Dependable Wireless Communication and Localization in the Internet of Things

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Abstract

Wireless technologies suffer from physical and man-made impairments (e.g., multipath propagation and interference from competing transmissions, as well as from the effect of temperature variations and other environmental properties): this impairs the reliability, timeliness, and availability of IoT systems. At the same time, we see a wave of new safety-critical IoT applications that require performance guarantees. This chapter surveys methods to increase the dependability of the IoT, specifically focusing, firstly, on increasing the frequency bandwidth from narrowband, over wideband, towards ultra-wideband to better handle multipath effects and interference. Secondly, the chapter focuses on increasing the adaptability such that a networked system can compensate disturbances also dynamically, eventually striving for cognitive abilities. A distinguishing feature of this chapter is its comprehensive treatment of dependability issues across multiple layers, from signal processing, over microwave engineering, to networking.

1 Introduction

Wireless technologies enabling the Internet of Things (IoT) are gaining momentum and pave the way for applications with high societal relevance and impact. Appli-

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cation domains include smart cars communicating to each other and with the road infrastructure for a safer drive, smart factories controlling and optimizing production processes, smart grids improving the efficiency of the distribution and consumption of energy, as well as smart buildings maximizing the comfort of its inhabitants while reducing the monthly energy bill. All the aforementioned applications impose vastly diverse requirements on system performance, ranging from highly-efficient operation in order to maximize the lifetime of battery-powered devices, to ultra-low communication latency in order to enable high responsiveness. As an example, safety-critical IoT systems used to build smart cars, smart cities, or smart factories, require a high *reliability* and *timeliness*, as opposed to IoT systems for long-term monitoring that instead demand energy-efficient operations and hence a high *availability*. Reliability (continuity of correct and accurate service), availability (readiness for correct service), and timeliness (continuity of timely service) are key *dependability* attributes affecting the performance of an IoT system. Combined together with safety, confidentiality, and integrity, those attributes summarize the properties of a system and specify how much a user can rely on and trust its operations [1, 2].

Both research community and industry have long striven to produce solutions at all ISO/OSI layers to maximize these three key dependability metrics. At the physical layer, the focus has been on the design of highly-efficient radio transceivers minimizing energy consumption and bit error rate, while maximizing range and throughput. This includes the design of reconfigurable filters as well as antennas operating on an increasingly broader frequency spectrum.

At the signal processing level, significant work has been carried out to increase the robustness of wireless communication and minimize the influence of multipath propagation and fading, as well as to achieve accurate indoor localization. The accuracy of the latter particularly affects the reliability of IoT applications that combine accurate positioning information with business logics. Examples of such applications include dynamic personalized pricing, product placement, and advertisement [3], the estimation of the popularity of exhibitions [4], as well as supply chain management and logistics.

At the networking level, a “soup” [5] of communication protocols has been developed in order to allow multiple devices sharing the same medium to communicate in a dependable fashion. These protocols address not only efficient operations allowing to increase the system lifetime and hence its availability, but also the ability to avoid collisions with other devices operating in the same frequencies, hence increasing the reliability and timeliness of communications.

All this work led to a plethora of wireless technologies and standards being proposed and commercialized in the last decade specifically for IoT devices. Technologies such as Bluetooth Low-Energy (BLE), DigiMesh, and Z-Wave address IoT applications requiring low-range ultra-low power communications. Newly-developed standards such as Wi-Fi HaLow (IEEE 802.11ah), LoRA, SIGFOX, Weightless, On-Ramp Wireless, and NarrowBand IoT allow to form wide area networks on a large scale. WirelessHART, ISA100.11a, ANT+, and IEEE 802.15.4e, instead, focus on reliable and timely communications and hence specifically target safety-critical and industrial settings, whereas IEEE 802.15.4a explicitly supports ranging and is hence well-suited for IoT applications requiring accurate localization.

In this chapter, the broad spectrum of solutions that have been developed in the past decades to achieve dependable wireless communication and localization in the Internet of Things is analyzed. Differently from works that address the design of dependable IoT solutions only on individual ISO/OSI layers, this chapter gives a comprehensive view that spans across different disciplines: from microwave engineering, over signal processing, to networking. This broader scope allows us to show that the efforts in increasing the bandwidth and the adaptability of the system (i.e., its ability to adapt and react dynamically to changes) do help in increasing the overall dependability of an IoT system. This concept is highlighted by outlining the design space of the solutions developed within the aforementioned disciplines. The discussions put in relation the adaptability of the solution (i.e., whether it is static, switchable, reconfigurable, reactive, predictive, or cognitive) to the employed bandwidth (i.e., narrowband, wideband, or ultra-wideband), and describe the different trade-offs from a high-level perspective. It is observed that dependability generally increases as the level of adaptability increases. For example, a networked systems that is aware of specific disturbances in the environment can adapt to counteract these disturbances. While a switchable or reconfigurable system can be adjusted by the operator to fit a certain environment, reactive systems do automatically perform such an adjustment based on past observations, predictive systems employ sophisticated models to extend the time horizon across which disturbances can be anticipated. Ultimately, the aim is to strive for cognitive networked systems that perceive their state and environment and adjust its behaviour in a smart way. The second dimension, bandwidth, is also crucial for dependability. By moving towards higher bandwidths, narrowband disturbances and signal propagation effects, such as multipath fading, can be better handled. The chapter shows that the ongoing efforts towards the design of cognitive solutions operating on ultra-wideband promise to increase the dependability of IoT communication and localization even further, although plenty of work is still required in this direction.

This chapter proceeds as follows. Section 2 provides a description of how the propagation of radio signals affect the robustness of a wireless link and shows how these effects are related to two parameters of the design space, namely signal bandwidth and radio adaptability. Section 3 follows up with a description of the signal processing task for a single radio link, on the one hand to enable reliable communication over the link, and on the other hand to determine the position of the involved IoT devices. Section 4 provides an overview of modern transceivers used to build IoT applications and their most important building blocks, namely filters and antennas. Section 5 discusses the impact of medium access control layer protocols on key dependability attributes such as timeliness, availability, and reliability. It then introduces the design space in the networking domain, showing that there is still plenty of room to improve the dependability of IoT systems operating at high bandwidth. Finally, Section 6 wraps up our analysis and summarizes our conclusions.

2 Fundamentals of Wireless Propagation Channels

The reliability of a wireless link between two IoT nodes is mainly influenced by two factors: the physical radio channel (including multipath propagation and additive white Gaussian noise (AWGN)) and man-made interferences (from competing transmissions and unintended radiations). In this section, the focus is placed on the former, showing how multipath propagation affects the radio signal sent from a transmitter (TX) to a receiver (RX). In typical IoT application scenarios, it is intended to use low-cost and low-power devices which are faced with cluttered environments resulting in dense multipath that significantly deteriorates the transmitted signals. Hence, to develop dependable IoT systems it is crucial to take the multipath propagation effects into account. Without modeling these channel imperfections and without taking them into account in the design process it is not possible to give guarantees on the overall performance of the system. The discussion will lead to a system classification with respect to the signal bandwidth, demonstrating that this parameter has a major influence on the reliability of a wireless link. The need for adaptability is also highlighted, addressing temporal and spatial variations of the channel. The signal processing required to implement a reliable wireless link is discussed in Section 3.

Interfering radio signals will undergo similar propagation effects. To mitigate the interferences, a typical IoT radio will rely on the transceiver front-end (which is discussed in Section 4) and the MAC protocol (see Section 5). This is the most efficient way forward to achieve low-power operation and low complexity and thus availability.

2.1 Modeling of Multipath Channels

When one examines the radio signal seen by the receiver, it can be observed that a change of the receiver position relative to the transmitter results in fluctuations of the received signal power. These fluctuations are referred to as fading [6, Ch. 2.1]. The covered distance between TX and RX in relation to the used carrier wavelength λ determines different *scales of fading*.

For a distance variation greater than approximately 10λ, the power variations are denoted as *large-scale fading*, characterized by two mechanisms, *path loss* (PL) and *shadowing*. PL indicates how much the received signal is attenuated with increased distance d between TX and RX. PL is described by an exponential decrease of power, which can be defined by a loss of $n \cdot 10\log(d)$ dB. The loss exponent n depends on the considered environment. For example, in free space, without any interacting objects, the loss exponent would be $n = 2$ described by Friis' equation [7, Ch. 3.9]. In line-of-sight (LOS) indoor scenarios it can be below 2 due to constructive interference of reflections, while for environments with many obstacles, values between 2 and 6 have been observed [8, Ch. 3.6].

Shadowing is caused by obstacles in the environment blocking off signal paths and thus leading to deviations from the deterministic PL law. It causes variations in the received power that are often described by a log-normal distribution, i.e., a Gaussian distribution in dB. For more details on large-scale models, the reader is referred to [6–8].

For small distance changes of less than approximately 10λ, the resulting received power fluctuations are called *small-scale fading (SSF)* which is due to multipath propagation. Multipath is caused by reflections and scattering of the transmitted signal within the physical environment. The receiver sees the signal from the direct path – the LOS component, overlapped with reflections called multipath components (MPC). These MPCs have different phases resulting in constructive or destructive interference, which is known as multipath fading. Mathematically, the multipath propagation can be described by the time-variant channel impulse response (CIR):

$$h(\tau;t) = \sum_{i=0}^{\infty} \alpha_i(t) e^{j\phi_i(t)} \delta(\tau - \tau_i(t)), \tag{1}$$

given in baseband equivalent form, where τ describes the delay time while t describes how the channel (the environment) changes over time. This formula describes the effect of (theoretically) infinitely many signal paths between TX and RX. The length of each path determines its time delay, denoted by the Dirac pulses $\delta(\tau - \tau_i(t))$. This delay also determines the phase shift $\phi_i(t) = -2\pi f_0 \tau_i(t)$, where f_0 is the carrier frequency, and the amplitude $\alpha_i(t)$ that decreases due to PL. Both amplitude and phase also experience variations due to interactions with the physical environment, i.e., reflections from different materials [8, Ch. 5].

The impact of the CIR (1) on radio signals can be analyzed by probing the channel at frequency $f_0 + f$, using the (baseband) signal $s(t) = e^{j2\pi f t}$. Convolution with (1) yields the received signal $r(t) = h(f,t)s(t)$, where $h(f,t)$ is a time-frequency-variant *channel gain* which describes the multipath interference experienced as SSF. The MPCs add up with different phases. Small movements of the RX change each phase differently, which causes rapid fluctuations of the channel gain as illustrated in the top left of Figure 1. The channel gain is similarly influenced by a shift in frequency, illustrated in the bottom left of Figure 1.

To characterize the SSF, statistical models are used, justified by the large number of MPCs. For the assumption that the MPCs have uniformly distributed phases and there is no "dominant" MPC with exceedingly large amplitude, the SSF can be described with a *Rayleigh model*: The central limit theorem states that the channel gain will be a complex Gaussian random process, because it is the summed effect of a large ensemble of MPCs [9]. Correspondingly, its amplitude distribution will be described by a Rayleigh probability density function [6]. It is needless to say that the amplitude (and power) gain of the radio channel is of key importance for the performance and thus the dependability of a wireless link between IoT nodes.

Time variations of the channel gain are (for example) caused by movements of the TX or RX. The upper left of Figure 1 shows such variations caused by the RX moving at a constant velocity v. The Fourier transform of this time-variant gain is

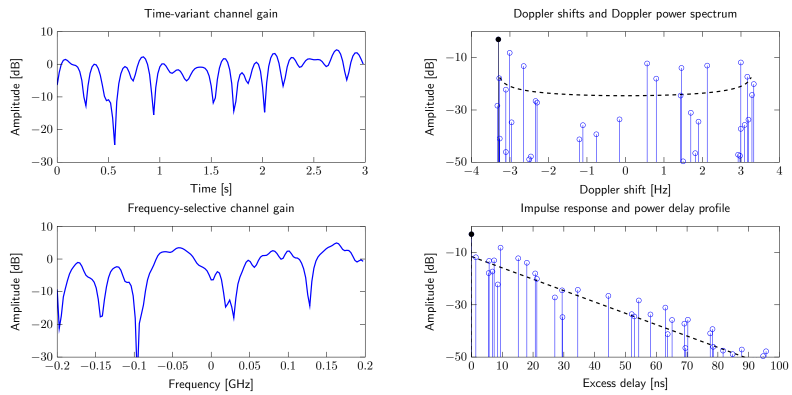


Fig. 1 Channel gain variations in time / frequency domain (left) and the resulting Doppler shifts / delay dispersion (right).

shown in the top right part of the figure. It can be seen that frequency shifts, so-called Doppler shifts, are introduced for each MPC i. Each Doppler shift is determined by $\nu_i = \frac{v}{\lambda}\sin(\theta_i)$, where θ_i describes the angle-of-arrival (AoA) of the i-th MPC. Hence, it is related to the speed of movement, the carrier frequency (which determines the wavelength $\lambda = c/f_0$), and the AoA. The dashed line shows the *Doppler power spectrum* (DPS) which quantifies the mean power output of the channel at a certain Doppler shift and thereby characterizes the time variations statistically.

