Introduction to DASH7 Technologies

1st Edition

Author: JP Norair
Date: 16 Mar 2009

Abstract

DASH7 is a new, market alliance with the goal of increasing the market size for ultra-low-power wireless product lines by cultivating a global network of partners in this space. As the name hints, the basis for DASH7's goal is with the ISO 18000-7 standard for low power RF. Together, DASH7 partners affectively address interoperability as well as the development and ratification of improved functions into the standard.

In this series of whitepapers different aspects of DASH7's technological agenda will be addressed. The topics include: low power RF technical overview, ISO 18000-7 technical overview, supplemental usage of low frequency (LF), and RTLS.

1.0 Introductory Notes on DASH7

The goal of DASH7 is to expand the market for low power wireless technologies by leveraging ISO 18000-7 ("DASH7" itself is a loose acronym that stands for "Developers' Alliance for Standards Harmonization of ISO 18000-7"). Partnerships among technology companies, product companies, and end-users will have to be formed in order to accomplish the goal, and we can expect that soon after these partnerships begin to bear fruit, new feature requests will come from all kinds of players involved.

The methods by which feature requests may be integrated into the DASH7 interoperability matrix – and ultimately ratification into the ISO 18000-7 standard itself – are not within the scope of this white paper, but let it be said that there are big expectations for ISO 18000-7 to evolve through the integration of technologies from all interested partners.

1.1 About the Author

This series of whitepapers is authored by JP Norair, who, at the time of writing is a Sr. Applications Engineer at Savi Technology, Inc and co-chair of the DASH7 Technology Working Group. JP has a bachelors' degree in electrical engineering from Princeton University followed by several years industry experience working with passive and active RFID systems. On the side, JP used to be very interested in image processing but has lately shifted interest to electrical properties of materials.

1.2 Editions

Future editions of this document will include chapters on:

- Technical overview of ISO 18000-7
- Supplemental usage of low frequency (LF)
- Real time location system (RTLS)

Contents

2.0 Low Power RF Technical Overview

This section is targeted towards marketers looking to get up to speed on low power RF technologies as well as engineers who expect to be developing DASH7 products. In order to accommodate both audiences, an appendix containing technical details follows the chapter.

2.1 What "Low Power RF" is All About

2.1.1 Defining "Low Power"

The obvious: a solution where the RF transceivers use a minimum of energy to communicate with each other, and where periods without communication are characterized by a minimal amount of energy spent idling. To quantify this statement for 2009, a low power RF technology worth its salt has no problem operating at an average current draw under 0.1 mA and a max current draw under 50 mA. Some technologies achieve far lower figures; for example, a well-conceived ISO 18000-7 solution can easily average under 0.05 mA and max under 20 mA when using a low-leakage lithium battery (see table 2.2a).

2.1.2 Defining "RF"

RF stands for "Radio Frequency," and it is used to mean just that. The nuance here has more to do with the application than the method of communication. Low Power RF products need:

- RF silicon parts, ideally with as much integration as possible (i.e. a single chip is better than two chips).
- Power supplies, which are usually batteries. Recently, no shortage of attention has been paid to so-called "energy harvesting," where the idea is for the low power RF device to absorb energy from its environment.
- A microcontroller, which contains a small CPU and memory. Again, integration is important. For 2009 and beyond, designers should expect RF silicon and the microcontroller to be in one package.
- Some kind of antenna for conveying the RF energy.
- Optionally sensors, which are typically silicon parts themselves and hence also benefit from integration.

2.1.3 RFID

In the most basic sense, RFID (Radio Frequency Identification) encapsulates several low power RF technologies and product lines. These are referred to as "active RFID." In the other corner is "passive RFID," whose inherent asymmetry makes it a poor example of low-power; it requires a very high-power transmitter (often called an interrogator) while the transponder (tag) must exhibit very low power characteristics. These systems do not require batteries in the transponders, which, behaving in a similar way to RADAR, reflect and modulate the incidental signal from the interrogator. No one considers RADAR to be a low power technology – even though RADAR targets do not contain batteries – and neither should they consider passive RFID a low-power technology.

Of course, logical arguments do not always win. Market forces have led to confusion when it comes to RFID. The general perception among laymen and even some self-styled industry experts is that passive RFID embodies the general term, RFID. For this reason, we also will attempt to divorce ourselves from the practice of using the term "RFID" with respect to any low-power RF system.

2.1.4 BLAST

DASH7 has been designed to operate using the "BLAST" concept: Bursty, Light-data, ASynchronous, Transitive. Despite being another acronym of questionable genuineness, BLAST does actually correlate to the DASH7 operational philosophy on a one-to-one basis:

- Bursty: Data transfer is abrupt and does not include content such as video, audio, or other isochronous (i.e. streaming) forms of data.
- Light-data: In conventional applications, packet sizes are limited to 256 bytes. Transmission of multiple, consecutive packets may occur but is generally avoided if possible.
- Asynchronous: DASH7's main method of communication is by command-response, which by design requires no periodic network "hand-shaking" or synchronization between devices.
- Transitive: A DASH7 system of devices is inherently mobile. Unlike other wireless technologies DASH7 is upload-centric, not download-centric, so devices do not have to be to be managed extensively by fixed infrastructure (i.e. base stations).

Most wireless technologies throughout time have been designed to replace wired networks (it's called "wireless" after all). Wired networks cannot possibly be conceived to meet the needs of DASH7 applications. DASH7 applications are inherently mobile; devices and infrastructure can be mobile, and it is even difficult to consider an alternate, wired network that could provide roughly similar function.

BLAST as a concept fits into this application model, and it suits low power RF extremely well. DASH7 systems should be understood not as conventional networks where the organization is top-down and hierarchical, but instead as somewhat structureless pools of data which were not previously accessible. We call this concept "ambient data," and it is possible largely by the "transitive" attribute. Virtues of simplicty are able to cascade into all other areas of operation because we are able to ignore the cost of maintaining a top-down hierarchy structure. Where other standards have floundered by their lack of focus, these BLAST design principles dramatically clarify the requirements for implementing an aggressively low power RF standard.

2.2 A Survey of “Low Power” RF Standards

2.2.1 Standards and Their Proponents

There are many self-proclaimed “low power” RF products that have been available for years. At least by their names, most of them should be familiar to anyone who keeps in touch with the high-tech economy. The successful standards are backed by a couple of industry heavyweights, but when it comes to low power operation, not all of them are in the same league.

