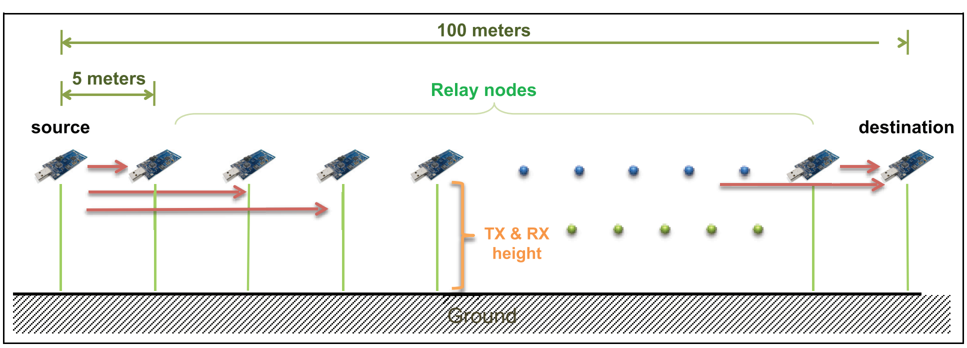

Figure 4. Multihop line topology experiment setup to measure the impact of deployment height on network depth and energy efficiency.

Improving energy efficiency with height

While increasing connectivity is important, another important aspect on a system's perspective is whether or not this increased connectivity actually impacts the number of hop counts in a network and leads to improved packet delivery performance and energy usage reduction.

To quantify this, we configured a 100-m line topology (20 nodes, each 5 m apart) of CC2420 radio-based TelosB motes, as depicted in Figure 4, and change the height of all nodes from 0 (ground) to 1.25 m at 0.25 m interval for each different test case. Here, we make the first node (e.g. the source node) in the network issue periodic packets every 1 s and record the number of hops that a packet travels to reach the final destination node in the line topology. All intermediate nodes retransmit the packets from nodes closer to the source node using ID-based filtering and ignore the packets heard from nodes closer to the destination node (father

Table 1. Hop count statistics of 100-m line topology of 20 nodes for achieving >90% reliability.

Height (m)	0.00	0.25	0.5	0.75	1.00	1.25
Average hop count	11.6	10.2	6.2	4.9	3.1	2.0
Minimum hop count	7	6	3	2	1	1

away from the source). Table 1 plots the resulting minimum and average hop count that assures at least 90% PRR from this experiment. Notice that as the deployment height increases, the average hop count gradually decreases and the 100 m topology can become a single-hop network when nodes are raised by more than a meter.

The fact that the hop count required to communicate between the edge nodes in the 100-m topology decreases also suggests that within the same network, a smaller number of packet transmissions can be issued for sending the same amount of data if a routing protocol was employed. Mainly, this is caused from freeing (or reducing) all intermediate nodes from the role of packet forwarding. We quantify this by presenting the average number of packet transmissions in the network for sending 1000 end-to-end transmissions in the 100-m line topology (from first node to last node) in Figure 5 (with the error bar representing the standard deviation for five independent runs). We can see here that with increasing deployment heights, the amount of packet transmissions gradually decreases. Naturally, this means that with an appropriate low-power MAC protocol, nodes in the network can increase their system lifetime: nodes can reduce the radio on-time for packet reception of neighbors' packets and also the time for relaying these packets.

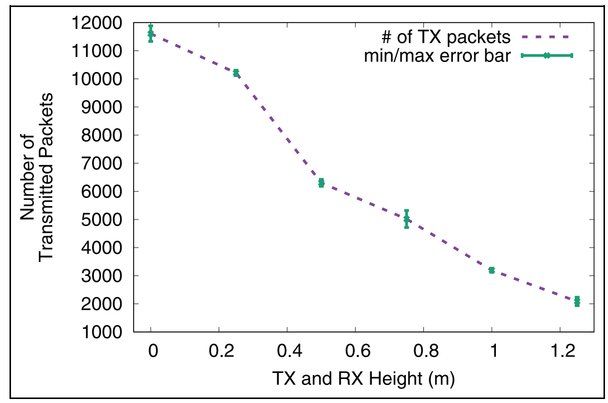

Figure 5. Total transmission packet count for sending 1000 end-to-end packets on a 100-m line topology of 20 nodes with varying installation heights from 0 (ground) to 1.25 m at 0.25 m interval (same height for both transmitter and receiver).