An important parameter that can be derived from the DPS is the *coherence time* of the channel. It is indirectly proportional to the width of the DPS and determines how long the time frame is in which the channel gain is (widely) unaffected by Doppler effects. For system design this sets an upper limit on packet duration before the TX / RX needs to re-adapt to a new channel gain. The illustrated example corresponds to a maximum Doppler shift of ± 3 Hz and a coherence time of about 0.5 seconds.

In the same fashion, one can regard variations of the channel gain in the frequency domain as shown in the bottom left of Figure 1. Applying the Fourier transform results in the impulse response shown in the bottom right, the shown impulses are related to the MPC delays τ_i and amplitudes α_i which were described before. It should be noted that the term *excess delay* on the axis means that the time when the LOS arrives at the RX has been set to zero.

The dashed line indicates the statistical characterization of the impulse response, named the *power delay profile* (PDP). The PDP determines the *average* power output of the channel as a function of the delay time. The broadness of the PDP, and thus the *dispersiveness* of the channel indicates how long-lasting and powerful reflections and scattering in the environment are, i.e., it shows how much a transmitted waveform is spread out in time. This is called time dispersion.

The frequency variations are characterized by the *coherence bandwidth* related to the reciprocal of the PDP broadness. It indicates how fast the channel changes in the frequency domain due to multipath propagation. This parameter will be used later to distinguish narrowband and wideband systems, which have flat-fading and frequency-selective channels, respectively. The shown example relates to a coherence bandwidth of about 10 MHz.

Spatial variations can be regarded similarly since a movement of the TX or RX also leads to phase variations of the MPCs and therefore to multipath fading. The amount of the variations is related to the wavelength and the distribution of the AoAs. The *coherence distance* of the channel is a parameter which is important for designing antenna placements in multi-antenna systems as will be shown later.

2.2 Signal Classification in Terms of Bandwidth

The impact of the propagation channel on a transmitted signal can be classified with respect to the signal bandwidth. The propagation of a transmitted signal $s(t)$ is described as a linear filtering with the time-variant channel impulse response $h(\tau;t)$ or — in frequency domain — as a multiplication with the channel gain $h(f;t)$. The signal is modulated onto the carrier f_0 and B denotes the biggest deviation in the band, thus the signal bandwidth ranges from $f_0 - \frac{B}{2}$ to $f_0 + \frac{B}{2}$.

When a *narrow bandwidth (NB)* is used for the transmitted waveform with a bandwidth less than the coherence bandwidth, the channel response is flat over the respective band. More specifically one has $h(f;t) \approx h(t)$ for $f \in \left[f_0 - \frac{B}{2}, f_0 + \frac{B}{2}\right]$, which means the only effect of the channel is an attenuation of the original signal by $h(t)$. This is called *flat fading*. However, the value of $h(t)$ fluctuates due to the Rayleigh fading as described before. Figure 2 indicates the flat fading case on the left-hand side, with a nearly constant spectrum in the (small) region between the dashed lines.

When a signal with a significantly *wider bandwidth (WB)* is used, a filtering (multiplication of spectra) results in a larger part of the channel frequency response being "visible" or "cut out". The resulting spectrum is not flat anymore, which is known as a *frequency-selective* channel. An example is shown in the right-hand side of Figure 2. In time domain the effect corresponds to linear distortions which will introduce, for example, inter-symbol-interference (ISI) that has to be dealt with in receiver systems. In terms of system design, the coherence bandwidth defines the limit between NB and WB.

For even higher bandwidths, the region of *ultra-wideband (UWB)* is reached. Standardization bodies have introduced definitions of *absolute UWB* for bandwidths of more than 500 MHz and *relative UWB* for bandwidths larger than 20% of the carrier frequency [10, 11]. These definitions are not clearly related to physical properties of the radio channel in contrast to the boundary between NB and WB. However, the average power over a bandwidth in this range is almost constant (indicated by the dashed line in the right-hand side of Figure 2), regardless of the channel realization, i.e., the small-scale variations of the power gain become negligible, thus a dependable link can be provided.

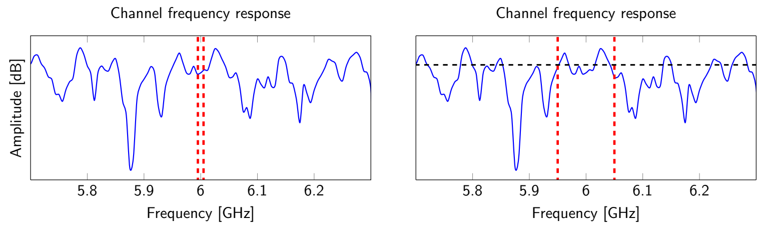


Fig. 2 Effect of propagation channel on NB ($B = 10$ MHz) and WB ($B = 100$ MHz) pulses in the frequency domain. Vertical dashed lines show the frequency range of the transmitted signal.

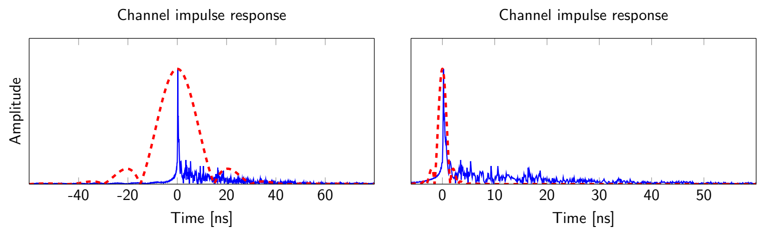


Fig. 3 Effect of propagation channel on WB ($B = 100$ MHz) and UWB ($B = 1$ GHz) pulses in the time domain.

The UWB boundary is also related to time resolution properties. One can speak of UWB when MPCs can be resolved in time domain, e.g., when the LOS component does not overlap with any MPCs arriving later. This is illustrated in Figure 3, where the effect of the channel onto a WB and an UWB pulse is shown in time domain. The red, dashed curve shows the transmitted pulse, which indicates its length in relation to the CIR. It can be seen that in the WB case, resolvable time taps equivalent to the pulse width still contain many MPCs and thus they are strongly influenced by multipath fading.

3 Physical Layer Signal Processing

Following up from the discussion on the wireless channel in Section 2, the main *signal processing* task in an IoT radio concerns overcoming the impact of physical propagation effects, in particular multipath fading. Compared to traditional wireless systems, IoT systems may operate in cluttered environments with lots of obstacles. This produces a high amount of multipath components which could interfere destructively with the line-of-sight component and possibly results in weak links.

Two related receiver signal processing tasks will be addressed, namely the recovery of the transmitted data in multipath-rich environments (see Section 3.1) and the measurement acquisition for positioning (Section 3.2). For each, the design space will be outlined, showing how the bandwidth and adaptability influence the reliabil-

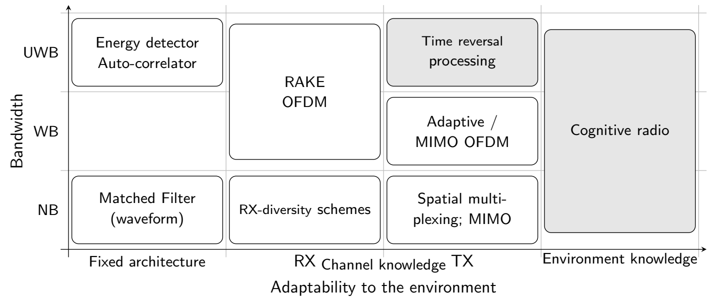


Fig. 4 Design space for systems to mitigate fading in wireless propagation channels.

ity and availability of the wireless links and position estimation. It will be argued that the adaptability is related to the channel knowledge of the radio nodes, which is used to adapt the RX and/or the TX to the current channel state.

3.1 Signal Processing for Wireless Communications

To address the data recovery, it will be shown how communication systems can be designed to deal with fading effects. Figure 4 presents the design space, classifying physical-layer processing schemes regarding their bandwidth and adaptability. The bandwidth is represented by the classification given in Section 2.2, while the adaptability is related to the channel knowledge that must be available at the RX and/or the TX in order to obtain a reliable radio link. A cognitive radio also takes interference of competing users into account, which is denoted as "environment" knowledge. This box (and the "time-reversal" scheme) are shown in gray, because these approaches are considered to be "less practical", in particular under the complexity constraints of an IoT. An increase of bandwidth and/or adaptability helps in general to overcome the fading effect, mitigate interferences and thus leads to an improvement of the reliability of wireless radios.

Narrowband transmission will be predominant in many IoT applications, due to their low complexity. In fact a "fixed" RX architecture can be used in this case, shown in the bottom left corner of the design space. The optimum receiver design for this case would be a *matched filter* (MF) with impulse response $h(-t) = s(t)$ [12, Ch. 7.5] [13, Ch. 5.3], matched to the transmitted waveform denoted by $s(t)$ which is the only thing that must be known at the receiver. The sampled output of the MF can be modeled by

$$r = \sqrt{E_s} h \cdot s + n, \tag{2}$$

with h describing the complex-valued gain of the flat-fading (NB) channel, the energy E_s of the transmitted symbol s, and a noise sample n. Due to the multipath fading, the gain $|h|$ exhibits a Rayleigh distribution. Figure 5 depicts the required

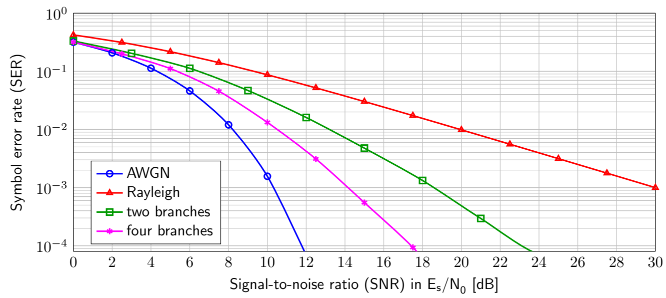


Fig. 5 Comparison of AWGN with Rayleigh channel for single and multiple antennas.

signal-to-noise ratio (SNR) to reach certain average symbol error rates (red curve) in comparison to a non-fading (h is constant) AWGN channel performance[1]. It can be seen that there is a large gap. E.g., to achieve an error rate of 10^{-3} one needs approximately 20 dB more SNR for the (Rayleigh) fading channel. Hence, the multipath fading has a strong impact on the availability and reliability of wireless links and thus its treatment is also highly relevant for designing dependable IoT applications.

3.1.1 Overcoming the Fading Effect: Diversity Principle

This subsection considers how to overcome the previously described performance gap. The fading is addressed by *diversity schemes*, which make use of multiple observations of the TX signal over independent paths (or branches) with channel gains $h_i, i = 1 \dots M$. When the channel gains of each branch are known at the RX, the observations can be processed according to the *maximum ratio combining* (MRC) principle [14, Ch. 9.1], which can be seen as "correcting" the received branches for their suffered phase shifts through the Rayleigh channel, allowing to add the branch contributions coherently. Furthermore, proper weighting is applied to maximize the resulting SNR (diversity gain). Making use of independent channel gains is essential for exploiting diversity. It results in a significant reduction of the performance gap as illustrated in Figure 5. Independent channels can be found in various domains, as outlined in the following.

Time / Frequency diversity. Depending on the coherence time and bandwidth, different observations spaced in time or (carrier) frequency can be combined. However, this means that the same signal is sent multiple times, thus, assuming one has the energy E_s available, the SNR effectively decreases by $1/M$.

Antenna (RX) diversity. In the spatial domain, multiple receiving antennas (spaced farther than the coherence distance) can be used to combine their measurements and obtain the diversity gain. The advantage here is that the SNR is not decreased; a

[1] The AWGN is characterized by a flat double-sided power spectral density of $N_0/2$.

single transmission is sufficient. However, more hardware and thus complexity is needed with M_R RX antennas.

TX diversity. At the TX side, using M_T transmit antennas, one has to prepare the transmitted signals to be able to separate the individual branches at the RX. There are two different methods:

- Pre-coding: Using encoding and transmission sequences, the branches can be separated even without channel knowledge available at the TX [15].
- Pre-filtering: This method is equivalent to the RX diversity scheme, the ratios from the MRC scheme are applied before transmission, hence, channel knowledge is required at the TX.