2.2.2 Strong Standards are Important

ISO 18000-7 is unique among all of the standards described herein because it is an ISO standard. While this is a seemingly redundant observation, it does emphasize both the ability to enforce the standard globally as well as the responsibility of its backers to cultivate effective structures for compliance and interoperability. Only with mixed success have the alliances that govern many of these standards been able to enforce compliance, interoperability, and industry cooperation:

- The WiFi Alliance has been generally successful but the internal battle between versions a and g cost members unneccessary time and money. The draft-n process is another example of mediocre cooperation in standardization.
- Since ZigBee’s inception, the alliance has had difficulty in getting solutions developers to adopt ZigBee for low power RF. The IEEE is now attempting yet another variation (f) in hopes of success [1].
- Proprietary technologies deny their markets entirely of all of the re-sources available to technologies supported by alliances, including interoperability.

ISO 18000-7 honors the ISO tradition by granting explicit terms of what complies and what level of functionality is mandatory, and also stipulating explicit compliance metrics via ISO 18047-7. Of course, it is possible to maintain a strong standard without ISO: Bluetooth is a good example of an older standard whose SIG has been successful in cultivating a sound level of interoperability as well as a marketplace full of low-cost silicon amid a constantly evolving strata of feature-sets.

2.2.3 Simple RF Interface, Low Power

Despite evidence that the “usual suspects” from table 2.2a have observed varying degrees of success as standards, there is room in the marketplace for all of them. They each perform certain tasks unquestionably better than do the others. However, when it comes to delivering an industrial, low-power RF system, it is hard to beat ISO 18000-7. It has been designed to perform a small but well-defined set of features with maximal efficiency, these being inventory collection and bursty, asynchronous communication between small transceivers (e.g. tags) and infrastructure products. In comparison the other standards seem less focused.

Table 2.2a should open up the floor for some debate. The bandwidths, channels, and data rates are more or less objective. The operating power figures are more subjective, but they are founded on both empirical research (they are advertised attributes of real products) and assumptions cataloged in section 2.4.4.

Operating Electrical Current

The “best in breed” chips that were analyzed may not exemplify ceteris paribus comparison, but they are all state of the art for their particular technology. Short of a breakthrough, future advances for each technology can be expected to improve along the same ratios that the existing implementations exhibit.

As we can see, the existing best in breed implementation for ISO 18000-7 has an impressively miniscule power budget. This is in part due to its use of the 433 MHz frequency band because, from a scientific standpoint, there are some inescapable rules when it comes to electric current requirements for semiconductors:

- In any given RF system there's a point at which increasing maturity of the silicon delivers marginal returns on reducing system's current draw. This is due mainly to electric current leakage. [2]
- No matter how mature the digital silicon, amplifying the RF circuits will always expend more energy when the bandwidth is large and the band is high. This is due to the dynamic characteristics of the silicon-CMOS transistor topologies used in practically all modern, integrated RF chips. [2]

The combination of these two rules yields this corollary: for a given application, if in place of wideband, higher data rate, higher frequency RF systems it is realistic to substitute narrowband, lower data rate, lower frequency RF systems, the latter will always yield the lower system power.

Communication Range:

The standards above do not all put the same limits on transmit power. For Bluetooth, ZigBee and ISO 18000-7, 0dBm @ 50 Ohms is the reference value which yields the nominal range as discussed in product or standards literature. It is certainly possible to improve range by increasing the transmission power or increasing the sensitivity of the receiver, although governments often have regulations

	Low Energy Bluetooth	DASH7 (ISO 18000-7)	Low Power Wi-Fi (IEEE 802.11)	ZigBee (IEEE 802.15.4)
General Specifications				
Frequency Range	2.402-2.482 GHz	433.04 - 434.79 MHz	2.40-2.50 GHz	2.402-2.482 GHz
Discrete Channels	3	1 to 5	3	16
Max Channel Bandwidth	~8 MHz	0.5 to 1.75 MHz	22 MHz	5 MHz
Modulation	GFSK	FSK or GFSK	CCK /QAM64 (b/g)	QPSK
Nominal Data-Rate	1 Mbps	27.8 Kbps	1 Mbps	250 Kbps
Est. Max Potential Data-Rate*	1 Mbps	100 Kbps	54 Mbps	500 Kbps
Nominal Range (0 dBm)	10 m	250 m	25 m	75 m
Standard Related				
Alliance & Standards Bodies	Bluetooth SIG	DASH7 Group, ISO	WiFi Alliance, IEEE	ZigBee Alliance, IEEE
Major Proponents	Sony-Ericsson, CSR, Casio	Savi, US DoD	Cisco, Broadcom	Formerly Philips
Protocol (MAC) Complexity	Low	Low	High	Med to High
RF layer (PHY) Complexity	Low	Low	High	Med
Best-in-breed Solution Power				
Sleep Power	8 µW	4 µW	10 µW	4 µW
Receive (RX) Power	28.5 mW	7.5 mW	90 mW	84 mW
Transmit (TX) Power	26.5 mW	31 mW	350 mW	72 mW
Average Power for ten (10) 256-byte messages per day†	50 µW	42 µW	570 µW	414 µW

Table 2.2a: the cream of the low-power RF crop, compared. In order to honor confidentiality agreements, the components analyzed for the best-in-breed solutions must remain anonymous.

* Estimated maximum given by the channel bandwidth, data encoding, and/or modulation method. For frequency-hopping standards this will obstruct the ability of the radio to hop (ZigBee).

† Power estimation technique is analyzed in 2.4.4

regarding allowable transmit power. Incidentally, both of these techniques also increase the power requirement of the system.

2.2.4 Simple Protocol, Low Power

Referring back to Table 2.2a, we can see that in each solution the power differs for receive, transmit, and sleep modes. Techniques for optimizing low-power RF systems always seek to maximize the amount of time spent in sleep mode, or, from another perspective, minimizing the amount of time spent in active modes. More-so than data-rate, the protocol is the means by which time spent in active modes can be determined. Good low-power RF solutions have protocols that do not specify extraneous features. In other words, these solutions are defined by considering not what features you could use but instead what features you could do without.