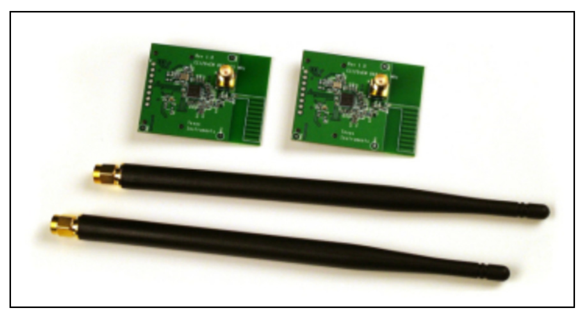

Figure 6. CC1200 radio module used in our experiments.

Impact of sub-GHz, narrowband radios

Recent advances in hardware and wireless communication technology have influenced the manufacturing of high-performance narrowband radios for low-power networks. While detailed performance specifications can be found in the datasheet,[20] here we present results from a selected set of experiments to show that with these newly introduced radios, achieving a smaller network depth is much easier compared to using IEEE 802.15.4 standard-compliant radios at 2.4 GHz as the only low-power option. Figure 6 is the image of the CC1200 RF module that we have used for this experiment.

Figure 7 plots the PRR and RSSI performance of the TI CC1200 radio at 900 MHz for varying distances (from 0 to 100 m) with different (symmetrical) transmitter and receiver heights at 0 (ground), 0.5, 1, and 1.5 m. Notice here that with these sub-GHz, while the data rate is lowered to 38.4 kbps, the radio connectivity well exceeds 100 m at 1 m height. The RSSI plots further suggest that this communication range can be much longer. For many wireless sensing system applications,[11,28–30] this is sufficient enough performance to meet application requirements. We present this result as an indicator to emphasize that achieving less hops, or even a single-hop network, is no longer a difficult network architecture design when combining the height factor and newly introduced radios.

Applying height to real deployments

In reality, despite reducing the number of hops, a multihop routing protocol may still be useful in deployments covering wide area or complex environments. While our results show that ~100 m connectivity over a single-hop using well-used CC2420 radios is possible, deployments that exceed this length or deployments

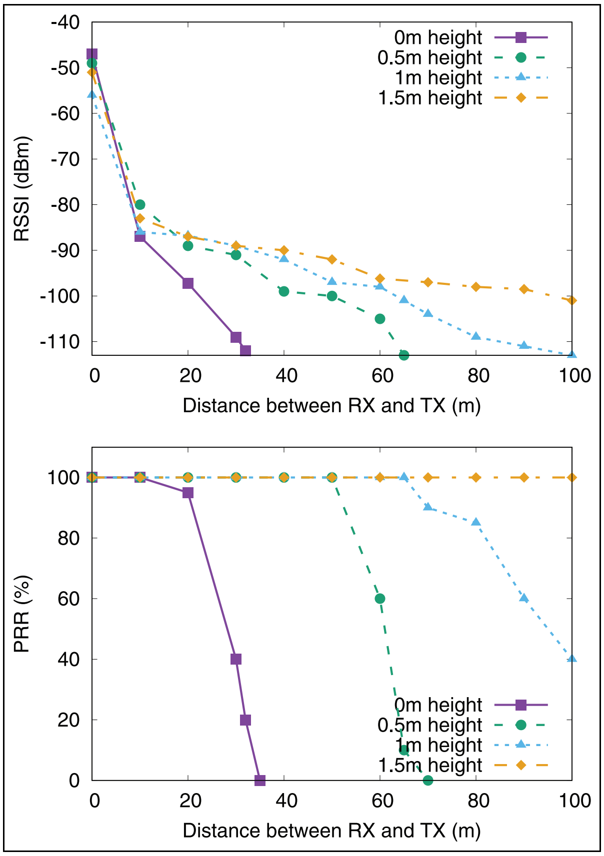

Figure 7. RSSI and PRR performance of CC1200 radio at 900 MHz versus transmission distances with varying heights for both the transmitter and receiver.

that cannot practically deploy a 1 m pole in the field will need to utilize multihop protocols. These protocols typically use link-quality measurement algorithms to determine the next hop node by combining metrics such as RSSI, link-quality indicator (LQI), expected number of transmissions (ETX[31]), or simply hop count to determine the link or routing path quality.[5,32]

However, while simply increasing deployment height can reduce the number of hops and increase energy efficiency, using the routing protocols we have today, we will not be able to easily enjoy these benefits. Keep in mind that we are dealing with low-power networks, typically cored by resource-limited platforms. The conflict in utilizing deployment height arises here. While the increased connectivity brings more nodes into the routing table (as potential next hops), the device's memory resources may not be able to store all of them. As an example, in the RPL ("IPv6 Routing Protocol for Low-power and Lossy networks," RFC6550[5]) implementation in TinyOS,[33] memory constraints of the MSP430 microcontroller (MCU) limit the number of entries in the routing table to only 20. This is similar in the ContikiOS implementation of RPL as well.[34] Naturally, the link-quality measurement layer can select only a subset of the nodes as potential neighbors. For RPL in both TinyOS and Contiki, we noticed that as the network scales, nodes that are distant but are still connected were often removed from the routing table. This is due to the use of instantaneous link-quality metrics such as RSSI and LQI in determining the nodes to store in the routing table. Since node farther away will have lower RSSI and LQI compared to nodes nearby, they are relatively discriminated when constructing the routing table even if they are still good enough to maintain reliable connection. In fact, those nodes are removed despite that they are the beneficial ones that can help reduce the network depth by enabling longer range transmissions.

