Chapter 7

Fundamentals of Wireless Communication Link Design for Networked Robotics

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Abstract

This chapter aims to present the fundamentals of the design of wireless communication links for networked robotics applications. First, we provide an overview of networked robotics applications, motivating the importance of the wireless communication link as an enabler of these applications. Next, we review the wireless communication technologies available today, discussing the existent tradeoffs between range, power, and data rate, and introducing the main concepts regarding the design of wireless communication links. Finally, we present a design example of a wireless communication link and the results obtained. We conclude the chapter with a discussion of the results and the challenges faced in the design of wireless communication links for networked robotics.

Keywords: wireless communications, networked robotics, wireless networks

1. Introduction

According to Ref. [1], service robots are defined as "reprogrammable, sensor-based mechatronic devices that perform useful service to human activities in an everyday environment." Also, service robots "perform tasks in a specific environment and should be able to perform services semi- or fully automatically." However, service robotics is different from industrial robotics, where robots are employed for the direct manufacture of goods. In service robotics, a robot performs services for humans and institutions, in an environment that often cannot be redesigned [2], and even it might be a hazardous one [3].

Examples of hazardous environments where service robots may operate include high-altitude (e.g., wall-climbing robots for inspection, painting, and cleaning of high-rise buildings [4–6]) and high-risk conditions (e.g., inspection and maintenance in nuclear and power generation industries [7–11]). Yet, in such conditions, service robots might need to be teleoperated or remotely controlled, and therefore a communication link is required [7, 12–13].

Beyond teleoperated robots (TRs), some sort of wireless communication capability is also required by autonomous robots (ARs), which are a subclass of networked robots (NRs) [14]. Accordingly, autonomous networked robots operate (possibly in group) supported by a wireless sensor network in order to fulfill their tasks [14]. Thus, the wireless sensor network extends the effective sensing range of the robots, and allows them to communicate over long distances to coordinate their activity. Yet, more recently, wireless sensor, actuator, and robot networks (WSARN) have been introduced as a means not only for extending the sensing range of the robots but also for their actuation capabilities in the surrounding environment, in order to accomplish their missions [15].

Clearly, the communication link plays an important role in networked robots applications [16], such as ubiquitous robotics [17], cloud robotics [18, 19], and remote sensing [20, 21]. For such applications, use cases may be different (e.g., robot-to-robot communication (R2R), robot-to-sensor/actuator/machine (R2S/R2A/R2M), and robot-to-cloud (R2C)) and, thus, impose different requirements for the communication (e.g., range, bit rate, latency, and energy consumption). Next, we present some of these applications.

2. Networked robotics applications

The almost ubiquitous presence of the Internet worldwide and the fast technological development in computing, sensing, and communication systems has led to envisage a new era for robotics, where robots are networked and work cooperatively with sensors, actuators, and human beings [14]. These networked robots may use external resources for computing, data gathering, sensing, learning, and working collaboratively through the "Cloud" [17, 19], or even they may "live in the Cloud" (e.g., software agents/robots) and teleoperate other robots (e.g., mobile robots and autonomous vehicles).

In **Figure 1**, we illustrate such diverse range of networked robotics applications. Networked robots may be teleoperated by a human being or by a software agent (teleoperation), sending commands to the robot(s) and receiving measurement/feedback data, thus requiring a reliable and low latency communication through the Internet. The robots also may work cooperatively, locally exchanging data in a multi-robot system and performing collaboratively a given task, thus requiring low-power and long-range wireless communication. Long-range wireless communication is also required in robotics remote-sensing systems, where mobile robots are collecting data far away in an unknown environment. On the other hand, if robots can have access to the Internet through a reliable communication link, they can possibly offload some of its processing tasks to the cloud. In cloud robotics, the robots can have access to an elastic pool of services, data, storage, and applications, extending their capabilities beyond their computing and physical constraints [19, 22].