Of the depicted solutions, the simplest protocols belong to ISO 18000-7 and low energy Bluetooth (aka wibree), although they operate very differently. The diagram below intends to show time spent in active modes vs. sleep for these two protocols, while also showing the amount of power consumed during each operational state. As we can see, low energy Bluetooth does not adhere to BLAST principles, but because it is just a wire-replacement technology it can succeed nonetheless.

The other technologies, ZigBee and WiFi, have protocols that are complicated enough that a diagram such as the ones below cannot come close to representing the many modes of operation. In section 2.4.4 we show how ZigBee cannot deliver low-latency (BLAST-like) behavior without expending a lot of power.

2.2.5 Symmetric Protocol, Flexible Use

A symmetric protocol is one where there is little or no difference between the way any sort of device communicates with any other sort of device. Symmetry does not necessarily make a standard low power optimized, but it does allow for more flexibility or innovation in the way that standard's technology is implemented and ultimately used. ISO 18000-7 uses a symmetric protocol, and certain modes of ZigBee are symmetric, as well. Low energy Bluetooth, WiFi, and other modes of ZigBee, on the other hand, are asymmetric as they are predicated on the existence of base-station or coordinator type devices.

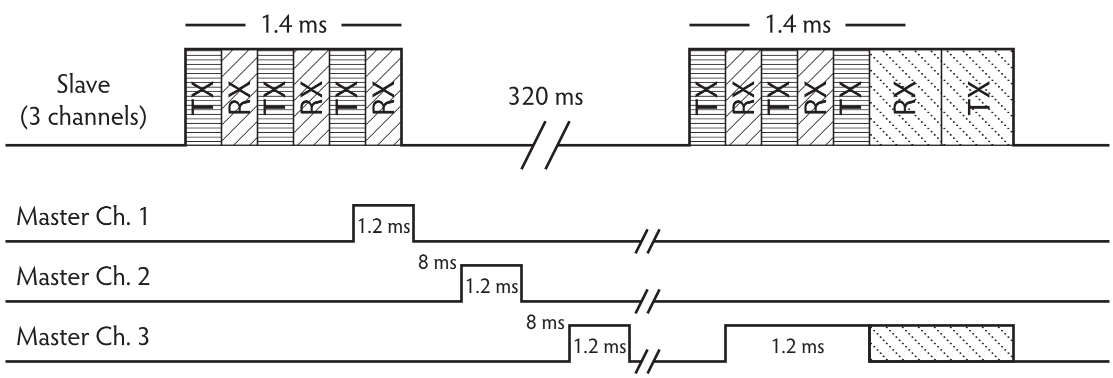
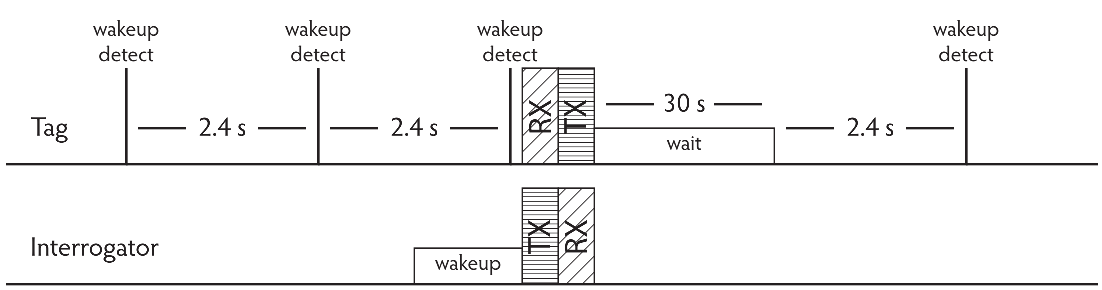


Figure 2.2a: Above, an example of a "low energy Bluetooth" timing diagram. It follows an asymmetric master-slave topology designed to minimize the amount of time the slave spends in an active mode. The master is not always well suited to be a low-power device. Below, an example of an ISO 18000-7 timing diagram. A tag or an interrogator may be easily implemented as a low-power device, because their function is nearly identical, or symmetric.



2.3 The Technical Merits of UHF vs. Microwave

Given the number of products in the 2.45 GHz band (the "microwave" band), it may seem counter-intuitive to heap praise on 433 MHz to 900 MHz bands (UHF). There will always be tradeoffs when selecting technologies, and this section will examine those. By the end, it should be clear that simpler, lower power UHF systems can outperform more complex 2.45 GHz systems for BLAST type applications.

In Table 2.3a is a matrix of tradeoffs that engineers (and some marketers) must face when architecting an RF solution. Keep these relationships in mind throughout this section.

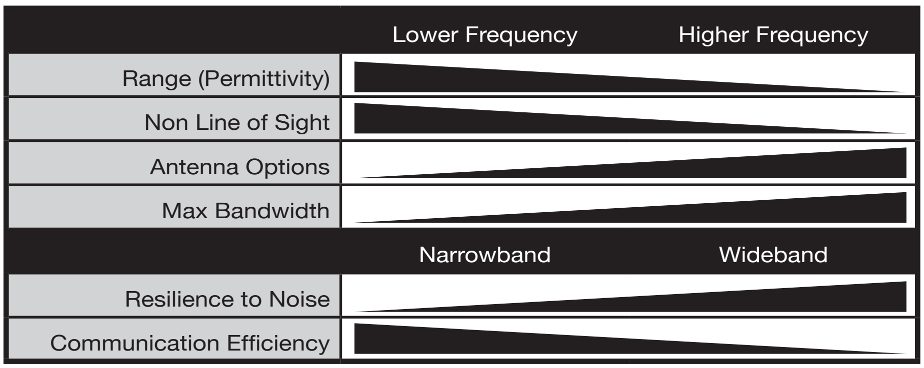


Table 2.3a: Tradeoffs between different RF options. Depending on the needs of the target markets, the optimal solution will differ. For DASH7's target markets, we argue that it uses the optimal frequency and bandwidth (bandwidth ≠ data rate!)

In addition to the metrics in the table ...

- Lower Frequency solutions with small bandwidths are simple.
- Simple radios are cheap.
- Simple radios use less power.