Systems that use multiple TX and RX antennas are called *Multiple-Input-Multiple-Output (MIMO)* systems. Concerning diversity, a MIMO system is capable of achieving a diversity gain related to the product $M_T \cdot M_R$. However, it can also multiplex ($\min[M_T, M_R]$) parallel data streams to the same frequency band at a given time. A prerequisite for MIMO signal processing is channel knowledge at the TX and RX. The more channel knowledge available, the higher the spectral efficiency and reliability of the radio link. However, the required high adaptability to the channel at the TX and RX comes at the cost of higher complexity. The application of (adaptive) directive antennas can yield — in principle — similar gains. Directive antennas could thus be a low-complexity alternative to multi-antenna systems for the IoT.

3.1.2 Wideband Systems

Instead of introducing multiple antennas, one can also exploit frequency diversity from a WB signal to increase the reliability. In the WB case, the effect of the channel is described by a linear convolution with the CIR, leading to linear distortions of the transmitted signal, ISI, and (still) multipath fading. For these signals, channel knowledge is always required to *efficiently* deal with the channel effects.

The received signal is spread over different delay bins because of the delay dispersion. A bank of correlators which is called *rake receiver* [6, Ch. 18.2.4] can be used to collect the energy at different delay bins (rake "fingers"). At each finger, the received signal energy will still suffer from multipath fading because each finger sees the combined effect of a large number of multipath components as shown in Figure 3 (left-hand side). However, the rake receiver can combine these delay branches using MRC. It thereby exploits frequency diversity and can thus decrease the performance gap of the symbol error rate. The rake receiver is usually employed with spread spectrum signals which occupy more than the minimum Nyquist bandwidth, given some desired data rate. Spread spectrum systems are also robust with respect to NB interference, hence improving the dependability [16].

Orthogonal frequency division multiplexing (OFDM) is a multicarrier technique where the transmitted WB signal is split into NB subchannels, which are densely packed in frequency, exploiting orthogonality properties [17]. It is the method-of-choice for high-rate transmission at high spectral efficiency, avoiding the ISI, fading, and signal distortion issues in an elegant way. Again, frequency diversity is exploited to increase the robustness to frequency-selective fading, using coding and interleaving to correct for deep fades affecting certain subchannels. OFDM is used in state-of-the-art high data-rate communication standards, e.g., in wireless LANs according to IEEE 802.11a, g, n, ac [18] and in LTE [19, Ch. 3].

When channel knowledge is also available at the TX, an adaptive ("waterfilling") OFDM technique can be used [20] where the modulation order of the data symbols is adapted to the SNR at individual subchannels. OFDM is also the method-of-choice to implement MIMO systems in frequency-selective (WB) channels [21].

3.1.3 Ultra-wideband Systems

Moving to the top row in the design space, sufficient bandwidth is available to achieve the time resolution to resolve individual MPCs and mitigate multipath fading to a large extent. For communications, the same principles can be used as in the WB case (rake, OFDM). The available frequency diversity will be high enough to reach a performance close to the AWGN channel, which is a key characteristic of a UWB system (see Section 2.2 and [22, 23]). Hence, it is not needed to implement multiple antennas in order to overcome the multipath fading. However, the practical hardware implementation is still problematic. The RX processing requires high sampling rates leading to high power consumption (see Section 4.1).

Systems that tackle the high cost problem are situated in the top left corner of the design space: Noncoherent UWB receivers with simple structures like the *energy detector (ED)* or the *autocorrelation receiver (AcR)*. The basic function of these systems is to multiply the received signal with itself (or a delayed version, in case of the AcR) followed by an integration over a certain time frame. Via the multiplication, the carrier phase information is lost and only the envelope of the signal is obtained. The integration yields an accumulation of energy for a specific time window. Hence, transmitted symbols can be detected in certain time frames, enabling time-hopping schemes for multiple access [24, 25]. In case of the AcR, the delay is an additional tuning parameter which allows for more sophisticated transmission schemes such as transmitted-reference [26,27] where time-hopping pulse sequences can be detected. The ED method is also supported by the IEEE 802.15.4a standard (see Section 5.2) which describes a UWB air interface for sensor networks and (indoor) positioning.

Moving towards the top right of the design space means that on top of high bandwidths, more channel knowledge is available. This allows the application of the conceptual method of *time reversal (TR)*. It is assumed that the TX knows the CIR, which is then time reversed and used as a prefilter to transmit a pulse. This results in all MPCs arriving at the same time instant and adding up in a constructive way, resulting in a high SNR with simple processing at the RX [28].

Finally, the concept of *cognitive radio* should be mentioned. Radio nodes are assumed to be aware of their surroundings (in this case the radio environment) and adapt their state to it. In addition to channel state information, cognitive radio also takes interferences of other radios into account, which again increases the amount of available information and also the dependability of the wireless links [29–31].

3.2 Signal Processing for Wireless Localization

Localization (or positioning) describes the process of estimating the position of mobile devices in a defined coordinate system. Radio signals transmitted between “agents” and “anchors” can be used for positioning, in environments where satellite-based systems are useless, for example indoors. Such radio positioning systems “measure” parameters of the received signal which are related to the geometry of the arrangement of the radio nodes, for example the time-of-flight (ToF) or the received signal strength (RSS) which relate to the distance, or the angle-of-arrival (AoA).

It remains a tremendous challenge to obtain a dependable (indoor) positioning system, one that has sufficient accuracy and reliability so that for example the navigation of an automated vehicle could rely upon it. Multipath propagation is a key reason hindering the implementation of an accurate and robust positioning system. In this section, the impact of multipath propagation on the measurement acquisition and positioning tasks is discussed.

3.2.1 Overview of Dependable Positioning Systems

A taxonomy of positioning approaches is found in Figure 6 in a design space that again spans the signal/system bandwidth and the adaptability of the system. The great advantage of a large bandwidth (UWB) system lies in the fact that the line-of-sight (LOS) component of the channel response can be separated from the multipath, hence its parameters, in particular the ToF and the free-space path loss can be measured accurately. At a lower bandwidth, many MPCs will interfere with the LOS, which will introduce fading and pulse distortions and thus reduce the potential accuracy. These properties of the radio channel have already been introduced in Section 2.2. An in-depth analysis of the influence of bandwidth on ToF ranging will be given below.

With an RSS approach, one can for instance use *fingerprinting*, an approach rooted in machine learning. In a first step, a database is created that maps certain positions to RSS values from multiple anchors. This map then allows wireless nodes to associate any measured RSS values with a certain position [32]. The system is configured for a certain environment. Map matching is an approach, where prior information about a building floorplan is used to avoid position fixes that disagree with the geometric constraints of an environment. *Multipath-assisted indoor navigation and tracking* (MINT) also uses floorplans. More specifically, it associates reflected MPCs with the environment requiring UWB signals to achieve sufficient time resolution [33]. A simultaneous localization and mapping (SLAM) approach

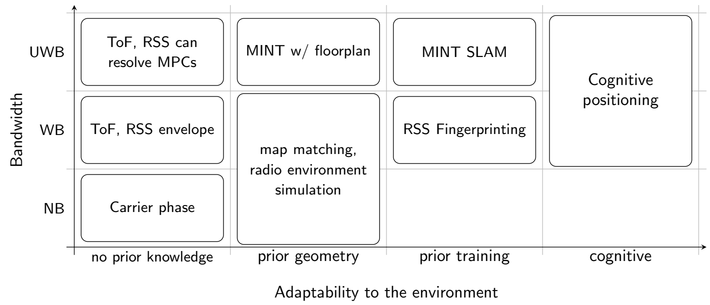


Fig. 6 Design space for dependable positioning systems.

learns a suitable feature map online, exploiting past measurements of the environment, which is then used for the self-localization [34–36]. More prior information in general enhances the performance and thus supports the goal of dependable positioning.

A cognitive positioning system, finally, also learns environment information on its own [31, 37]. It goes beyond the capabilities of a SLAM algorithm in that it implements "cognitive" features such as active feedback on the environment, attention, and memory. It can for instance schedule measurements in a way that the expected information gain is maximized, it can focus on relevant information—consider a system that has to deal with an abundance of clutter measurements—, and it can use a hierarchically structured memory to allow for different layers of abstractions. This approach is found to the very right of the taxonomy. It is a research topic that is widely unexplored as of today in particular under the low-power constraints of the IoT.

3.2.2 ToF Positioning in a Multipath Environment

ToF methods are robust in the sense that the accuracy depends only little on the actual range between transmitter and receiver, as long as the SNR of the received signal is sufficient. In the following, the impact of multipath on such ToF-based positioning systems is explored. While the focus lies on ToF, some of the conclusions will generalize to other measurement methods as well.

The bandwidth of an RF signal determines its time resolution. An optimal estimator for the ToF in AWGN simply correlates the RX signal with the transmitted signal that is assumed to be known for this purpose (consider, e.g., a training sequence). The duration of the main lobe of the correlation function is directly linked to the time resolution.

Figure 7 shows examples of correlator peaks for different bandwidths and different channel realizations. The differences in the waveforms are due to variations of the multipath. It should be noted that the time-scales — encoded in terms of distance

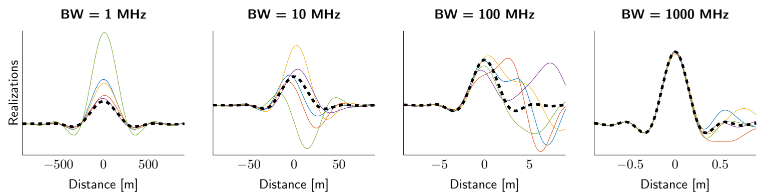


Fig. 7 Correlator outputs for different bandwidths (BW) and positions (realizations of the channel).

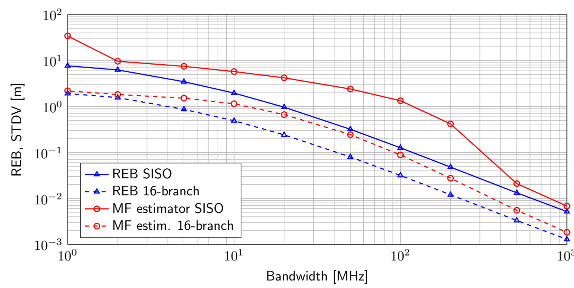


Fig. 8 Standard deviation (STDV) of the ranging error bound (REB) in relation to bandwidth for different diversity branch setups.

in meters — vary heavily according to the signal bandwidth. For comparison, the LOS without multipath is shown by the boldface, dashed curves.

In the NB case it can be seen that the transmitted signal has a length of hundreds of meters, which means that the LOS component overlaps with all later arriving multipath components, resulting in a flat fading case as discussed before. Even though there is no pulse distortion here, the rise time of the TX signal is extremely long, spanning hundreds of meters or more, thus an NB signal is not suitable for accurate positioning. One could try exploiting the carrier phase for ranging instead of the NB envelope. This would tremendously improve the accuracy, but the big issues with that approach are the need for synchronized oscillators and calibrated radios, ambiguity among successive cycles of the carrier, and the random phase shift of a Rayleigh channel.

Considering a bandwidth increase towards WB, the dispersiveness of the channel becomes visible that unfortunately distorts the pulse. Depending on the channel realization, this can significantly shift the correlation peak.

Going towards UWB yields an extremely narrow pulse and hence resolves the LOS component from other MPCs as described before. This would allow for an accurate measurement of the arrival time corresponding to cm-level accuracy.

A mathematical quantification of the BW dependence yields deeper insight. The Cramer-Rao lower bound (CRLB) [38] defines the theoretical lower limit on the variance of the estimated arrival time of the LOS component. In a dense multipath channel, the CRLB can be written as [39]

$$\mathrm{var}\{\hat{\tau}\} \geq \left(8\pi^2\beta^2\widetilde{\mathrm{SINR}}\right)^{-1},$$

where β^2 is the mean-squared bandwidth of the signal and SINR is a signal-to-interference-and-noise ratio that accounts for the power of the interfering multipath and is thus *limited by the physical propagation environment*. The error variance scales reciprocally with the BW β^2. Furthermore, the interference from multipath also scales reciprocally with bandwidth, which additionally affects the ranging performance. An illustration of this result is given in Figure 8. Between 10 MHz and 1 GHz, the *Ranging Error Bound (REB)* (consider the "SISO" curve) scales by more than a decade when changing the bandwidth by a factor of ten. At very low bandwidth the slope reduces [39], but here the accuracy is not at a useful level any more.

According to the REB, a bandwidth of 100 MHz is needed to obtain an accuracy in the 10-cm-region. However, a simple matched-filter (MF) estimator of the ToF (which computes the cross-correlation with a known training sequence) cannot achieve this bound as also illustrated in the figure. The MF will produce many positively-biased outliers that cause a deviation from the theoretical bound.