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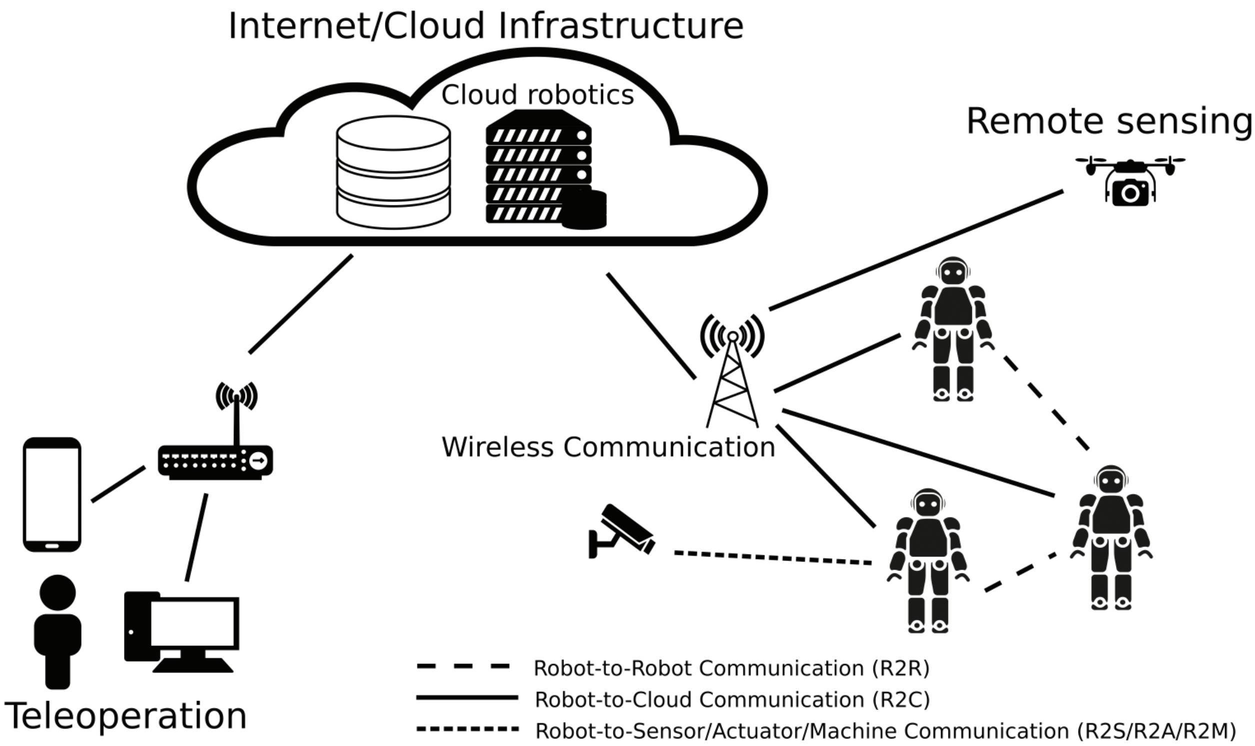

Figure 1. Representation of several envisioned networked robotics applications.

The diverse applications of networked robots impose different requirements (e.g., range, latency, reliability, bandwidth, etc.) on the communication system they rely upon, making the design of the communication network a challenging task. For example, in teleoperated robots for surgical operations, low latency and time delay are of primary concern [23], while mobile robots for outdoor mapping and the teleoperation of unmanned aerial vehicles (UAVs) require long-range communication [24, 25].

Indeed, depending on the networked robotics application, different quality-of-service (QoS) requirements (reliability, bandwidth, end-to-end delay, etc.) are imposed for the communication system design. On the other hand, there are several tradeoffs (e.g., performance, cost, range, mobility, energy consumption, etc.) involved in the design space of a communication system, which must be specifically and carefully addressed for the envisioned networked robotic application. Therefore, in the sequel, we present an overview of the design space of wireless communications systems, given its paramount importance in networked robotics [17].

3. Wireless communications overview

Wireless communication is one the major concerns in networked robotics, mainly in networked service robots [17]. However, different than wired communication, wireless is usually less reliable and more interference prone. Thus, the design of the wireless link and the wireless network is usually more challenging. The design space of a wireless communication link includes several variables, such as frequency and modulation selection, power and link-budget constraints, signal propagation characteristics, a huge set of wireless communication standards to choose from, and so on.

Wireless communication may use different portions of the electromagnetic spectrum, including radio (10 kHz to 100 MHz), microwave (100 MHz to 100 GHz), infrared (100 GHz to 400 THz), and visible light (400–790 THz). The higher the frequency, the higher the bandwidth available and more bits per second (bps) can be transmitted according to Shannon's theorem. This theorem, given in Eq. (1), relates the amount of information (C, in bps) that can be carried by a signal, such as an electromagnetic wave, with the received power (S, in Watts), the noise power (N, in Watts), and the available bandwidth (B, in Hz) for the communication system, subject to additive white Gaussian noise (AWGN)

$$C = B\log(1 + S/N) \tag{1}$$

Infrared (IR) and visible light communication (VLC) have higher bandwidth and use light-emitting diodes (LEDs) and photodetectors (PDs) for intensity modulation and direct detection (IM/DD) of the light signal [26, 27]. However, signal propagation at such high frequencies is very directional and may be easily blocked by obstacles and walls, thus requiring line of sight (LOS) for communication. Therefore, IR and VLC are more suitable for short-range indoor communication. These types of communication have been standardized by the IrDA association [28] and IEEE 802.15.7 [29, 30], respectively.