2.3.1 The Friis Equation

It the form below, the Friis equation solves for free-space communication range when receiver sensitivity (P_r), transmission power (P_t), receiver antenna gain (Gr), transmitter gain (G_t), and wavelength (λ). The range value derived here is highly optimistic for real world scenarios – at least because it doesn't account for bandwidth or modulation – but more refined models of the Friis do exist and the ranges values these produce remain proportional to the basic form, nonetheless. The basic relationship is that as frequency goes up, range goes down.

$$Range = \frac{1}{\frac{4\pi}{\lambda}\sqrt{\frac{P_r}{P_t G_t G_r}}}$$

Table 2.3b shows how frequency relates to range and requisite antenna gain. The first three rows show that a 433MHz radio can have the same range as a similar 2.45GHz radio even if the 433 MHz antenna system is only 3% as efficient. This is important in real world applications where antennas are routinely de-tuned by environmental factors, often quite severely. In the lower rows, typical book values are plugged-in to show the theoretical maximum range of each researched solution at 1 mW transmit power (0 dBm). These values deviate from the nominal values of table 2.2b due to many factors: signal bandwidth, modulation, noise, and interference to name a few (a more thorough study of these effects is available in the appendix).

Solution	λ (cm)	Pt/Pr (dBm)	GtGr	Range (m)
Reference 433MHz	69	S	0.03A	R
Reference 900MHz	33	S	0.13A	R
Reference 2.45GHz	12	S	A	R
Typical DASH7	69	-100	0.25	4500
Typical Bluetooth	12	-83	0.7	160
Typical WiFi	12	-90	0.7	360
Typical ZigBee	12	-100	0.7	1100

Table 2.3b: Friis relationships at different frequencies

2.3.2 More Radio Wave Physics

From the Friis equation of the last section one can determine that, with all else equal, the lower frequency wave has a greater ability to penetrate space than does the higher frequency wave (i.e. it has a longer range). This relationship is also a topic of quantum physics. Early quantum physicist Louis De Broglie postulated that lower frequency waves can be represented by smaller particles, whereas higher frequency waves are represented by larger particles.

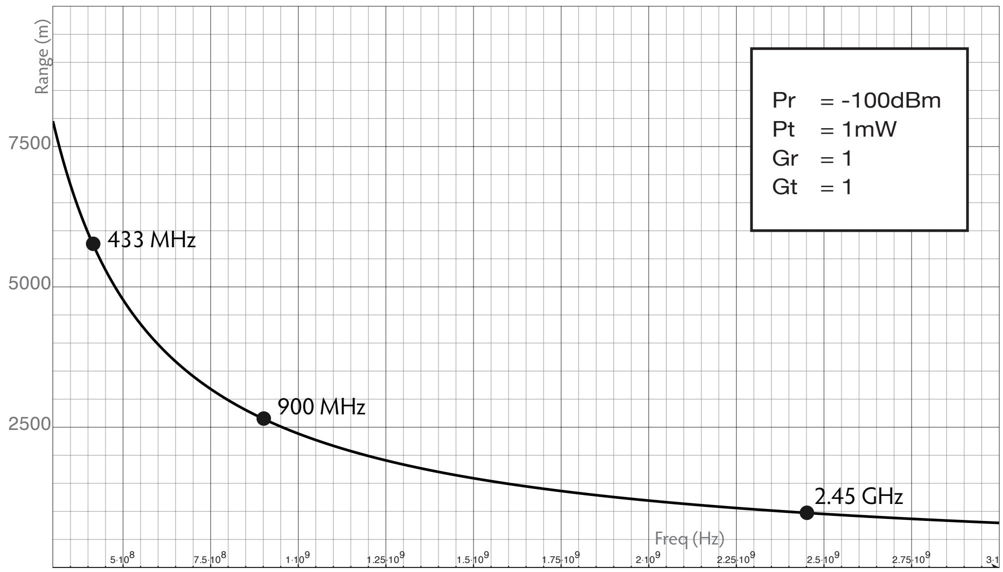


Figure 2.3a: Friis-derived optimum range assuming identical sensitivity, power, and antenna gain in each system.

The most telling feature of this chart is the non-linearity. 433 MHz signals propagate much better than those at either 900 MHz or 2.45 GHz.

It's beyond the scope of this paper to examine why, but the fact is that the smaller particles are more mobile carriers of energy and travel farther. A case in point is the US Navy's radio for communicating with deep-submerged submarines anywhere in the world. It runs out of a station in Michigan at the astonishingly low frequency of 76 Hz, and its waves (or particles) penetrate the Earth itself.

Besides their better permittivity characteristics, lower frequency waves have longer wavelength and diffract comparatively easily. (Diffraction is also outside the scope of this paper). The important thing to remember is that when encroached by interfering objects, longer wavelengths will more easily "bend" around these obstacles as light bends when put in proximity to a lens. This property contributes to the non-line-of-sight attribute in table 2.3a.

2.3.3 Antennas

It would seem from the last sections that the world is crazy and that we should all be using a lot more low frequency radios. While this is probably true in a general sense, there is one major drawback to low frequency aside from reduced maximum data rate: the antenna.

The classic antenna and one by which all others are judged is the half-wave dipole. It is similar in construction to the "rabbit ears" TV antennas (the kind the next generation of engineers will never have as a mental reference). This antenna is excellent in most respects. The trouble is that below 1 GHz, the half-wave dipole is simply not an option for smaller products. At 433 MHz, for example, a half wave dipole is 35 cm long. Even when using slightly less efficient folded-dipoles, the antenna preferred by most 2.45 GHz radios, the size is too big for most use below 1 GHz.