Again, diversity can be exploited to improve the performance, assuming that multiple measurements are obtained over independent channel branches. It has been discussed in [39] that the number of independent branches multiplies — and hence increases — the available SINR. That is, a lack of bandwidth can be compensated to some extent by a diversity scheme. Note from Figure 8 that also the simple MF estimator performs now closer to the theoretical bound. Indeed a standard deviation below 10 cm can now be achieved at a bandwidth of 100 MHz.

It is concluded that a higher bandwidth in particular, but also diversity from multiple measurements improves the reliability of a ToF estimator. Another advantage of the diversity approach lies in the availability that is improved by considering a larger set of independent measurements. While a single UWB link may provide the same accuracy, the risk of a severe outlier would be much higher, e.g., due to an obstruction of the LOS. The availability can be tackled with so-called *multipath-assisted methods* [40]. The solution is to "turn the enemy into an ally"; the enemy is multipath propagation that usually acts as a disturbance for ToF positioning. Multipath-assisted methods make use of detectable MPCs and treat them as separate observations originating from *virtual anchors* (VAs) [40]. These VAs can be determined when, e.g., the floor plan is known, moving towards the top right of the design space. Each surface that causes a clear specular reflection (such as a wall) yields a mirror image of the actual anchor which can be represented by the position of a VA. Hence, a single anchor "creates" a multitude of virtual sources as long as the pulses are short enough to be distinguishable. For longer pulses where less bandwidth is used, it was also shown that directional antennas could be used at the anchor to additionally explore the angle domain [41].

4 Hardware

This section elaborates on the hardware components that are an integral part of wireless IoT nodes. The section presents different transceiver structures that are used in wireless nodes and, in particular, their respective radio frequency (RF) stages and some of their most important components, i.e., filters and antennas that considerably mitigate interfering signals and thus enhance the IoT nodes' dependability. The presented discussions focus on these hardware components to realize dependability and in particular, on the components' impact on key dependability attributes such as availability, reliability, and timeliness. In Section 4.1, starting with an overview of modern transceivers used today in wireless IoT nodes, different transceiver structures and their specific RF stages are discussed based on the hardware design space shown in Figure 9. This discussion leads to the conclusion that dependable wireless nodes in IoT systems should ultimately rely on software defined radio (SDR)-based or rather cognitive radio (CR)-based transceivers that are able to sense the whole frequency spectrum and adapt the wireless communication scheme in real time, thus providing a high reliability and availability. To realize such transceivers, their filters and antennas also have to provide a continuous adaptability for the operation over a specific frequency range. These aspects of filters and antennas are discussed in Section 4.2 and Section 4.3, respectively, leading to the description of advanced filters and antennas for wireless IoT nodes, which enable different degrees of dependability for wireless IoT nodes.

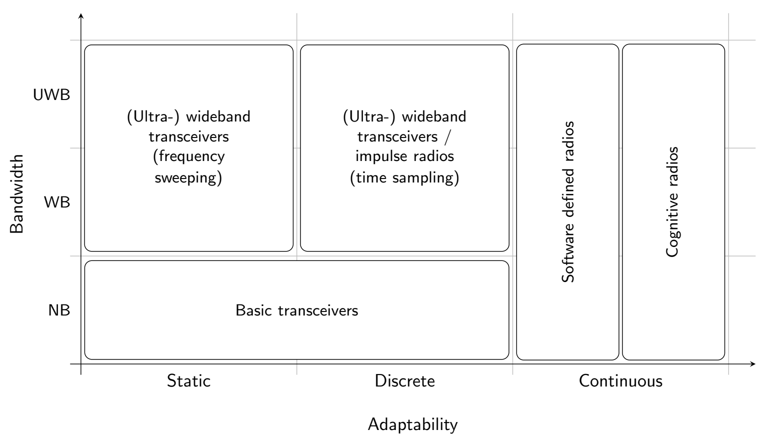


Fig. 9 Hardware design space for the transceivers of wireless IoT nodes.

4.1 Transceivers

The transceiver is a major component of wireless IoT nodes and thus is a critical component to ensure dependable wireless communication and localization in IoT systems. Figure 10 shows a block diagram of a basic modern transceiver, i.e., the most commonly used transceiver configuration in wireless nodes nowadays [42]. The data of the node that is transmitted wirelessly to adjacent nodes in the network is generated and modulated using a dedicated digital signal processing hardware. The digital to analog converter (DAC) then converts the digitally modulated signal to the analog domain. The signal is then up-converted to the respective operating RF frequency of the wireless node by the RF transmitter and radiated by the antenna. Typically, one common antenna is shared by the RF stages of the transceiver, i.e., the RF transmitter and the RF receiver; an RF switch is used to provide decoupling between the transmitted and received signals. The received signal at the antenna of the wireless node is down-converted to baseband by the RF receiver, converted to the digital domain using an analog to digital converter (ADC), and demodulated and processed using dedicated digital signal processing hardware. In the following, the RF stages of the transceiver are discussed in detail, while the aspects of digital signal processing are discussed in Section 3.

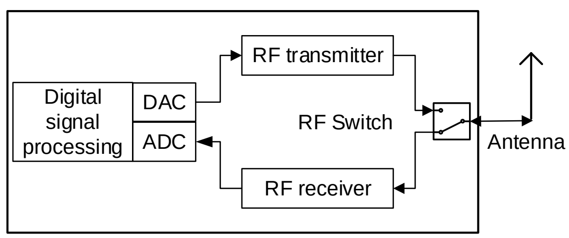
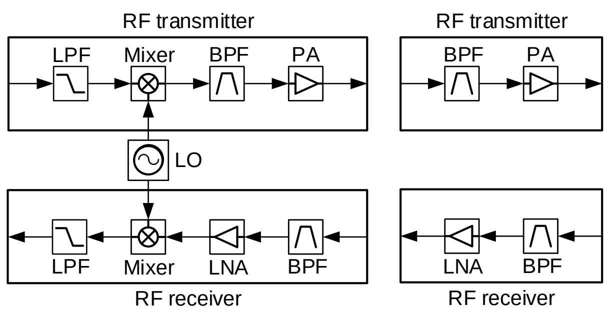


Fig. 10 Block diagram of a basic modern transceiver in wireless nodes.

RF transmitter and RF receiver. The RF transceiver stages of most wireless systems have a high degree of commonality, even though there are many variations in practice [43]. Figure 11 (a) shows the detailed block diagram of the RF stages of a basic modern transceiver typically used in IoT nodes. At the RF transmitter, the digitally modulated baseband signal is filtered by a low pass filter (LPF) and shifted up in frequency, i.e., the signal is up-converted to the desired RF operating frequency (e.g., to 2.45 GHz, see Section 5.2), using a mixer and a local oscillator (LO). A bandpass filter (BPF) allows the desired operating frequency to pass, while rejecting undesired frequencies generated during the up conversion. Subsequently, a power amplifier (PA) is used to provide the required transmitter output power, defined by wireless communication standards and regulations. Finally, the antenna converts the modulated carrier signal from the transmitter to a propagating electromagnetic wave to communicate wirelessly with an adjacent wireless node. The RF receiver retrieves the data transmitted by the adjacent wireless node, essentially reversing the functions of the RF transmitter components. The antenna receives electromagnetic waves radiated from many wireless nodes over a relatively wide frequency range. An input BPF provides some selectivity by filtering out received signals at undesired frequencies and passing signals within the desired RF frequency band. The BPF is followed by a low noise amplifier (LNA) that amplifies the possibly very weak received signal, while minimizing the noise power that is added by the amplification. Also, by placing the BPF before the LNA, the possibility is reduced that the sensitive amplifier will be overloaded by interfering signals of high power, generated, for example, by co-located wireless nodes that would impair the reliability of the IoT system. Next, the received RF signal is down-converted to the baseband by a mixer and the LO and filtered by an LPF.



(a) RF stages of a basic modern transceiver (b) RF stages of a SDR

Fig. 11 Block diagram of the RF stages of a basic modern transceiver and for the common implementation of the SDR concept as shown in [42]. See Figure 10 for whole transceiver structure.

4.1.1 Transceiver Adaptability

In this section, different transceiver structures for IoT nodes are investigated with respect to their adaptability, following the hardware design space introduced in Figure 9. In particular, the investigation highlights two key attributes with respect to the dependability of wireless nodes, i.e., their availability and their reliability. In the following, the transceiver adaptability is defined by the adaptability of the RF operating frequency of the transceiver. The transceiver structure is static and provides no adaptability, if the transceiver operates at a fixed operating frequency or at multiple fixed operating frequencies. The transceiver provides a discrete adaptability, if the transceiver is able to switch between a fixed set of operating frequencies, to support, for example, blind and adaptive channel hopping network protocols and thus to enhance reliability. The transceiver provides a continuous adaptability, if the transceiver is able to operate at any frequency within a certain range that supports, for example, adaptive and predictive channel hopping protocols and high reliability (see Section 5.3.5).

With respect to a static transceiver structure, RF transmitter and receiver structures, as shown in Figure 11 (a), are used that operate at a fixed operating frequency. Transceivers providing a multi-frequency operation can be realized by the design of an array of such RF transmitters and RF receivers, each operating on a specific frequency. Their combinations allows to operate at multiple fixed operating frequencies [44], thus providing no adaptability.

Transceivers for multi-frequency operation can also be designed using a single RF transmitter and receiver with a swept LO[2] [44], thus achieving a discrete adaptability. The RF stages shown in Figure 11 (a) can provide such a discrete adaptability by using a swept LO. Using these RF stages with a swept LO, makes it necessary to design and realize BPFs, a PA, an antenna, as well as an LNA that support the operation at the respective operating frequencies.

Continuous transceiver adaptability is provided by so called SDRs. Currently, a lot of research effort is devoted to realize SDRs [42,44–52]. The concept of an SDR has been first introduced by Mitola in 1995 [29], who proposed to create a radio that is fully adaptable by software in terms of operating frequency, bandwidth, and communication standard. A block diagram of the RF stages for a common implementation of the SDR is shown in Figure 11 (b). The baseband signals are generated and up-converted by dedicated signal processing hardware, converted into analog waveforms by a DAC, filtered by a BPF and amplified by a PA, before passing through an RF switch to be radiated by the antenna. The signal received by the antenna is routed to an LNA through the RF switch and a BPF and is then digitized by an ADC. Down-conversion, demodulation, and decoding are accomplished by dedicated signal processing hardware. To realize an SDR, a high sampling rate DAC has to be used at the transmitter side of the transceiver, as presented in [44]. At the receiver side of the transceiver, a so called bandpass sampling receiver [42] has to be used exploiting a high sampling rate ADC.

Next to the high reliability given by the continuous adaptability of an SDR, another benefit of SDRs in IoT nodes are the possible hardware cost savings [42]. Currently, the drawback of SDRs in IoT nodes is their negative impact on the availability of the wireless nodes due to the use of power-consuming components (e.g., high sampling rate ADC) [42], considerably reducing the battery lifetime.

4.1.2 Transceiver Bandwidth

In general, the transceiver bandwidth is defined by the RF operating frequency band, which can be NB, WB, or UWB (see Section 2.2). Following the hardware design space in Figure 9, this section presents two general transceiver concepts that provide

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[2] The RF operating frequency of the transceiver is switched between a fixed set of frequency values using a swept LO.

a wide or rather ultra-wide transceiver bandwidth and thus may pave the way to dependable IoT systems, highlighting the IoT nodes' availability and reliability.

One UWB transceiver concept relies on transceiver structures that perform frequency sweeping. In comparison to the second concept presented below, a frequency sweeping-based UWB transceiver is currently the preferred implementation due to its more practicable architecture (i.e., balanced complexity of the RF transmitter and receiver structures). The transceivers divide the spectrum into several frequency bands, using, for example, a stepped-frequency continuous wave (SFCW) transmitter [53]. A SFCW-based transceiver transmits a series of discrete tones in a stepwise fashion to attain a large effective bandwidth. In frequency sweeping based UWB transceivers, so called sweeping receivers are used [54] as shown in Figure 11 (a), exploiting a swept LO and thus a discrete transceiver adaptability. This kind of receiver uses electronically reconfigurable RF components to receive a large bandwidth by continuously sensing smaller portions of it [48, 53]. Examples of key reconfigurable RF components for these receiver architectures are reconfigurable BPFs for dynamic signal-band selections and reconfigurable notch filters for interference mitigation [47] as presented in Section 4.2. A major challenge within this type of receiver is the loss of phase information due to the sweeping operation [54]. To preserve this information and reconstruct the time domain wideband waveform, an accurate calibration and special hardware design is required that is rather expensive [54], being a major drawback with respect to the low cost requirements commonplace in the IoT.