Signal propagation is better for outdoor and long-range communication in radio and microwave. However, microwave suffers much more water absorption (e.g., rain) above 6 GHz, and signal propagation is more directional. Thus, at these portions of the spectrum, bandwidth is at a premium, mainly for outdoor communication. For indoor communication, 60 GHz ISM (industrial, scientific, and medical) unlicensed band is worldwide available and its use for Wi-Fi communication has been standardized as the IEEE 802.11ad specification [31, 32], offering up to 7 Gbps throughput and allowing the use of very small and low-cost antennas [33, 34].

For short-range communication, IEEE 802.11 (Wi-Fi) is an interesting option for applications requiring high throughput (e.g., video streaming). It may operate also in the worldwide available ISM bands in 2.4 (IEEE 802.11b/g/n) and 5.8 GHz (IEEE 802.11ac). However, IEEE 802.11 is more power and energy hungry than other wireless standards such as Bluetooth Low Energy (BTLE) [35] and IEEE 802.15.4 [36] standards, which are targeted for low-power and low-rate applications.

IEEE 802.15.4 is a standard for low-rate (e.g., 250 kbps in 2.4-GHz band) and low-power (<100 mW) wireless communication. It is available worldwide in 2.4 GHz and several other bands with availability depending on the country/region of operation [36]. Also, it has been adopted by other application and networking standards, such as ZigBee [37] and 6LoWPAN [38]. On the other hand, the BLTE standard has similar performance characteristics of IEEE 802.15.4, such as low power (<100 mW) and low rate (<1 Mbps), but operates solely in 2.4-GHz band. It is promoted by Bluetooth Special Interest Group and is widely used in smartphones and tablets.

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However, both IEEE 802.15.4 and BLTE are designed for short-range communication (<1 km), and thus they are not targeted for applications requiring long-range communications.

Long range is usually required in outdoor wireless communications. In such cases, lower frequencies are preferable due to lower path loss (PL), which is the attenuation of signal power between the transmitter (Tx) and the receiver (Rx), measured in decibels (dB), in a given wireless communication link. Free space path loss (FSPL), which does not account for obstacles and reflections, and depends solely on frequency (f in GHz) and distance (d in km), is given by Eq. (2) in dB

$$Lp = 92.45 + 20\log_{10}(d) + 20\log_{10}(f) \tag{2}$$

At a long distance, a more realistic model is the two-ray ground reflection model, which accounts also for the reflection of the signal on the ground. In this model, both the reflected wave component and the direct LOS wave component are considered. In this case, the path loss also depends on the gain (G) and the heights (ht, hr) of the transmitter and receiver antennas, and is given by Eq. (3) that is only valid for large d (i.e., $d \gg \sqrt{hr \times ht}$).

$$Lp = 40\ \log_{10}(d) - 10\log_{10}(Ght^2hr^2) \tag{3}$$

In fact, the heights of the antennas not only influence the path loss but also limit the maximum line-of-sight (LOS) distance, which is dependent on the earth's curvature. Accordingly, the maximum LOS distance, in meters, is given by Eq. (4), where R is earth's radius and equals 6365 km. For instance, considering antennas placed at 1-m height above the ground, the maximum LOS is 7136 m

$$LOS\max = \sqrt{2 \times ht \times R} + \sqrt{2 \times hr \times R} \tag{4}$$

In practice, however, even if the distance is lower than the maximum LOS, communication will not be possible if the received signal power is too low such that it cannot be distinguished from the noise present at the receiver. This relation is known as signal-to-noise ratio (SNR). Therefore, for a given modulation and communication bit rate R, there is a minimum SNR required by the receiver in order to achieve a desired bit error rate (BER) or packet error rate (PER). Such a minimum required SNR is usually defined in terms of the receiver sensitivity, which is the absolute input power level required to not exceed 1% BER or PER at the receiver. Thus, the receiver sensitivity, which is specified in the receiver's datasheet, is the input power level that gives the required minimum SNR for the wireless communication link.