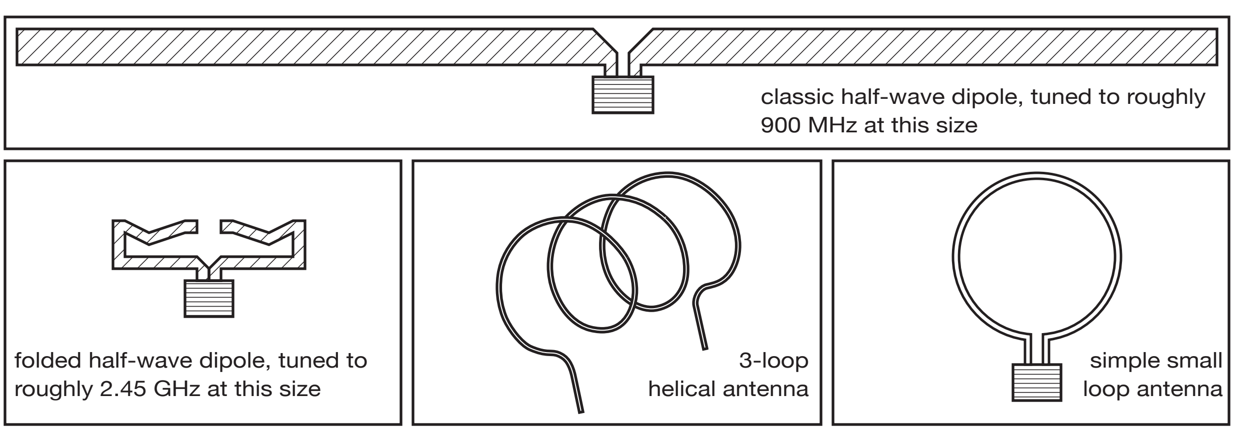


figure 2.3a: pictorial examples of common antenna designs

Fortunately, there are quite a few designs for small antennas workable at lower frequencies. Some of them even come close to matching the folded dipole in performance. A common design is the small loop antenna, which depending on the design typically have efficiencies between 1/3 and 1/8 of the half-wave dipole [3] (section 2.4.5). Small loops are popular because, in addition to being small and compact, they are easy to design, cheap, and easy to implement within a printed-circuit board. The "typical" DASH7 implementation from table 2.3b used a small loop system listed as 1/4th as efficient as the half-wave dipole system, even though more efficient antenna designs are available for use at 433 MHz

One such well-known antenna design is the helical loop antenna. It is, as you might guess, a series of small loop antennas. Helical antennas require slightly more know-how to design than simple loops do, and they can cost more, but the cost difference is rarely noteworthy for applications at 433 MHz. Common characterization models for Helical antenna designs show that a compact design, tuned at 433 MHz, is roughly 2/3 as efficient as a half-wave dipole (see section 2.4.5). Further performance improvements may be achieved by inserting a ferromagnetic core into the helix, particularly with smaller loop helixes [3].

2.3.4 Communications Theory 101

It has now been established that, from a purely scientific approach, lower frequency radio waves are more reliable than higher frequency waves are at delivering a signal over range, line-of-sight or otherwise. Communications theory is an engineering discipline focused on attaching rules (i.e. math) to phenomena involved in sending data via radio signals. When given a problem to solve, communications engineers go back to the rules to determine the best solution. There are always tradeoffs. Nonetheless, the primary solutions criteria depend on the following:

- Allowable minimum data rate
- Allowable signal to noise ratio
- Allowable complexity of transmitter
- Allowable complexity of receiver

Data Rate

In today's world, data rate is often confused with the term "bandwidth." The two are related, but they are not the same. Data rate is a digital phenomenon, expressing the amount of bits that a communication system can deliver in a given amount of time. Bandwidth is the frequency range between which a signal's energy can be realistically confined. Some modulation techniques are more efficient than others at cramming data into available bandwidth. Generally speaking, the more complex the modulation the more efficient it is at cramming raw data into a given amount of bandwidth, but sometimes further means are used to spread the band (i.e. spread spectrum technologies) in order to improve tolerance of noise. The latest exotic and complex methods manage to do both, although they are completely unsuitable for low power RF because the transmitters and receivers are too complex.

Signal to Noise Ratio

Maximizing signal to noise ratio (SNR) is a pursuit in which communications engineers put in a lot of time. Noise refers to any energy received [by the receiver] that does not come from the appropriate transmitter. Noise can be hard to predict, but there are some guidelines. A typical model for noise is additive gaussian white noise, as this is how "static" is modeled. It exists wherever there are charge carriers moving around randomly, for example in an antenna, and is often called thermal noise. The larger the bandwidth of the communication, the greater the received noise.

There are other types of noise, too, and they all have one thing in common: the larger the bandwidth, the greater the potential for noise ingress. We are interested, however, in signal to noise ratio, not just noise, and by increasing the bandwidth through modulation or encoding techniques it is possible to boost the signal energy in greater proportion than noise and interference. This is the basis for improving SNR and decreasing the affect of noise.

By convention, DASH7 uses a marginally wideband FSK modulation (check appendix for more on modulations). It is set up to provide reasonably good resilience to noise and interference without expending too much energy doing so. Low energy Bluetooth's modulation is very similar. ZigBee, on the other hand, uses a more complex modulation called QPSK that manages to be slightly more efficient at cramming data into bandwidth as well as better suited to delivering higher SNR. The added complexity, however, comes not without a price.

Simplicity vs. Complexity

Limits on targeted solution cost, development cost, and power requirements force communications engineers to be clever. Often we can evaluate two technologies, one simple and one sophisticated or complex, where the performance gap between the two can be closed by enhancing other areas of the total solution.

One good area of study is the receiver. At the cost of higher power requirements, a more advanced modulation scheme may prove to have superior SNR than a simpler one, and a higher data rate may allow error correction coding to be part of the message. However, by changing the carrier frequency of the signal or by taking special attributes of the signal into account, the simpler solution may even outperform the more complicated offering. Without considering interference, Section 2.4.3 shows how ISO 18000-7 offers a greater SNR link budget than does the more complex, more sophisticated IEEE 802.15.4. When interference is in fact considered, the busy 2.45 GHz band has an increasingly negative impact on the performance of IEEE 802.15.4 vs. ISO 18000-7, and it actually becomes distrastrous if newer 802.11n networks are in place [11] [12] [13] [14] [15].

Performance enhancements like these that trickle-down from total system design can be relied upon when a technology is well defined to attack a focused set of problems. For example, in [9] we can see how design simplicity is maximized to solve problems of communication with small satellites. Section 2.4.3 analyzes how a simple, clever solution (ISO 18000-7) can excel in BLAST type applications, one of which is even validated in [10]: RF performance of embedded devices in shipping containers.

The basic understanding is that ultimate performance for general purpose solutions will always require a complex system design, it will be expensive to develop, and it will be very difficult to test for and enforce interoperability. In such cases where a focused design philosophy can be applied – where simple, accessible technology can meet performance requirements – engineers can quickly develop products, testers can easily achieve interoperability, and marketers can immediately target users. It is the "prisoners dilemma" for wireless standards: pursue the holy grail or pursue the strategy of most probable success. Simplicity and focus lend themselves to success.