Another UWB transceiver concept relies on transceiver structures that perform time sampling, also known as impulse radios. Time sampling-based UWB transceivers transmit a sequence of single, very short pulses at the whole bandwidth instantaneously [53]. This kind of UWB transceiver features a simple transmitter architecture with a low power consumption. However, receiving the short duration UWB signals presents a considerable challenge. In these kind of UWB transceivers, sampling receivers are used, which capture instantaneously all the frequency components of the waveform by taking samples over time [54] (see RF receiver in Figure 11 (b)). Within such receivers, the required high ADC sampling rate for signals occupying UWB frequencies, often rules this approach out due to their high power consumption. This issue can be partially circumvented by means of properly conceived receiver architectures such as mixed-mode wideband receiver architectures, which hybridize the analog and digital domains [47] (e.g., the ED and AcR discussed in Section 3.1). The main advantage of sampling receivers is that the whole spectrum of the incident waveform is sampled at once [54]. Among many other things, this is important to acquire impulse response measurements as discussed in Section 3.2.

4.1.3 SDR/CR-based Transceivers

Ultimately, future transceiver developments for wireless IoT nodes will evolve towards UWB transceivers that provide a continuous adaptability, realizing SDRs or rather CRs. A CR combines all the features of an SDR and adds more intelligence by sensing the radio environment and by tracking and adapting to changes in the wireless IoT system in real time [44]. The concept of CRs has also been introduced by Mitola [55], who states that SDRs provide an ideal platform for the realization of CRs. This concept has driven many researchers to study CR approaches [45–49]. Following the vision of SDR/CR-based transceiver in IoT nodes, most of the components of the RF transmitter and RF receiver stages will be shifted towards the digital domain (cf. Figure 11 (a) and 11 (b)). However, some important components of the transceiver stages have to be still implemented in the analog domain as, for example, the BPFs, the PA, the antenna, the LNA, as well as the DAC and the ADC of the transceiver. This means that a lot of effort has to be put into the design of these components in order to provide highly reliable, highly available, and low-cost wireless IoT nodes. In the following subsections, filter and antenna realizations are investigated in more detail, which will be crucial to realize dependable wireless communication and localization in the IoT.

4.2 RF and Microwave Filters for the Internet of Things

As presented in Section 4.1, wireless transceivers rely on microwave and RF filters for different functions. Figure 11 shows that both RF transmitters and receivers make use of two types of filters: lowpass- (LPF) and bandpass filter (BPF). The reader is reminded that LPFs are circuits that block high frequencies and pass low frequencies, whilst BPFs let through only signals within a certain frequency band. Since the latter have a stronger link to dependability, the present section will be focused on BPFs, presenting their general aspects and potentials in the IoT domain. Challenges regarding their synthesis, physical realization, performance and tunabilty will be described in Section 4.2.1 and 4.2.2.

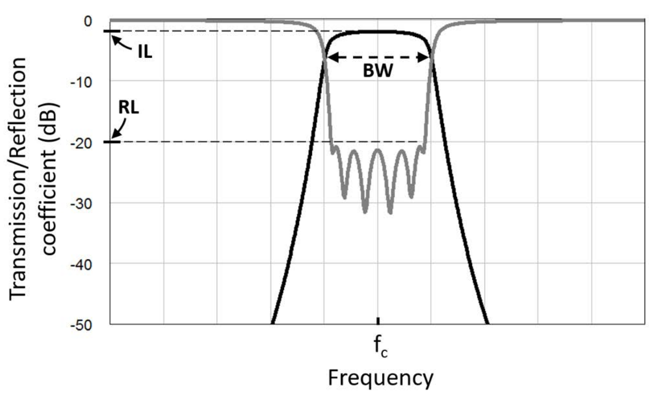

Fig. 12 Transmission and reflection coefficients of a 6^{th}-order BPF showing the main parameters to characterize a filter response.

The main parameters used to describe the response of a BPF are:

- Passband (PB) which defines the range of frequencies transmitted (ideally without attenuation), its width is expressed by the bandwidth (BW).
- Center frequency (f_c) defines the frequency at the middle of the pass-band.
- Insertion Loss (IL) describes the losses between the input and the output at f_c. It is the value of the transmission coefficient (represented by the black curve in Figure 12) at f_c expressed in dB; values close to 0 dB are sought.
- Return Loss (RL) describes the portion of the signal that is reflected back by the filter. It is the highest value of the reflection coefficient (represented by the grey curve in Figure 12) in the passband and it is expressed in dB; typical values are lower than -10 dB.
- Fractional bandwidth (FBW) is defined as the ratio between the center frequency (f_c) and the width of the passband.

The reader can refer to Figure 12 where the example of a filter response is reported along with the parameters defined above.

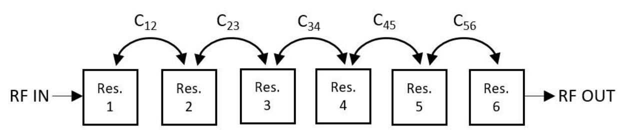

Fig. 13 Block diagram of a 6^{th}-order filter showing the building elements (resonators) and the energy transfer between them (couplings C_{ij}).

A comprehensive review on microwave filter technology has been reported in [56, 57], whilst filter design concepts and practical aspects can be found in [58] and [59]. The main building block of a bandpass filter is termed resonator. The number of resonators employed determines the order of the filter (a filter with N resonators is termed an N^{th}-order filter). For instance Figure 13 shows the structure of a 6^{th}-order filter having 6 resonators coupled one to the other. A resonator is characterized by its resonant frequency which ultimately determines f_c of the filter. The unloaded quality factor (Q_u) of a resonator which describes how much energy is stored in the resonator compared to the dissipated energy determines the performance of the filter. For instance in order for the filter to have a low IL the resonators need to have a high Q_u. In the normal working condition of a filter, it is required that the energy is transferred from one resonator to the adjacent one (simplest case). The entity of this energy transfer, referred to as inter-resonator coupling, must be designed opportunely since it determines the bandwidth (i.e., also the FBW) of the filter. From the theory of coupled resonators it is possible to demonstrate that the higher the coupling (also termed inter-resonator coupling) the wider the FBW [60]. The Q_u together with the FBW determines the IL of the filter, as shown by the formula [61]

$$IL = 10\log(e)\frac{1}{FBW}\frac{1}{Q_u}\sum_{k=1}^{N} g_k, \quad (3)$$

where the coefficients g_k depend on the approximation used to synthesize the filter (Chebyschev, Butterworth, etc.) and N is the order of the filter [62].

According to this formula, when the quality factor is fixed, wideband filters achieve lower IL compared to narrowband filters. This means that in WB and UWB filters Q_u is not a critical aspect. Vice versa, narrowband filters exhibit high IL when the quality factor of the resonator is low.

Such considerations are independent of the technology employed to implement the filter. However, the technology used to implement a bandpass filter does have an influence on the quality factor of a resonator and the maximum bandwidth that can be obtained. Indeed, while it is usually not a problem to achieve low coupling coefficients between resonators (which results in narrow-band filters) it is not always possible to obtain strong couplings between resonators which would lead to a wide and ultra-wide band filter response. This is the case for instance with dielectric-based resonators, often employed in order to shrink the size of the filter. In such resonators, where the electric field is strongly confined in the dielectric material the coupling of energy with adjacent resonators is difficult to obtain and so are strong couplings (wide and ultra-wide band filters cannot be obtained) [63]. This effect becomes more and more evident as the dielectric constant of the material increases. The considerations expressed so far are basic concepts valid for static filters but hold true also for tunable (or reconfigurable) filters that are key elements for tunable transceivers and will be described in detail below. The discussion will start with narrowband filters and continue with the description of wideband and UWB bandpass filters, where the latter may have adaptive notches in their response. A notch is a narrowband bandstop filter. The latter typology of filter aims to block narrowband interferences at the front-end stage to increase reliability by preventing the saturation of the LNA (the reader may refer to Figure 11 where the building blocks of RF receivers are shown).

4.2.1 Tunable Bandpass Filters

The tunability of a bandpass filter, for the most common cases, can be implemented in terms of center frequency and/or bandwidth. Their function enables dependability since the transmission of the signal is shifted to the most suitable frequency band at the time of the transmission. This is useful for example in case of interferences from external sources which may cause the LNA to saturate. In other words BPFs enable the implementation of frequency diversity schemes (see Section 3.1.1). The tuning elements employed for this purpose are usually switches and variable capacitors, to mention two representative examples. When switches are employed, the result is a filter response with a finite number of configurations, i.e., realizing *discrete reconfigurability*, given the nature of switches of having only two possible states.

When variable capacitors are employed, instead, the result is a continuous variation of the filter response, i.e., a *continuous reconfigurability* is achieved.

Both switches and variable capacitors can be realized in different technologies, e.g., they can be mechanical-, magnetic-, MEMS- or semiconductor-based. The technology determines the switching speed which has a direct impact on the timeliness of the system. As an example, pin-diodes provide very high switching speed and reliability (since the technology is very well-established) therefore they are usually preferred. However, a trade-off between performance and power consumption must be observed. Indeed, the high current required by pin diodes (order of few mA) might have a negative effect on the availability of a wireless node due to excessive power consumption. MEMS represent a valid alternative, although researchers have been working in the last decade toward more reliable solutions for this technology [64].

The highest possible frequency/bandwidth shift is termed tuning range. Tunable filters that have a wide tuning range are very appealing since they can execute the function of several filters with a single device which reduces the size of the system. The main challenge in tunable filters is achieving a wide tuning range and preserving high performance (a high quality-factor value within the entire tuning range, which ultimately results in maintaining IL and selectivity performance of the filter at an acceptable level). As already introduced, resonators are the building blocks of BPFs. By introducing a tuning element in a resonator that allows one to change its resonant frequency it is possible to control the centre frequency of the filter implemented with this resonator [65]. Similarly, if tuning elements are used to modify the coupling between resonators, the bandwidth of the filter is tuned. Such techniques are valid from NB up to UWB filters. However, for WB and UWB filters employed in IoT systems another type of tunability finds application, namely tunable notch filters which are presented in the next section.

4.2.2 Tunable Notch Filters

The last case of tunability presented in this section is that of WB and UWB filters with a reconfigurable notch in their response, referred to as tunable notch filters. UWB has emerged as a fast growing technology, however, a major impediment to the employment of UWB systems is the issue of narrowband interference that might exist in the same spectrum region. In UWB transceivers this results in the saturation of the LNA. For these reasons UWB filters able to reject specific frequencies are being developed [47]. Tunable notch filters contribute to achieve dependability as they enable notches (also more than one at the same time) in order to mitigate interference in a dynamic way. Depending on the way they are implemented, they can have a *discrete or a continuous reconfigurable* behaviour which means they employ switches or variable capacitors, respectively [66, 67]. The attenuation of the interference provided by a notch usually ranges from -15 to -20 dB whilst IL is usually not an issue in such filters given their wide FBW (e.g., in [66] IL is better than -1.1 dB). The latter statement can be verified referring to Formula (3) where the FBW appears at the denominator. Thanks to the fact that IL is not an issue, such filters can be implemented in technologies that usually provide low Q_u, for instance based on silicon processes which is a good candidate for integrated UWB RF front-end modules [66]. This represents a big benefit since, technologies that provide high Q_u (e.g., waveguide or cavities in general) are not suitable for IoT applications due to the unreasonable dimension of their hardware (e.g., a standard waveguide for 2.4 GHz signals has a cross-section of 86x43 mm).

4.3 Antennas

As presented in Section 4.1, antennas are indispensable devices that enable IoT nodes to communicate to one another [68]. Antennas can be defined as a one port network passive device enabling the transition of electromagnetic waves from a guided wave to a free-space wave, or vice-versa. Antennas have a strong impact on the dependability of a wireless communication link because of their direct influence on two main impairments, the multipath propagation and the interference from other radio sources. Antennas that are able to dynamically reconfigure/adapt their behavior by modifying one or more of their characteristics (frequency band, radiation properties, polarization, etc) enable therefore a higher reliability and timeliness [69, 70]. The directivity of an antenna can for instance influence the fading distribution by suppressing strong multipath components (see ”antenna diversity” in Section 5.3) or block interfering signals. Furthermore, increasing the antenna bandwidth contributes to increase the nodes’ reliability by offering frequency diversity, see Section 3.1.1. This section is devoted to an overview of antenna aspects and potentials in wireless IoT systems. Following the hardware design space shown in Figure 9, challenges for increasing the antennas bandwidth are briefly highlighted in Section 4.3.1 while the antenna adaptability is discussed in Section 4.3.2. The main parameters used to characterize antennas are [71]:

- Antenna efficiency: is the ratio of the total power radiated by an antenna to the power delivered to the antenna.
- Directivity: is a measure of how directional an antenna is compared to an isotropic source (an isotropic antenna has zero directivity). The directivity characterizes the radiation properties of the antenna.
- Radiation pattern: is a mathematical function or graphical representation of the antenna radiation properties (gain, directivity, etc) as a function of space coordinates.
- Bandwidth: is defined as the difference of two frequencies on either side of the operating frequency (f_0) at which the antenna can radiate/receive energy.
- Polarization: is defined as the plane where the electric field oscillates while propagating. An antenna is called to be linearly (i.e, vertically or horizontally) polarized if its electric field is perpendicular or parallel to the Earth’s surface. Circular or elliptical polarization occurs if an antenna electric field propagates in all planes (vertical, horizontal and in between planes).