The design of a reliable communication must be done in order to assure that the received power (*Rx power*) is at least equal to the receiver sensitivity (*Rx sens*) plus some safety margin (known as *link margin*), according to Eq. (5). The link margin must be chosen in order to have enough received power even in case of signal attenuation due to mobility and multipath propagation, which is known as fading and is the result of the destructive interference among the waves that travel through different paths and reach the receiver with different delays. As a rule of thumb, link margin, also known as fade margin, is usually set to 10–30 dB, depending on the desired link reliability

$$Rx\ power\ (dBm) = Rx\ sens\ (dBm) + Link\ margin\ (dB) \tag{5}$$

The received power can be determined taking into account the transmitted power (*Tx power*) plus the gains and losses through the wireless link, according to Eq. (6). Then, combining Eqs. (5) and (6), putting in the gains (*Gr, Gt*) of the receiver and the transmitter antennas, the path loss (in dB), and rearranging the terms, one obtains Eq. (7), which is the "link power budget" or "link-budget" equation. Therefore, the link budget, given in Eq. (8), is the maximum allowed amount of power that can be lost through the wireless link due to path loss and fading, and still maintaining the communication link working. Equation (8) can also be written as Eq. (9), where the term EIRP (dBm) is known as the *effective isotropic radiated power*

$$Rx\ power\ (dBm) = Tx\ power\ (dBm) + gains\ (dB) - losses\ (dB) \tag{6}$$

$$Path\ loss(dB) + Link\ margin(dB) = Tx\ power(dBm) + Gt(dB) + Gr(dB) - Rx\ sens(dBm) \tag{7}$$

$$Link\ budget\ (dB) = Tx\ power\ (dBm) + Gt\ (dB) + Gr\ (dB) - Rx\ sens\ (dBm) \tag{8}$$

$$Link\ budget\ (dB) = EIRP\ (dBm) + Gr\ (dB) - Rx\ sens\ (dBm) \tag{9}$$

For wireless systems operating in unlicensed ISM bands, the EIRP is limited by local regulatory agencies, such as the Federal Communications Commission (FCC) in the United States, the European Telecommunications Standards Institute (ETSI) in Europe, the Association of Radio Industries and Business (ARIB) in Japan, and the National Telecommunications Agency (ANATEL) in Brazil.

Note that the limitation imposed to the EIRP is very important in the design of a long-range communication link. If the link is bidirectional and the same antenna is used for transmission and reception, the maximum achievable link budget will be basically determined by the receiver sensitivity, as can be noticed from Eq. (9). Therefore, the selection of the receiver with enough sensitivity is a crucial step in the design of a long-range wireless communication system.

Basically, there are two main approaches in order to achieve long-range communication: ultra narrowband (UNB) radio-frequency (RF) and wideband spread spectrum (SS). Both approaches aim to increase the receiver sensitivity at the cost of reducing the effective data rate. Ultra narrowband RF is a technique for wireless communication where the bandwidth used is very small compared to carrier frequency (i.e., $\frac{\Delta f}{f} \ll 1$). Therefore, the signal energy is concentrated in this narrow band and the thermal noise is reduced, ultimately improving the SNR.

The reduction of thermal noise due to the reduction of the bandwidth can be noted from Eq. (10), which shows that thermal noise (N) is proportional to the bandwith B and the temperature T. In Eq. (10), the proportionality constant k is Boltzmann's constant and equals 1.38×10^{-23} J/K. Therefore, in room temperature (T = 290 K), the noise power in dBm can be calculated by Eq. (11). For example, in a communication system operating with a bandwidth of 10 kHz, the noise floor is -134 dBm

$$N = k \times T \times B \tag{10}$$

$$N(dBm) = -174 + 10\log_{10}(B) \tag{11}$$

The improvement of the SNR due to UNB results in the improvement of the receiver sensitivity, and thus allows for higher link budgets and longer ranges. However, the throughput is also reduced, making UNB suitable only for low-power and low-rate networks, such as low-power wide area networks (LPWAN) [39] and low throughput networks (LTN) [40]. For instance, Sigfox [41], which is a LWPAN/LTN provider operating in unlicensed bands (915 MHz in US and 868 MHz in Europe), employs UNB communication with a very small bandwidth of 100 Hz and a bit rate of 100 bps. With such a low bandwidth, the spectrum is efficiently used and the noise power is very low (around −150 dBm at 290 K), allowing a receiver to demodulate an extremely low-power signal of −142 dBm [42]. In [39], it is reported that a UNB test link of 25 km was deployed successfully with a transmission power of 14 dBm and an SNR exceeding 20 dB.