2.3.5 Conclusion

So, "why UHF?" If the solution doesn't need high data rate and can be band limited (partly a function of data rate), then using UHF makes a lot of sense. Compared to 2.45 GHz systems, UHF systems operate better in non-line-of-sight conditions, they use less power, and they are so much more permissive that they can still offer superior range even when using suboptimal antennas. For the bursty, asynchronous type of solution that DASH7 targets, the UHF band is the perfect choice to deliver the long range, highly reliable signal it needs, all the while preserving a tiny power budget.

2.4 Technical Appendix

The appendix exposes a summary of the canonical engineering principles that were used to analyze the solutions presented in the main chapter.

- Sections 2.4.1, 2.4.2, and 2.4.3 come to the conclusion that future ISO 18000-7 development may seek to include better means for error correction and post-filtering, despite ISO 18000-7's already formidable SNR link budget. All references from these sections are either original or may be attributed to [5], unless explicitly noted.
- Section 2.4.4 analyzes the criteria used to estimate power requirements for ZigBee, low energy Bluetooth, low power WiFi, and ISO 18000-7
- Section 2.4.5 shows a model used to evaluate helical antennas.

2.4.1 Power Spectral Density

The first step in analyzing wireless standards is to model their power spectral densities. After this, we can analyze the PSDs and determine the best methods for receiving and filtering in order to maximize SNR.

Low energy Bluetooth

Low energy Bluetooth uses GFSK modulation with σ =115kHz, and frequency space between subcarriers is 1 MHz (modulation index = 0.5). The data-rate is 1Mbps (2 Mbaud). as the datastream is manchester encoded.

ZigBee

ZigBee uses the 802.15.4 PHY and MAC, which is more complicated than those used by ISO 18000-7 or low energy Bluetooth. The modulation is O-QPSK with a symbol rate of 1 MSps, used to transceive 16 different pseudo random bitstreams. The actual data rate is 250kbps.

ISO 18000-7

ISO 18000-7 may use GFSK modulation, and we will consider a GFSK modulation with σ = 4kHz. The band space between the subcarriers is 100kHz (mod. index = 1.8), as the datastream is manchester encoded at 27.77 kbps (55.55 kbaud).

$$G(f) = G_+(f) + G_-(f) \qquad \text{eq. 2.2}$$

$$G_\pm(f) = A^2 2T\left(\frac{\sin(2\pi T(f \pm f_c))}{2\pi T(f \pm f_c)}\right)^2 \qquad \text{eq. 2.3}$$

Eq 2.2 forms the power spectral density for the real and complex frequency components, using equations 2.3 or 2.4. QPSK power spectral density may be modeled by eq 2.3 (this function may also be notated with *sinc* nomenclature). GFSK power spectral density may be approximated by the continuous wave FSK model shown as eq 2.3.

$$G_\pm(f) = \left(\frac{A^2\sin^2(\pi(f\pm f_1)T)\cdot\sin^2(\pi(f\pm f_2)T)}{2\pi^2 T(1 - 2\cos(2\pi(f\pm\alpha)T)\cos(2\pi\beta T) + \cos^2(2\pi\beta T))}\right)\cdot\left(\frac{1}{K}\right)\left(\frac{f_d}{f\pm f_1} - \frac{f_d}{f\pm f_2}\right)^2 \qquad \text{eq. 2.4}$$

$$f_1 = f_c - f_d$$
$$f_2 = f_c + f_d$$
$$\alpha = \frac{1}{2}(f_1 + f_2)$$
$$\beta = \frac{1}{2}(f_1 - f_2)$$

The definitions to the left apply to eq 2.4. In addition, f_c is the carrier frequency, f_d the FSK deviation frequency, and K is a scaling coefficient that may be determined by experimentation.

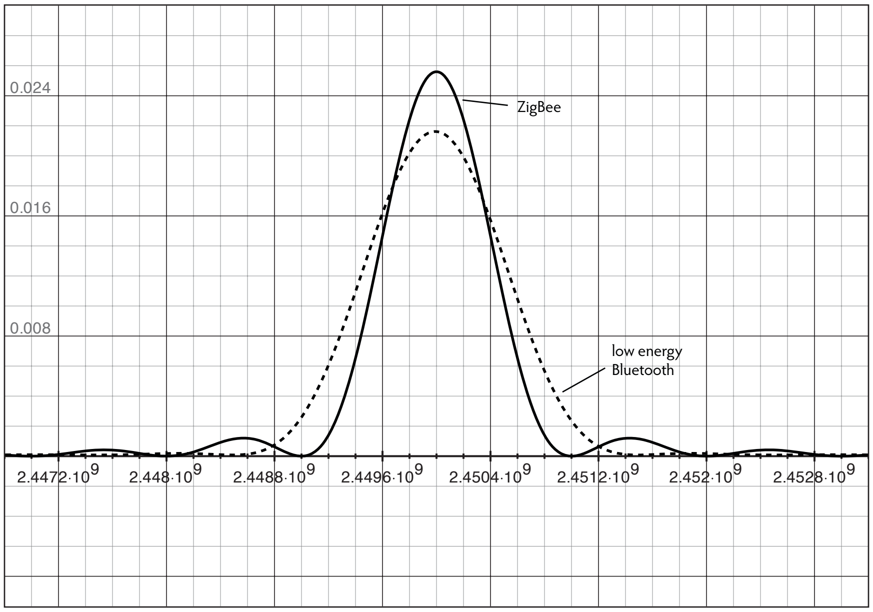


Figure 2.4a: nominal, modeled power spectral densities of a low energy Bluetooth transmission and a ZigBee (802.15.4) transmission.