In order to guarantee an efficient transmission/reception, all aforementioned characteristics must be examined and suitably designed for an antenna to work properly. For example, the impedance between the antenna and the transmission line should be matched to obtain a maximum power transfer between the antenna and transmission line and thus radiation. It is usually said that an antenna is matched at a return loss of more than 10 dB over its operating frequency band, an example of a RL response can be seen in Figure 12. Similarly, polarization matching is required for efficient transmission/reception as a vertically polarized antenna is not able to communicate with a horizontally polarized antenna. A detailed review of antenna design concepts and practical aspects can be found in [72–74].

4.3.1 Antenna Bandwidth: Towards Higher Bandwidth

Antennas can be classified in terms of bandwidth into narrowband, wideband and ultra-wideband antennas (see Section 2.2). The theory of narrowband antennas has reached a certain level of maturity where many off-the-shelf products for IoT applications are already available. Wire and microstrip antennas are widely used in narrowband IoT nodes as they can be easily designed to operate at a predefined center frequency and bandwidth with low profile, cost and ease of integration on printed circuit board materials. Narrowband antennas are typically resonant devices operating at a single resonance frequency at a time with a certain bandwidth, quality factor (see Section 4.2), and radiation efficiency. Chu and Harrington [75–77] investigated the fundamental limitation of electrically small antennas for achieving a broader impedance bandwidth. It was found that to increase the antenna bandwidth, its quality factor has to be reduced, and thus the antenna radiation efficiency will degrade as well. In addition, the reduction in the antenna size will lead to a rapid increase in the antenna quality factor and thus limiting its bandwidth. It can be concluded that the antenna quality factor, bandwidth, efficiency and size are related and a tradeoff between them is unavoidable to achieve an optimal design. Several techniques have been proposed to increase the antenna bandwidth. For instance, thickening the wire antennas and increasing the substrate thickness of microstrip antennas can lead to improvements of the impedance bandwidth by a few percent. Another way to obtain wideband antennas is by overlapping two or more resonant parts operating at their own resonances or by introducing multiple resonances within the same structure such as U-slot microstrip antennas, parasitic microstrip antennas and stacked microstrip antennas [78]. UWB antennas can be designed by a combination of one or more of the following techniques [79]: electrically small antennas, frequency independent antennas, multiple resonance antennas, travelling wave structures, and self-complementary antennas.

The main design challenges in UWB antennas for IoT applications are to realize a high radiation efficiency, linear phase, low dispersion, large bandwidth, compact size and compatibility with integrated circuits. While the radiation of high power is allowed in narrowband applications, UWB transceivers' transmission power is below the noise floor level (in fact below -41.3dBm/MHz as shown in Section 5.2) which requires antennas with high radiation efficiency, i.e., conductor and dielectric losses have to be minimized, while maintaining good impedance bandwidth matching. In general, UWB transceivers use impulse radio signals for communication (see Section 3.1). The high reflection coefficient in ultra-wideband antennas can lead to a non-linear phase and thus, to a high distortion in the transmitted signal. In comparison to narrowband antennas where phase is considered constant, UWB antennas' radiation properties are frequency-dependent. The distortion might make it impossible to recover the transmitted pulse at the receiver. This reduces the IoT nodes dependability, as more computational processing power is required to recover the distorted pulse.

A detailed review of UWB antennas, potentials and challenges can be found in [80–82]. An example of an UWB antenna with a continuously tunable and independent notch filters integrated on the same structure suitable for IoT applications can be found in [83]. In [84] a planar UWB antenna with an improved radiation performance versus frequency suitable for IoT applications is presented.

4.3.2 Antenna Adaptability/Reconfigurability

In general, a reconfigurable antenna can be realized by an antenna or an array of antennas and is capable of adapting its behaviour by modifying one or more of its parameters (operating frequency, bandwidth, and radiation properties) in real time via electrical, mechanical or other means. This section focuses on the reconfigurability of the antennas radiation properties (directionality), which contributes to spatial diversity utilisation (see Section 3.1.1 and 5.3.6).

Reconfigurability of antenna radiation properties considers steering the main beam of directional antennas towards the desired direction of communications and, in the most advanced cases, nulls in the direction of unwanted signals. This is equivalent to spatial filtering reducing interference and thus the IoT node reliability is improved. However, the use of reconfigurable antennas can degrade availability and timeliness when large numbers of switches, phase shifters and/or complex signal processing are used. The reduced battery lifetime might impair the availability of the sensor node drastically, as reconfigurable antennas' energy consumption depends on their complexity. Also, the IoT nodes timeliness might degrade drastically because of the delays caused by complex signal processing and/or mechanical antenna rotation. The main challenges in designing reconfigurable directional antennas lies in the system complexity (expertise is needed in different areas such as in antenna design, feeding networks, signal processing, complex measurement and steering/beamforming algorithms), cost, size, and power consumption.

As indicated in Figure 15 several realizations of reconfigurable directional antennas (depending on their level of adaptability) are existing. The classical approach are *switchable antennas*, which are switching between antennas with fixed radiation patterns. To focus the power in another direction, the antenna has to be either mechanically rotated, or a different antenna element has to be electronically switched on or off. Figure 14 shows an example of an electronically switchable directional antenna system for UWB-based IoT applications. It consists of four directional UWB antennas and a RF switching network controllable via two GPIO ports.

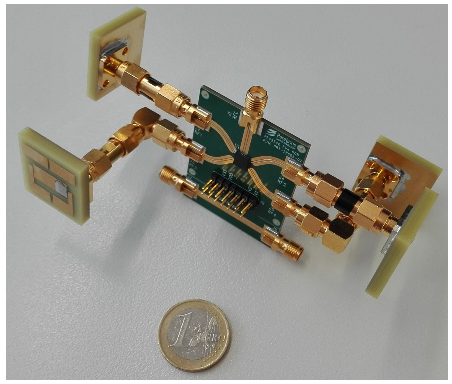

Fig. 14 Switchable antenna system for UWB-based IoT applications [85].

The disadvantage of switchable directional antennas is the limited degrees of freedom and typically also a higher form factor. An alternative are *smart antennas*, consisting of an array of several antenna elements and additional signal-processing capabilities, which results in more degrees of freedom, like directional and adaptive beamforming. This advantage typically comes at the cost of high computational power for the adaptive excitation of the antenna elements (which is typically done in a micro-controller or digital signal processor), as well as a bigger size of the antenna system. In the simplest implementation of a smart antenna, the phase shifts of each antenna element to achieve a certain beam are pre-programmed in the memory of the processing unit (*switched smart antenna*). In a more adaptable system the beam can be formed dynamically depending on the current interference sources and environment (*adaptive smart antenna*). In the most adaptable and cognitive case, several adaptive smart antennas are necessary to exploit multipath components and achieve highest diversity gain (*MIMO*), as described in Section 3.1.1.

Additional challenges arise, when ultra-wideband antennas are employed as radiating elements to form an array. As mentioned in the previous section, ultra-wideband antennas are frequency-dependent devices. Thus, the design of frequency-independent feeding networks is required to guarantee the IoT nodes' availability. The design of phase shifters and beamforming algorithms becomes more challenging with increasing bandwidth. A detailed review on reconfigurable directional antennas can be found in [86–88].

For more details about using switchable and smart antennas in wireless IoT networks and their positive impact on the dependability of IoT systems please refer to Section 5.3.6.

5 Networking

The previous sections described the wireless propagation channel and its characteristics focusing on a pair of communicating devices (i.e., considering only a single transmitter/receiver and the necessary hardware implementation). In most wireless systems and IoT applications, however, a large number of devices is forming a *network* in which nodes can broadcast information to several nodes, or in which pairs of nodes concurrently communicate with each other at the same time. This section hence investigates how multiple devices sharing the same medium can communicate in a dependable fashion. Section 5.1 first reviews the tasks of the medium access control layer in the context of IoT systems and discusses its impact on key dependability attributes such as timeliness, availability, and reliability. Thereafter, Section 5.2 gives an overview of the wireless communication technologies used to build IoT applications to date, and highlights how the community has, so far, mostly focused on lower bandwidth. Finally, Section 5.3 introduces the design space in the networking domain and shows that there is still plenty of room to improve the dependability of IoT systems by increasing the bandwidth and adaptability.

5.1 Impact of Medium Access Control on Dependability

Wireless communications are inherently broadcast. Therefore, the wireless channel has to be effectively shared between devices to ensure a dependable data transfer. Towards this goal, the Medium Access Control (MAC) sub-layer of the data link layer[3] plays a key role, as it controls the access of the devices to the shared medium and is hence responsible for avoiding collisions and interference between multiple nodes. Furthermore, as IoT devices are typically resource-constrained and operating on battery, the MAC layer has often also the responsibility to minimize the time in which the radio transceiver of a device is listening for incoming packets in order to increase the availability of the system. The remainder of this subsection briefly reviews the role of the MAC layer with respect to the three dependability attributes introduced in Section 1: availability, timeliness, and reliability.

Availability. The majority of IoT applications employs battery-powered devices embedding a radio transceiver. The latter is a power-hungry component (typically, by far the most power-consuming component in a wireless sensor node) and it is important to minimize its active time to guarantee energy-efficient operations. Traditionally, this task is fulfilled by *duty-cycling* MAC protocols, who efficiently control the time in which a radio transceiver is turned on and off and increase the energy-efficiency of the system and hence its availability. A large group of researchers have worked intensively on the design of energy-efficient duty-cycling MAC protocols since the early 2000s [5, 89, 90]. Influential examples are Sensor-MAC (S-

[3] Second layer in the OSI reference model.

MAC) [91], Timeout-MAC (T-MAC) [92], and X-MAC [93].

Timeliness. Periodically turning off the radio to save energy may increase availability, but may at the same time also have a strong impact on the ability of an IoT system to meet timeliness requirements. As an example, in vehicular communications it is essential that information about the road conditions are received in a timely manner from a central server. Similarly, in a smart parking application, the end user may demand updates about the current parking situation from a smartphone in real-time. This requires resource-constrained wireless sensors deployed in the streets to be reactive to such requests and hence to poll for incoming packets quite often (i.e., to frequently turn on the radio). This poses a sort of *catch-22* dilemma between low latency and high availability when meeting the application requirements – a very well-known problem that the research community is still trying to properly address [94]. For applications that clearly privilege only one of the two requirements (e.g., high availability over low latencies), quite a number of solutions have been proposed, such as Dozer [95] and BailighPulse [96].

Reliability. The MAC protocol also plays a crucial role in providing a high delivery rate and in satisfying minimum reliability requirements imposed by the application. In particular, the medium access control layer is often responsible for recovering from transmission errors and avoiding collisions caused by interference. Sources of interference can be internal to the network of interest or external [97]. External interference is traditionally caused by co-located wireless devices or appliances that radiate electromagnetic energy in the frequency bands used by the network of interest. Internal interference, instead, is caused by concurrent transmissions of other wireless devices operating in the same network. An overview of the solutions investigated by the community to mitigate external interference can be found in [97]. To solve the internal interference problem between devices operating in the same network, MAC protocols can either adopt a *contention-based* or a *schedule-based* approach.

Schedule-based MAC protocols assign the medium exclusively to a specific set of wireless devices. Frequency division multiple access (FDMA) protocols [98, 99] subdivide the available bandwidth into smaller bands and assign each device to one of these frequency bands to communicate. Although this approach minimizes interference and maximizes the bandwidth available for communications, it may not scale to dense networks. Time division multiple access (TDMA) protocols [100, 101] employ the same frequency band for all transmissions, but split the time domain into several time-slots. A time schedule indicates which device(s) may transmit frames during a certain time-slot: the larger the frame size and the number of wireless devices, the higher are the delays before a node can get access to the medium. Protocols based on code division multiple access (CDMA) use the same frequency and time-slot throughout the network, but employ simultaneous transmission by means of orthogonal codes. Typically, multiple access schemes can also be combined into hybrid approaches: the Time Slotted Channel Hopping protocol (TSCH) is an exemplary protocol using a combination of FDMA and TDMA [102].