Another alternative for increasing the receiver sensitivity is through the use of some spread spectrum technique. In such technique, the bandwidth used to transmit the signal is β times larger than the minimum required, where β is known as the spreading factor (SF), repetition factor, or processing gain. The effect of spreading factor is the reduction of the spectral efficiency η, which is the ratio between the bit rate R and the bandwidth B, while maintaining the bandwidth B constant [43]. Ultimately, this reduces the minimum required SNR, thus lowering the receiver sensitivity, according to Eq. (12), where $SNR_{\min}$ (dB) is the SNR required without the spreading technique and SNR_β (dB) is the SNR required with the use of the spreading factor β [44]

$$SNR_\beta(dB) = SNR_{\min}(dB) - \ 10\log_{10}(\beta) \tag{12}$$

The spreading technique is used by a state-of-the-art modulation known as LoRa, which is promoted by the LoRa Alliance for LPWAN deployments based on the LoRaWAN specification [45, 46]. LoRa is based on chirp spread spectrum (CSS) modulation, which uses wideband linear frequency-modulated pulses whose frequency varies linearly over time in order to encode information [47, 48]. LoRaWAN has been designed to operate in several license-exempt bands, including 868-MHz band in Europe and 915-MHz band in US, with configurable bandwidth between 125, 250, and 500 kHz and configurable spreading factor between 7 and 12. According to the chosen spreading factor, the data rates range from 336 to 48 kbps [49], as calculated by Eq. (13), where B is the bandwidth and R is the data rate

$$R = \frac{B}{2^{SF}} \times SF \tag{13}$$

LoRa can offer a receiver sensitivity lower than −130 dBm, thus allowing long-range communication links [47]. In Ref. [46], working LoRa links operating in 868-MHz band with ranges up to 15 km over the ground and 30 km over water were reported, when using the highest spreading factor (SF = 12) and the maximum allowed transmission power (14 dBm), with the bandwidth set to 125 kHz. However, in order to achieve those long ranges, the bit rate was reduced to only 293 bps, thus showing a clear tradeoff between the distance and the data rate in the design of a wireless communication link. **Table 1** shows the achievable data rates, expected range, and time on air for LoRa according to the spreading factor.

Spreading factor (at 125 kHz)	Bit rate (bps)	Expected range (km)	Time on air (ms) (for 10 bytes payload)
SF7	5470	2	56
SF8	3125	4	100
SF9	1760	6	200
SF10	980	8	370
SF11	440	11	700
SF12	290	14	1400

Bandwidth set to 125 kHz with coding rate 4/5 and 1% PER.

Table 1. Data rates, time on air, and expected range (depending on propagation conditions) for LoRa according to the spreading factor.

4. Design example of a wireless communication link

In this study, a scenario is considered where long-range communication is required. Thus, it is a representative case for networked robotics where large distances are involved, such as in the monitoring of inspection robots for power transmission lines [13] and pipes [50], UAVs control, remote sensing, and navigation of mobile robots in large open fields. The choice of such scenario (i.e., a large outdoor area) was motivated by its importance for some envisioned applications of networked robots (e.g., smart cities, smart grids, agriculture, mining and military applications, etc.) and by the challenge it represents for the design of the wireless communication link (e.g., link budget, range, fading, obstacles, mobility, etc.).

The selected frequency band is 915-MHz band, which is an ISM band in Americas with a maximum EIRP of 36 dBm for spread spectrum systems [51]. Therefore, path losses at 915 MHz for 130 different positions, with ranges varying from 1 to 40 km, have been obtained through simulations with the software LINKPlanner [50], as shown in **Figure 2**. LINKPlanner performs the calculations from the International Telecommunication Union (ITU) recommendations ITU-R P.526-10 and ITU-R P.530-12 to predict NLOS (non-line-of-sight) and LOS paths for anywhere in the world [52]. As can be noticed from **Figure 4**, path losses vary from 90 up to 160 dB, thus requiring high link budgets in order to cover all possible ranges in the scenario of study.

Given the high link budgets required and the limitation of EIRP, the receiver sensitivity must be as low as possible, such as the availability in UNB and LoRa transceivers. Therefore, in this design example, the SX1272 LoRa transceiver has been selected, which can transmit at up to +20-dBm output power and has a sensitivity as low as −137 dBm at 125 kHz with a spreading factor of 12 [53].