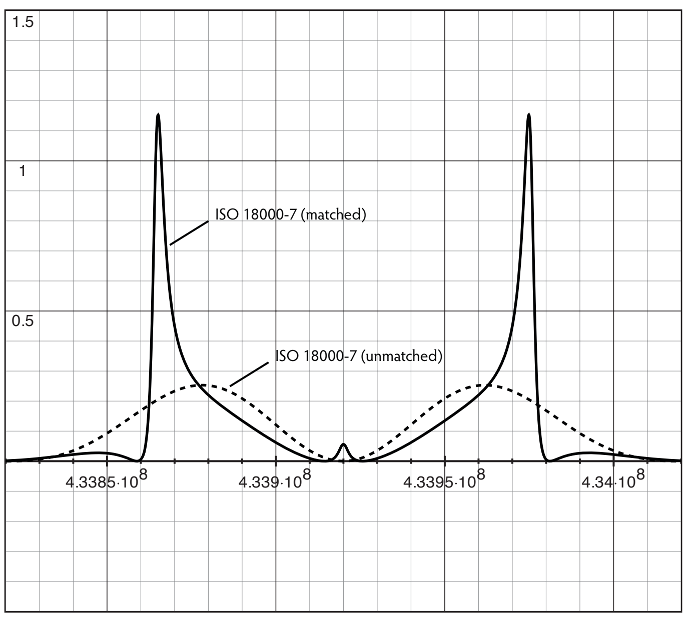


Figure 2.4b: nominal, modeled power spectral densities of an ISO 18000-7 transmisson matched to the specified modulation index of 1.8 and an ISO 18000-7 transmission that is slightly mismatched (modulation index = 2.0).

All power spectral densities (PSD's) from figures 2.4a and 2.4b are plotted on a horizontal axis of Hertz and a vertical axis of arbitrary, relative energy, representative of equal power transmission (nom. 1mW) in all PSD's. Energy values from figure 2.4a may thus be compared to figure 2.4b.

Power Spectral Density Analysis

Figures 2.4a and 2.4b indicate that the power of the ISO transmission is very different in shape than either the Bluetooth spectrum, which uses narrowband FSK modulation, or the ZigBee spectrum which uses QPSK and heavy spreading.

We can assume that channel filtering does exist in each of these solutions, and that it takes the standard approach of passing 90% or more of the band power. In conjunction with figure 2.4b table 2.4a shows that ISO 18000-7 has relatively good in-band power utilization and that it does not, in fact, employ a narrowband modulation. Low energy Bluetooth, on the other hand, does use an especially narrowband modulation, and this should be considered in any study concerning interference. ZigBee employs substantial spectrum spreading techniques and thus has the lowest bandwidth efficiency.

One final observation is the nature of the power peaks at ± 55.55 kHz in the frequency-matched ISO 18000-7 PSD. If special filtering is used, roughly 70% of the power of the ISO signal can be received from only 40 kHz bandwidth – yielding a Hz/bit of 1.44. When using receivers designed to take advantage of this special property, ISO 18000-7 can deliver the interference robustness of a wideband modulation and the bandwidth efficiency (i.e. free-space propagation capacity) of a narrowband solution.

Solution	BW @ ~99%	BW @ ~90%	BW @ ~80%	bit/Hz [90%]
ISO	200k	120k	110k	0.23
ISO unm.	200k	135k	120k	0.21
leB	3M	1.5M	1.3M	0.67
ZigBee	4M	2M	1M	0.125

Table 2.4a: approx. bandwidth at percentages of full spectrum power, and bandwidth efficiency at 90% in-band-power bandwidth.

2.4.2 Improving the Tolerance of Noise

Comparing SNR of different communication systems is a good way to judge their relative effectiveness in delivering data in noisy vs. noise-free conditions. There are only three direct ways to improve SNR: improve the performance of the receiver (typically by changing the modulation), increase the power of the signal, or decrease the level of the noise. Increasing the signal power is out of the question in our study, as notably we are surveying low power technologies but we also must consider local emissions regulations. Changing the modulation is also not something that can be easily accomplished in a standard with a notable installed base, because it leads to fundamental incompatibility. So we are left with the prospect of reducing the impact of noise by filtering, processing, or by improving the receiver's tolerance to noise by coding the signal.

Data coding techniques to improve noise tolerance

By manipulating the message data, redundant data is added to the message in order to improve the ability of the receiver to filter the message. ZigBee uses a method of mapping each 4-bit data sequence in the original message to a unique, nearly-orthogonal 32 bit pseudo-random noise vector, also known as block coding [5]. ISO 18000-7 and Bluetooth use manchester coding to ensure the PSD is independent of the signal, but this technique provides no inherent improvement to noise tolerance.

	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0		16	18	20	20	20	18	16	16	12	14	20	20	20	14	12
1	16		16	18	20	20	20	18	12	16	12	14	20	20	20	14
2	18	16		16	18	20	20	20	14	12	16	12	14	20	20	20
3	20	18	16		16	18	20	20	20	14	12	16	12	14	20	20
4	20	20	18	16		16	18	20	20	20	14	12	16	12	14	20
5	20	20	20	18	16		16	18	20	20	20	14	12	16	12	14
6	18	20	20	20	18	16		16	14	20	20	20	14	12	16	12
7	16	18	20	20	20	18	16		12	14	20	20	20	14	12	16
8	16	12	14	20	20	20	14	12		16	18	20	20	20	18	16
9	12	16	12	14	20	20	20	14	16		16	18	20	20	20	18
A	14	12	16	12	14	20	20	20	18	16		16	18	20	20	20
B	20	14	12	16	12	14	20	20	20	18	16		16	18	20	20
C	20	20	14	12	16	12	14	20	20	20	18	16		16	18	20
D	20	20	20	14	12	16	12	14	20	20	20	18	16		16	18
E	14	20	20	20	14	12	16	12	18	20	20	20	18	16		16
F	12	14	20	20	20	14	12	16	16	18	20	20	20	18	16	

Figure 2.4c: Hamming distance matrix for block codes (0 - F) used by ZigBee (802.15.4).

Figure 2.4c is the result of a computer program written to compute hamming distance between each block code. By inspection we can find that the shortest hamming distance is 12, and by rule a minimum distance decoder can tolerate an erroneous block code that's less than half the hamming distance. In ZigBee this means 5 code errors per block code can be tolerated, yielding an acceptable probability of error of 5/32 (1.56×10^{-1}). Using similar rhetoric we can determine that manchester encoding offers no error correction gain, because the codes have a hamming distance of 2, thus an acceptable probability of error of 0. Instead, acceptable probability of error for manchester encoded data is determined by the length of the transmission, which for 64 bytes data is roughly 10^{-4}.