In *contention-based* approaches, instead, the medium is shared by multiple devices simultaneously. The simplest example of contention-based protocol is the so-called “pure” or *unslotted* ALOHA [103], which allows each device to transmit packets as soon as data is available. However, as the transmission time can be chosen arbitrarily, it is likely to generate collisions when several transmitters want to communicate simultaneously. In a *slotted ALOHA* system, instead, the transmission is just allowed in specific time-slots. Each transmitter can pick one of these slots, i.e., it synchronizes with the beginning of a time-slot, and a collision can only occur if multiple devices are sending during the same time-slot. This reduces the probability of collisions and doubles the maximum achievable throughput of unslotted ALOHA [6]. ALOHA, however, is particularly inefficient in crowded channels. To reduce the number of collisions, Carrier Sense Multiple Access (CSMA) based protocols have hence been introduced [104]. CSMA is based on clear channel assessment (CCA), which senses the wireless channel to check if there is an ongoing transmission. If this is the case, the transmitter backs off and postpones its transmission. If, instead, the channel is not occupied, the packet can be transmitted immediately. A clear advantage of CSMA is that it does not require a close coordination among nodes (such as time synchronization), which is typically the case for TDMA-based protocols. One of the biggest drawbacks of CSMA protocols, however, is the “hidden node” problem [105] that occurs when a node A is visible from another node B, but not from other nodes communicating to B. A countermeasure to overcome this problem is to carry out an handshake with special request-to-send/clear-to-send (RTS/CTS) messages, as introduced by MACA [106]. By sending an RTS message, the transmitter signals that it has a packet to be sent and includes the duration T of the planned transmission. If the receiver is ready to receive the message, it answers with a CTS message and all nodes receiving this message postpone their transmissions to avoid generating collisions.

5.2 Impact of Bandwidth on Dependability

Today, most of the deployed Wireless Sensor Networks (WSNs) and IoT applications are based on the IEEE 802.15.4 standard [107], which defines the physical (PHY) and medium access control layers for low-cost, low-power, and low-rate Wireless Personal Area Networks (WPANs). The last revision of the standard defines 19 different PHYs, most of which use globally reserved industrial, scientific, and medical (ISM) radio bands. Among those bands, the most popular and used ones are:

- 868-868.6 MHz (Europe), one available channel
- 902-928 MHz (America), 10 available channels, channel spacing: 2 MHz
- 2400-2483.5 MHz (Worldwide), 16 available channels, channel spacing: 5MHz

IEEE 802.15.4 is not the only wireless technology employing these frequencies. In recent years, quite a number of standards, addressing IoT systems, have been specified, such as Bluetooth Low Energy (BLE)[4], LoRa, SIGFOX, Z-Wave, Wi-Fi HaLow, just to name a few. Each of these technologies has different strengths and fields of application. BLE, for example, has the advantage of being ubiquitous nowadays, as most commercial tablets, smartphones, and laptops support it. LoRa, SIGFOX, and Wi-Fi HaLow offer long-range communication over several kilometers. However, all these technologies share a common limitation: they are inherently narrowband communication technologies. This causes these systems to be highly susceptible to multipath fading (see Section 2.1) and cross-technology interference, which reduces throughput and leads to an increased amount of network traffic due to re-transmissions [97, 108, 109].

A promising alternative to tackle these limitations is the shift towards higher bandwidth. The high bandwidth (allowing short pulses) results in beneficial properties such as a high immunity to multipath fading, a very good time-domain resolution allowing for precise localization and tracking, as well as possible high data rates. The IEEE 802.15.4 working group recognized this potential and published in 2007 the IEEE 802.15.4a amendment. The latter specifies additional PHYs to add a ranging capability with an accuracy of one meter or higher, an extended communication range, as well as improved robustness and mobility support as compared to the IEEE 802.15.4-2003 standard [110]. One of the added physical layers is the impulse radio ultra-wideband (IR-UWB) technology. As briefly introduced in Section 2.2, UWB-based devices spread the signal power over a wide bandwidth ($\geq$ 500 MHz) yielding extremely low power spectral density and, as a consequence, reduce interference to other systems. In February 2002 the Federal Communications Commission (FCC) allocated the 3.1-10.6 GHz frequency band for unlicensed use with a maximum equivalent isotropically radiated power (EIRP) of -41.3dBm/MHz, which is also the limit for unintentional radiators (e.g., TVs and monitors). Gradually, also other countries - with slight differences to the FCC spectrum mask - published their own UWB regulations [111].

In the wireless sensor networks and IoT research communities, UWB communication systems have drawn significant interest in the past, but without making the breakthrough and without finding the way into off-the-shelf consumer products [112]. For this reason, as shown in the next subsection, most work on dependable networking has been focusing on narrowband technologies only. However, this may change in the coming years, especially after the publication of IEEE 802.15.4a standard and the commercialization of the first low-cost IEEE 802.15.4-compliant UWB transceiver, the DecaWave DW1000 [113]. These two key factors, together with the outstanding localization performance of UWB technology [114,115] (which was also proven in harsh environments such as mines [116]) aroused the enthusiasm for UWB technology and its potential for dependable IoT applications.

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[4] BLE is marketed as Bluetooth Smart and was originally introduced as Wibree by Nokia. It is merged by the Bluetooth Special Interest Group (SIG) into the Bluetooth Core Specification v4.0.

5.3 Impact of Networking Design Space on Dependability

The design space of the networking section holds, as before, *adaptability* on the x-axis and *bandwidth* on the y-axis as shown in Figure 15. The x-axis is subdivided into *static*, *switchable*, *adaptive/reactive*, *cognitive/predictive*, whereas the y-axis is subdivided into *narrowband* and *ultra-wideband*. The presented design space covers state-of-the-art technologies in the networking domain while presenting their impact on the dependability of a wireless system. In particular, each of the techniques shown in Figure 15 is treated separately and analyzed in relation to bandwidth and adaptability, as well as exemplary MAC protocols are discussed. Finally, it is highlighted that there is significant room for future work in the region of higher bandwidth and higher adaptability (indicated by the red rectangle) and it is argued that future research should address this area.

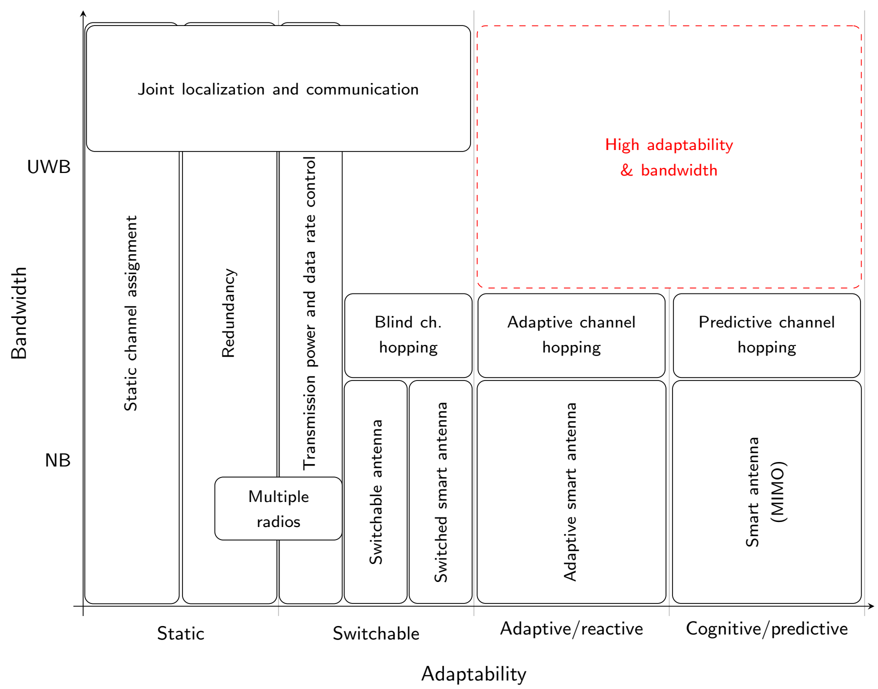

Fig. 15 Networking design space. State-of-the-art techniques used in the networking domain.

5.3.1 Static Channel Assignment

When designing a wireless system, it has to be defined which frequency bands and wireless channels should be used for communication. In the simplest case, a static channel is assigned during the deployment phase and is not to be changed throughout the lifetime of a network. The selection of the channel may take communication range or surrounding interference into account. As indicated in Figure 15, static channel assignment in a wireless system is used by all technologies regardless of their bandwidth. Still, the external interference in the narrowband case and the usage of preamble codes in ultra-wideband motivate a few important remarks.

Narrowband. Especially in the crowded 2.4 GHz ISM band, several technologies and devices are coexisting in the same frequency range [108]. In the likely case of concurrent wireless transmissions in the surroundings (e.g., caused by a Wi-Fi access point or a Bluetooth-enabled smartphone), the quality of the statically defined channel may decrease significantly and, as a result, the link could become highly unreliable [97]. The only degree of freedom to increase the reliability within this approach is the selection of a channel with minimal overlap to other technologies. For example, several WSN applications employ IEEE 802.15.4 channel 26 to escape at least the interference of surrounding Wi-Fi devices operating in the 2.4 GHz ISM band [117, 118].

Ultra-wideband. UWB-based applications typically use a static channel. Nevertheless, as specified by the IEEE 802.15.4 UWB standard, several networks can coexist on the same channel by using different preamble codes. The preamble code is sent before the physical header and data field of the IEEE 802.15.4 packets for synchronisation and channel estimation. The low cross-correlation between several preamble codes allows simultaneously operating networks. In the case of a decentralized multiple access technique, a smart way to assign preamble codes to the devices and networks is required. Three code assignment approaches can be found in the literature [119, 120]:

1. Common code: the simplest principle is that just one code is used for all transmissions. If several nodes are transmitting simultaneously, collisions may occur.
2. Receiver-based code: each user has a unique receiving code. Therefore, the receiver has to monitor only its receiving code. Collisions are possible when several users try to transmit data to the same receiver.
3. Transmitter-based code: each user is assigned to a unique sending code. Collisions between different transmitters do not appear anymore, but it is necessary that the receiver knows with which code to listen.

Practical implementations often use a hybrid approach, such as common-transmitter (C-T) or receiver-transmitter (R-T) codes. These are then combined with the RTS/CTS mechanism to form the so called MACA/C-T or MACA/R-T protocols [121]. In MACA/C-T, RTS/CTS messages are transmitted via the common code approach and the data via the unique sending code (transmitter-based). In MACA/R-T a unique receiving and sending code is assigned to each node. RTS is sent with the destination's receiving code, whereas CTS and data are transmitted with the appropriate sending code.

5.3.2 Redundancy

Regardless of the employed bandwidth, a classical approach used to increase the dependability of a communication link is to mitigate the impact of errors in the data transmission by means of redundancy. The simplest example is to repeat the whole information multiple times (see time diversity concept in Section 3.1.1): this is for example done by default in the IEEE 802.15.1 standard (Bluetooth), and also proposed in IEEE 802.15.4 (in the context of packet headers) to mitigate the impact of surrounding external Wi-Fi access points [122] . A more efficient approach is *forward error correction* (FEC), in which additional information is added to the original packet and is then used to detect or even correct possible errors. If the latter are corrected directly at the receiver, no packet re-transmissions are necessary. However, embedding redundant information in a packet results in a larger overhead in terms of a longer transmission time, as well as additional time for encoding and decoding of the error-correcting code. Therefore, FEC is used when re-transmission is costly or even impossible, i.e., in unidirectional or multicast communications.

Another way to introduce redundancy is the so called *backward error correction* (BEC). In BEC, the additional message types acknowledgement (ACK) or negative acknowledgement (NACK) are used to inform the transmitter whether a packet is successfully received or lost, respectively. Depending on the implementation, the transmitter has to decide whether a packet should be re-transmitted.

Basic FEC techniques are clearly static approaches, which is indicated in Figure 15. Whereas, BEC techniques include some adaptive elements, since the amount of sent ACKs is depending on the quality of the link and the reception rate. Furthermore, several BEC algorithms are, for example, adaptively determining the timeout before re-transmitting a packet [123]. In the bandwidth domain of the design space the redundancy block covers the whole axis, which indicates that the usage of redundancy techniques is in theory not influenced by the bandwidth.