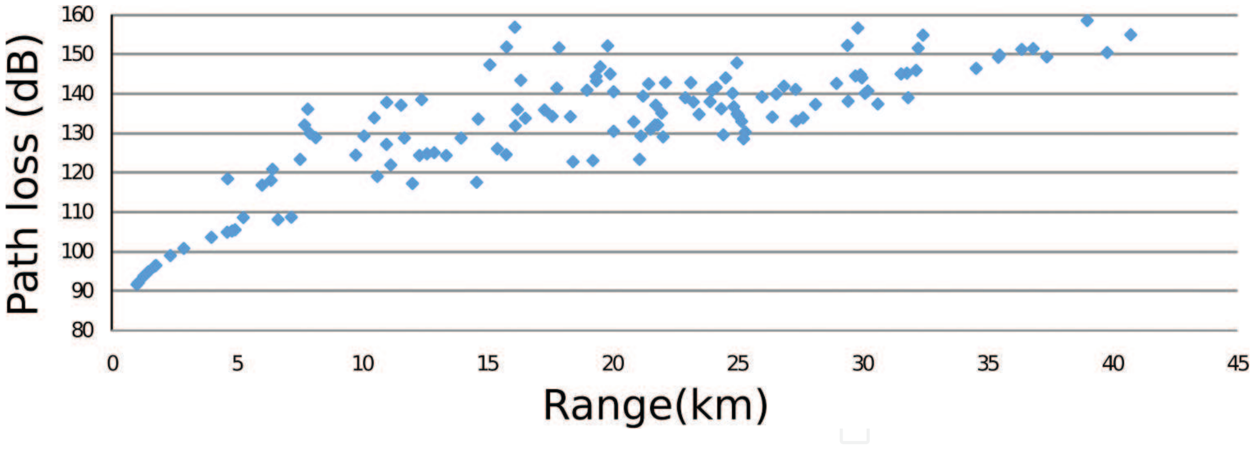

Figure 2. Path losses (dB) versus range (km) at 915 MHz obtained through simulations with LINKPlanner [50]. Antenna heights ht = 50 m and hr = 1 m.

Using the maximum transmit power with unitary gain antennas, the link budget is limited to 157 dB, thus 3 dB below the minimum required to cover all possible ranges in the scenario of study (i.e., 160 dB). However, with 6-dBi gain antenna at the transmitter and 9-dBi gain antenna at the receiver, 15-dB gain is added to the system, leaving still 12 dB of link margin and covering all considered ranges, as shown in **Figures 3** and **4**. In **Figure 5**, the distribution of the required spreading factors with and without a 10-dB signal fading is shown.

Yet, as the maximum EIRP is 36 dBm with +30 dBm of transmit power and 6 dBi of antenna gain, there is still a margin to add more 10 dB of link budget. This can be done using another transceiver with more output power capability (i.e., up to +30 dBm) or, preferably in case of a bidirectional link, through the use of antennas with higher gains. The reason is that the antenna not only increases the EIRP but also adds gain for signal receiving, however, at the cost of less area coverage due to the increase of the antenna directivity.

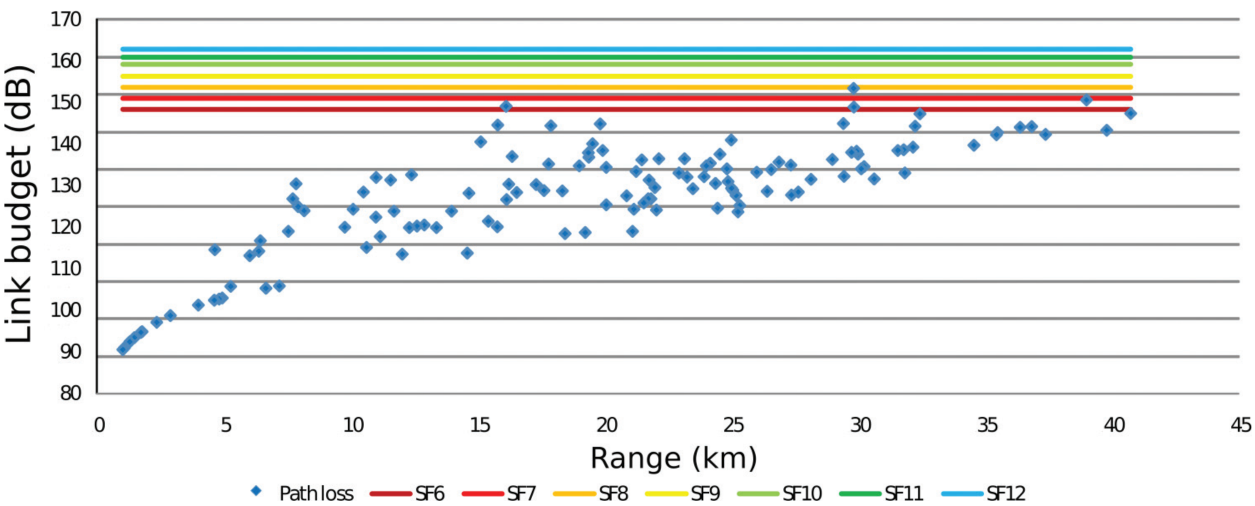

Figure 3. Link budgets (dB) versus range (km) with LoRa transceiver at 915 MHz for different spreading factors (6–12). Antenna heights ht = 50 m and hr = 1 m, with gains Gt = 6 dBi and Gr = 9 dBi.