To quantify this finding, we extended the aforementioned 20-node line topology to 30 nodes in the same 100 m line with node heights of 0.5 m and evaluated the performance of RPL using different link-quality metric options. Specifically, we tested four cases where in the first and second, instantaneous link-quality metrics such as RSSI and LQI were used to filter nodes in the node's routing table, respectively, and in the third and fourth, only end-to-end path-scale metrics such as hop count and ETX were used, respectively. The plots for PRR and the number of transmissions in Figure 8(a) show that overall, using path-scale metrics reduces the number of packet transmissions (e.g. in-turn, the energy usage of the nodes) and the use of ETX improves the network performance by maintaining a high PRR. Within these experiments, the test cases using instantaneous link-quality metrics failed in fully utilizing the increased connectivity and showed hop counts ~1.3 times larger than the path-scale metric configurations on average. We note that this degree of inefficiency increases with the number of hops in the network. While somewhat expected, Figure 8(b) confirms that with an increased communication range from the added deployment height, the use of instantaneous link-quality metrics in multihop protocols may potentially harm the overall system-level efficiency.

Conclusion

The multihop networking paradigm has benefited the development of various low-power embedded wireless systems over the past decade by providing a way to easily extend network coverage while minimizing energy usage for a single data transmission. However, system designers were captured in the axiom of multihop networking, trying to solve last-mile optimization issues on a two-dimensional plane even while simply increasing the deployment height by a few meters (or even less) can easily bring significant performance benefits. This article serves as a quantitative evaluation of how deployment height impacts the network performance for widely used

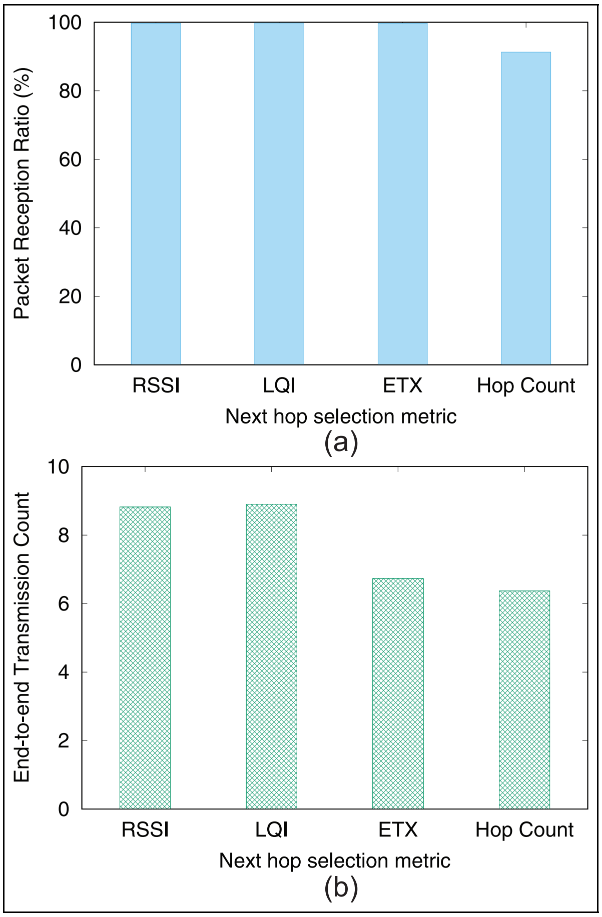

Figure 8. Performances from 20-node 100-m topology network installed at 0.5 m height with different link-quality measurement metrics: (a) packet reception ratio (PRR) and (b) total number of packet transmissions.

low-power radios. We have shown that a small increase in the deployment height of wireless transceivers can improve the PRR on a single link and extend its radio coverage significantly, thereby reducing the depth of a multihop network. Shallower multihop network results in significant overall performance improvements not only in terms of packet delivery ratio and aggregate throughput but also in energy efficiency. Furthermore, we have also shown that newly introduced narrowband and long-range radios make the management of energy resources in low-power wireless networks even easier based on our findings. With new data collection platforms at aerial dimensions (e.g. drones), we believe that node deployment height will be an important factor for reducing hop count and increasing energy efficiency in low-power wireless network deployments.

Declaration of conflicting interests

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