5.3.3 Multiple Radios

As indicated in Section 4.1, a cost- and space-intensive solution is to increase the number of transceivers embedded on a wireless device to improve the dependability of a network. In this regard, it has to be differentiated between having transceivers using the same radio technology (as an example, Draves et al. [124] use two 802.11 transceivers per node, where the individual radios are tuned to different, non-interfering channels) and having independent radio technologies (as an example, the BTnode from ETH Zurich [125] is equipped with a Bluetooth radio and a low-power sub-GHz ISM band radio that can be operated simultaneously or independently powered off).

Although the introduction of Bluetooth Low Energy may have diminished the need for a low-power technology in addition to Bluetooth, the concept of dual- or multi-radio is widely used in the research community. As also indicated in the design space in Figure 15, so far, this technique was mainly used in narrowband applications. However, because of its outstanding ranging performance, UWB radios are increasingly used as a localization technology, mainly in combination with an additional narrowband communication module (see Section 5.3.7). Individually switching between different radio models requires a certain level of adaptability. For this reason, this technique is placed in the cross section between static and switchable in the design space.

5.3.4 Transmission Power and Rate Control

The control of transmission power and data rate is a useful tool to manage the interference level and network reliability. Transmission power control is a well-known technique in narrowband applications. Lin et al. [126] have presented ATPC, a lightweight algorithm to adapt the transmission power and minimize internal interference in a wireless sensor network. Similarly, Shen et al. [119] and Cuomo et al. [127] have also shown the importance of transmission power control for higher bandwidth. The technique, therefore, covers the whole y-axis of the design space depicted in Figure 15.

It is important to highlight that transmission power control has also an impact on network availability, as it often allows to decrease the transmit power levels of the devices in the network to the minimum amount necessary to reach the intended receiver(s). Additionally, in IEEE 802.15.4-compatible UWB transceivers, physical layer parameters such as pulse repetition frequency (PRF) or preamble length can be changed, depending on the application and environment [128].

5.3.5 Channel Hopping

Instead of transmitting on the same highly-congested frequency band, a device can hop across different channels. Channel hopping reduces fading by means of frequency diversity [129]. This assumes that the channels are spaced apart by more than the coherence bandwidth to reduce the probability of a simultaneous deep fade at both channels (see Section 2.1 for further details). Depending on their level of adaptability, one can differentiate between blind, adaptive, and predictive hopping [97].

Channel hopping is essentially exploiting frequency diversity, and implies that a higher bandwidth w.r.t. the static channel approach is used, which is also mapped in Figure 15 accordingly. It is important to highlight that accurate time synchronization in the network is traditionally necessary in order to allow all nodes to hop in unison.

Blind channel hopping. In blind hopping the wireless nodes follow a pseudo-random sequence to hop continuously between the available channels and there is no prior knowledge of the link quality of the channels necessary. If not all channels are highly congested, the average interference level should be significantly decreased. However, if most of the channels are crowded, blind channel hopping is ineffective. Since the IEEE 802.15.4e amendment was released in 2012 [102], also the IEEE 802.15.4 standard explicitely supports channel hopping. The employed protocol is called TSCH, and supports time-slotted access together with channel hopping. Other standards that make use of continuous hopping are WirelessHART [130] and ANT+ [131].

Adaptive channel hopping. To avoid hopping back to congested channels, a device can store and remember the number of the congested channel and hop accordingly in the next hopping cycle. This technique is also called blacklisting. An adaptive version of TSCH was presented by Du et al. [132]. Since version 1.2 (2003), also Bluetooth supports adaptive hopping by avoiding the use of crowded frequencies, called adaptive frequency hopping (AFH). The challenge is to identify whether a channel is sufficiently "good" or not. This requires an efficient and well-performing CCA, which is difficult to achieve for impulse radio ultra-wideband (see Section 5.3.7). A drawback of adaptive channel hopping is the necessity for sharing the list of blacklisted channels throughout the network.

Predictive channel hopping. Before blacklisting channels and adapting the hopping sequence to the interference in the surroundings, the wireless device has to first estimate the quality of available channels. This may require to periodically send or (attempt to) receive one or more sample packets for each frequency band. However, sampling interfered channels may cause significant packet loss or trigger a number of re-transmissions that may significantly degrade performance. For this reasons, the most desirable concept is to predict the deterioration of channel conditions beforehand. This is typically referred to as *predictive* or *proactive channel hopping* [97]. A fundamental role in this regard is played by channel quality estimation metrics that can detect an early degradation of the channel [133, 134], as well as by an efficient link quality ranking algorithm [135] and interference classification schemes [136, 137]. Although a number of predictive protocols have been proposed for wireless sensor networks operating in the 2.4 GHz band [138, 139], the main disadvantage of these approaches is that they heavily rely on high-rate and accurate energy detection, which is very costly in terms of energy consumption.

5.3.6 Antenna Diversity in the Networking Domain

The key idea behind antenna diversity is that the received signals of different antennas are uncorrelated, which is either achieved by spacing the antenna elements sufficiently far away from each other (see Section 3.1.1), or by making use of reconfigurable directional antennas (see Section 4.3.2).

The majority of wireless networks in use nowadays are still using omnidirectional antennas, i.e., the radio signal is transmitted in each direction equally (in the idealized case of isotropic radiation) and no other network user is allowed to transmit to avoid collisions, which results in a low spatial reuse and a reduced network capacity. For this reason, several research groups are investigating directional antennas. Advantages such as reduced contention and increased throughput [140], reduced interference [141], minimal packet error rate, as well as improved energy-efficiency [142] were already shown for narrowband applications.

All the aforementioned work is using the classical approach of switchable antennas, which is the least adaptable version of directional antennas, as shown in Figure 15. Antenna systems with a higher level of adaptability, such as smart antennas, and their design challenges are presented in Section 4.3.2. But the usage of switchable and smart antennas, despite their enormous potential, not just complicates the design of the physical layer in terms of size and computational complexity, but even more the design of the upper layers, e.g., the MAC layer [143]. Most MAC protocols are indeed using CCA to detect if a channel is free and packets can be transmitted. Also the receiver has to sense the channel and, in the case of an incoming message, has to wake up the CPU. However, the receiver does typically not know the direction of an incoming message, which is why it either activates all antennas (and hence loses the advantage of directionality), or it activates the beams one after each other (which comes at the price of a higher power consumption and latency). This implies that the antenna beam has to be focused in the appropriate direction before the transmission and reception of packets in order to reach the highest quality of the communication link and escape interference. This task is even more challenging in dynamic and highly mobile networks with frequent node movements [144].

While setting-up a network, users have no knowledge when and in which direction they have to point their beam. Therefore, when using directional antennas a proper localization of each node is crucial. In this regard, several concepts are presented in Section 3.2 and joint communication and localization is covered in more detail in the next subsection. Besides self-localization, wireless devices also need information about the position of the neighbouring nodes in the network (neighbour discovery). Using directional antennas at the receiver and transmitter increases the complexity of this operation [143].

5.3.7 Ultra-wideband MAC Protocols and Joint Localization and Communication

Several survey papers on existing MAC-protocols for narrowband communication technologies have been published in the last decade [89, 90]. However, only limited work has been published about the influence of higher bandwidth on the design of low-power and reliable MAC protocols. As shown by Radunovic et al. [145], simply reusing MAC protocols that have been originally designed for narrowband systems might not be a good idea. Nevertheless, UWB MAC protocols can benefit from existing narrowband solutions, although the unique characteristics of ultra-wideband have to be properly addressed.

Because of their success in narrowband MAC protocols, it is a logical step to consider CSMA-based protocols also for ultra-wideband technologies. For this purpose, however, achieving accurate clear channel assessment is necessary (see Section 5.1). Typical narrowband receivers perform this by means of energy detection of carrier waveforms, so the channel is considered as clear as soon as the received signal strength is below a pre-defined threshold. This is in impulse radio UWB transceiver systems a challenging task, as the extremely low power density of a UWB spectrum causes an energy level that is typically below the noise floor. Hence, a conventional energy detection method based on a threshold does not work for UWB systems [146]. Consequently, a CSMA-based protocol without the ability to sense the channel results in a simple ALOHA-based protocol. As an alternative CCA procedure for UWB systems, the received preambles that are sent in IEEE 802.15.4 packets for synchronisation and channel estimation can be used as an indicator for an ongoing transmission [111]. Such a preamble-detection-based CCA technique is presented by Qi et al. in [146]. Preamble symbols are inserted also in the header and payload parts of the IEEE 802.15.4 packet. This technique was adopted by the IEEE 802.15.4a standard.

Joint localization and communication. In many applications for the Internet of Things, knowing the exact position of wireless nodes and their neighbours is a key aspect. Several measurements and sensor data collected from deployed wireless devices, indeed, just make sense if they include temporal and spatial information. However, RF-based narrowband localization technology cannot provide enough accuracy for most IoT applications. That is why current implementations use a radio technology for communication (e.g., BLE, WiFi, and IEEE 802.15.4) and a different, more precise, technology for localization (e.g., ultrasound or light), which unfavorably affects the form factor and costs of the devices. For example, Lazik et al. [147] use a combination of BLE and ultrasound to achieve decimeter-accurate localization.

Ultra-wideband technology can possibly provide a solution for both communication and localization purposes [148] to enable location-aware networking with a single wireless technology. Because of its physical properties, UWB technology has the ability to provide centimeter-accuracy for ranging between nodes, and therefore outclasses all of its narrowband competitors (see Section 3.2.2). The compatibility to the IEEE 802.15.4 standard makes it suitable for communication purposes. Still, UWB transceiver manufacturers typically motivate developers to use their chip either for communication or ranging, one at a time. But Alcock et al. [149] have already shown that also synchronous communication and positioning is possible by using specialized ranging packets. They have modified the contention-based low-power MAC protocol *FrameComm* to make also use of distance measurements. This has the advantage that ranging does not consume additional energy and does not degrade the throughput, because existing messages are used for calculating the distance. Additionally to the communicating nodes, also other devices in the network overhear the communication and can react with a ranging acknowledgement. In this way, ranging information to more than one node can be collected. Another location-aware UWB MAC protocol is presented in [150]: the proposed protocol (PMAC) is TDMA-based, distributed, and supports a dynamic network topology.

6 Conclusions and Future Work

The design space presented in the previous sections has shown the gradual shift of the research community towards highly-configurable solutions targeting the vision of fully-cognitive systems. This shift allows to design IoT systems that can satisfy the stringent requirements imposed by safety-critical applications on a large scale. Furthermore, the community also started to increase the bandwidth and exploit the resulting high time resolution for improved ranging and localization applications. Although the employment of ultra-wideband and highly configurable systems is challenging in terms of hardware requirements (as shown in Section 4), the research in the networking domain should expand to this area.

Indeed, despite the enormous amount of techniques and technologies that have been proposed so far, still significant work remains to develop energy-efficient fully-cognitive radios and protocols. Especially in the networking domain, as shown in Figure 15, there is still significant room for future work in the region of higher bandwidth and higher configurability, which would push the dependability of IoT communication even further. Towards this goal the author's research is aiming at employing location-resolved models of the environment together with adaptive ultra-wideband radio front-ends (i.e., tunable filters and antennas) to support low-power operation and to increase reliability on a large scale [2]. By mapping the problem to a model-predictive control system that includes the adaptable radio front-ends, physical layer signal processing for environment modeling and localization, and communication protocols for distributed control of the radio transceivers, we can gain control over and satisfy the required dependability attributes. The low-cost and low-power UWB transceiver DecaWave DW1000 [113] enables the use of UWB technology in IoT deployments. In [151] this device was analyzed in terms of localization performance in comparison to a high fidelity measurement system. As an initial step, the authors proposed the application of a switchable UWB antenna system to enhance IoT communication and localization [85] and showed its potential for multipath-resolved positioning [41]. Future work will focus on extending the capabilities of this RF front-end by using antenna arrays to decrease the degrees of freedom and provide a higher form factor. Furthermore, the antennas will be combined with tunable filters.

As shown in Section 4, in the hardware domain the efforts are leading towards SDR/CR-based transceivers for IoT nodes [67, 152]. These nodes will then operate by dynamically sensing the frequency spectrum, finding the available spectrum bands in a target spectral range, and then transmitting immediately without introducing harmful interference to other nodes. Consequently, this allows efficient energy use of RF devices, which results in a high availability by maximizing the lifetime of IoT nodes [46].

This book chapter illustrated the complexity of providing dependable communication and localization for future IoT applications and emphasized the need for close cooperation between different domains, like signal processing, microwave engineering, and networking. Furthermore, aiming towards highly-configurable and cognitive techniques as well as higher bandwidth was motivated by highlighting that current and past research shows a substantial gap in that area.

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