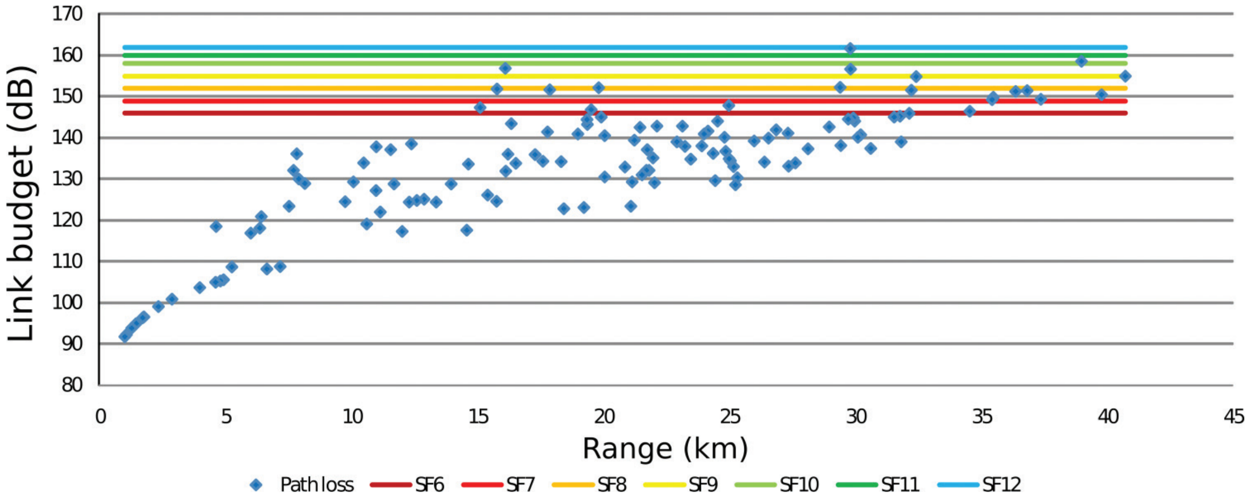

Figure 4. Link budgets (dB) versus range (km) with LoRa transceiver at 915 MHz for different spreading factors (6–12), with 10-dB link margin for signal fading. Antenna heights ht = 50 m and hr = 1 m, with gains Gt = 6 dBi and Gr = 9 dBi.

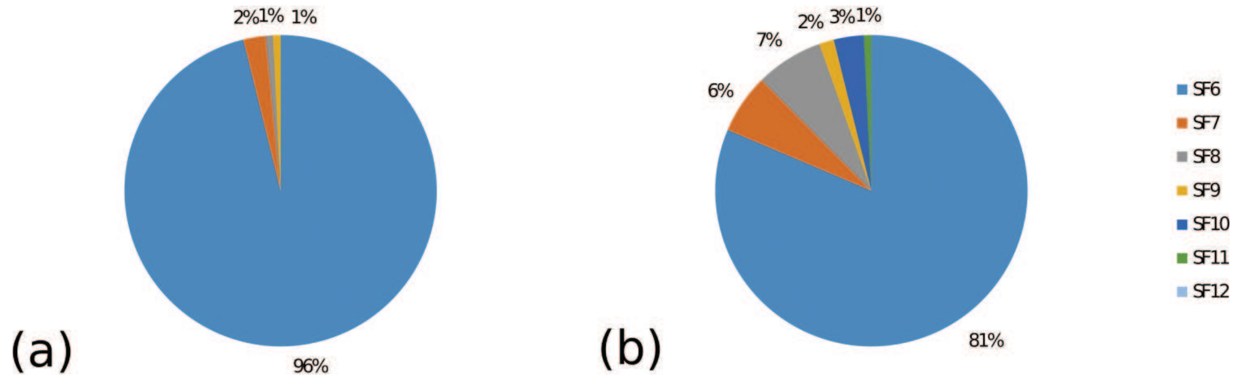

Figure 5. Distribution of spreading factors without (a) and with (b) 10-dB signal fading. LoRa transceiver at 915 MHz with 125-kHz bandwidth. Antenna heights ht = 50 m and hr = 1 m, with gains Gt = 6 dBi and Gr = 9 dBi.

In **Figure 6**, the time on air for different spreading factors and payload sizes ranging from 10 to 50 bytes is shown. It can be noticed that the time on air is longer for higher spreading factors (i.e., lower bit rates) and longer payload sizes. Thus, it is important to use, whenever possible, small packets and higher bit rates for applications that require low communication delay, such as robot teleoperation.

5. Conclusion

In this chapter, we have presented the fundamentals of the design of wireless communication links. We have discussed the importance of this topic for networked robotics applications,

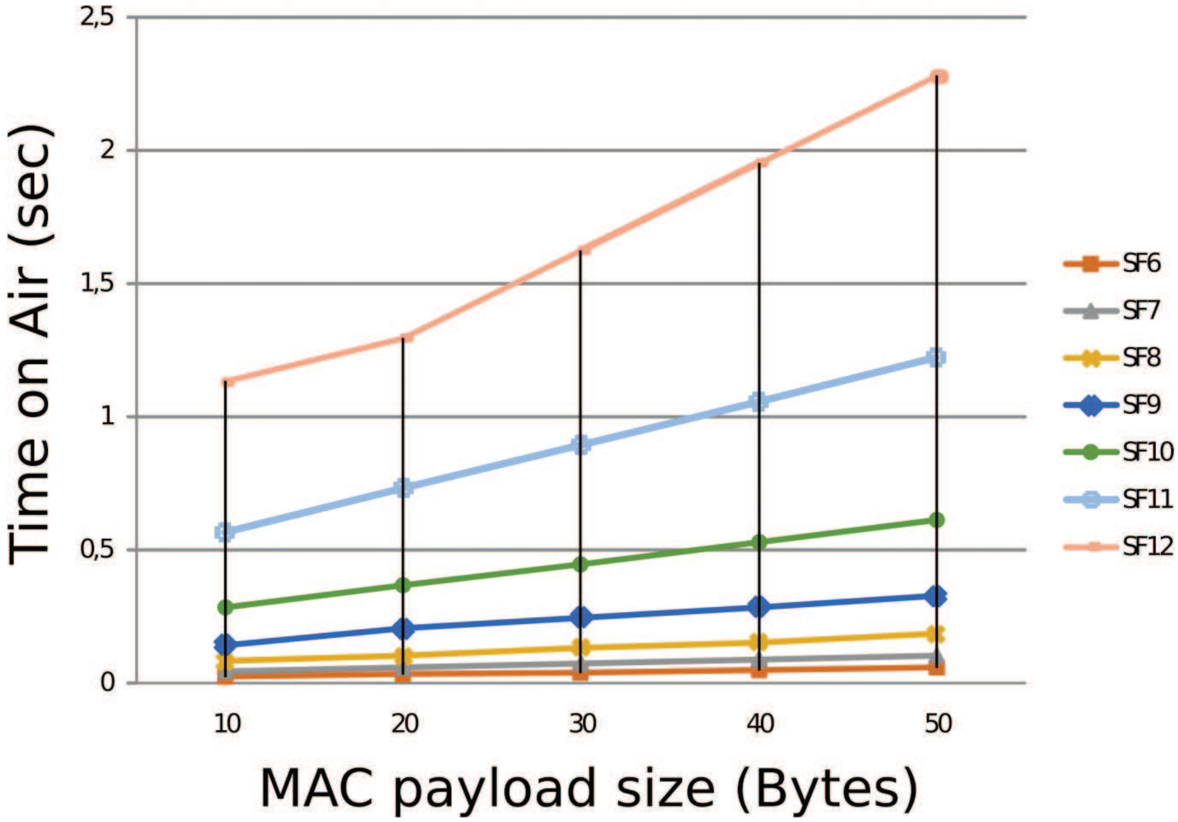

Figure 6. Time on air with different spreading factors and MAC payload sizes. LoRa transceiver at 915 MHz with 125-kHz bandwidth and coding rate 4/5.

which usually require some sort of wireless communication. After reviewing the fundamentals of wireless communication and several wireless communication technologies, we have shown a design example of a wireless communication link based on Lora modulation, one of the latest available wireless technologies for long-range communication. The obtained results allow us to show the existent tradeoff between communication range, data rate, and delay in the design of a wireless communication link. Although long-range communication is possible, the data rate needs to be reduced, negatively affecting the communication delay. Therefore, networked robotics applications that require long-range communications must be able to work properly with low data rates (e.g., using data compression algorithms) and withstand temporarily network disconnection due to signal fading (e.g., using opportunistic communication [54]).

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