Some error correction may still be extracted from manchester encoded datastreams by oversampling at the receiver. In the case of a 3:1 oversampler the hamming distance is 6 samples, ideally yielding a maximum acceptable probability of subsample error of 1/3 (3.33×10^{-1}). Given the vast gap between 10^{-4} and 10^{-1}, an improved level of error correction could easily be a future objective for ISO 18000-7.

Noise tolerance of a given data channel

The following treatment considers additive gaussian white noise, which has the two following properties:

- Its amplitude is independent of frequency.
- It results in a gaussian relationship between the probability of a bit error (P_E) and the SNR (eq 2.5).

Given this understanding of noise, the Shannon-Hartley law dictates that the minimum decodable SNR (E_b / N_0) is related to the following equation (eq 2.5):

$$\frac{E_b}{N_0} = \frac{T_b B_N}{P_F}\left(2^{\frac{1}{T_b B_F}} - 1\right) \quad \text{eq 2.5}$$

The curve produced by eq 2.5 (Fig 2.4d) shows the theoretical minimum SNR at which coding can allow for error detection, which is -1.6 dB at its theoretical best. P_F in this case is a power scaling factor equal to the percentage of total signal power passed after all filtering. As usual T_b is, the bit period, B_N is the bandwidth of the received noise and B_F is the total, post-filtered signal bandwidth. Typically, P_F will be 1 and $B_F = B_N$, but clever filtering or processing gain techniques may be modeled by taking into account the impact these have on P_F, B_F, and B_N accordingly.

Solution	P_F	T_b (sec)	B_N (Hz)	B_F (Hz)
ISO	1	18×10^{-6}	120k	120k
ISO filtered	0.7	18×10^{-6}	120k	40k
IeB	1	5×10^{-7}	1.5M	1.5M
ZigBee	1	1×10^{-6}	2M	2M

Table 2.4b: Values used to compute points for each solution shown in Figure 2.4d.

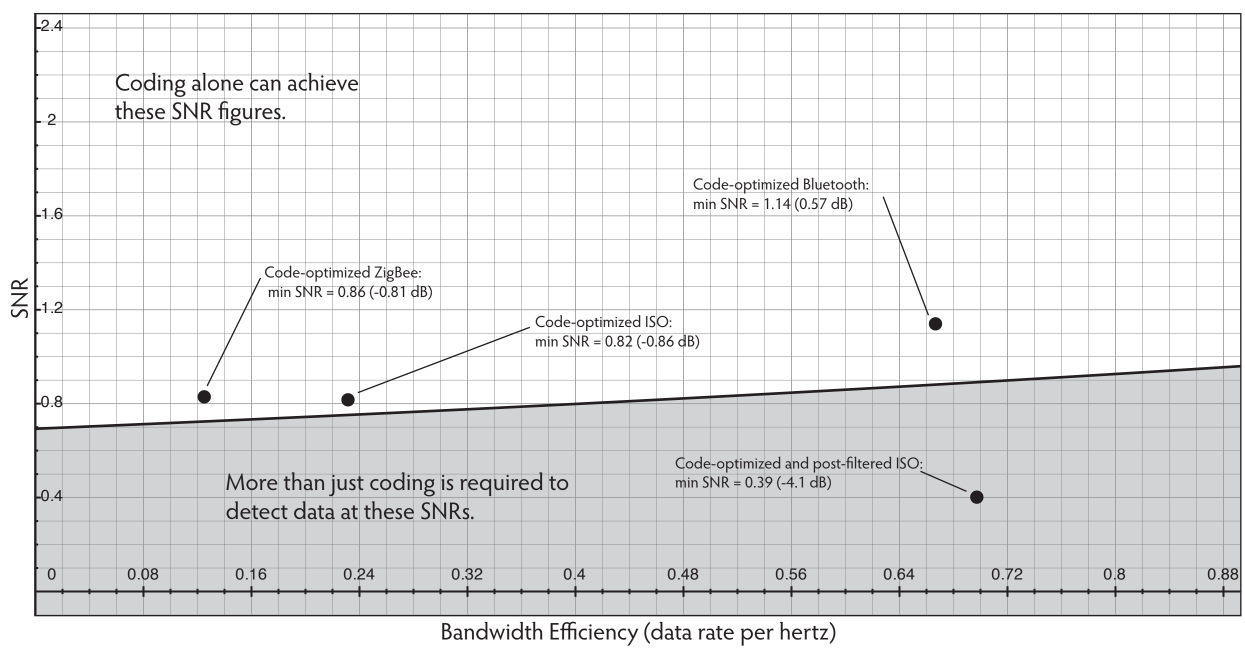


Figure 2.4d: Best case noise tolerance achievable by coding, as well as clever filtering. These data points show figures for a theoretical, optimized coding. Comparing current implementations ZigBee comes closest to theoretical, but the 3.24dB gain achievable in ISO by post-filtering should not be overlooked, either.

Filtering Gain

By filtering the signal within the passband, as made possible by ISO 18000-7's PSD, even greater gain is possible. Of the standards surveyed, only ISO 18000-7 has a noticeable concentration of signal power in a limited amount of its total bandwidth, so likewise it is the only one suitable for passband filtering beyond general channel filtering. Figure 2.4d shows the 3.24 dB advantage ISO 18000-7 can achieve if post-filtered with two, 20 kHz-wide peak detectors.

2.4.3 SNR Link Budgets

The coherent FSK and QPSK receivers used in typical ISO 18000-7, Bluetooth, and ZigBee silicon are well studied. In addition we will consider a non-coherent receiver for ISO 18000-7, as these can be necessary for environments with heavy signal fading.

Table 2.4c shows the results of computations comparing necessary SNR for reliable communication at each solution's max probability of error, determined previously. The message here is that even a non-coherent receiver can be part of an ISO 18000-7 communications link while exhibiting similar or even superior communication reliability as the ZigBee solution, despite the ZigBee solution's aggressive error correction coding. If oversampling or another error correction mechanism is used to boost noise tolerance on the ISO 18000-7 receiver, the results can be even more compelling.

Solution	Base SNR (relative)	max P_E	min SNR @ max P_E	Link Budget (relative)
ISO 18000-7	*0 dB*	10^{-4}	11.4 dB	*0 dB*
ISO, post-filtered	**3.24 dB**	10^{-4}	11.4 dB	**3.24 dB**
low en. Bluetooth	-11 dB	10^{-4}	11.4 dB	-11 dB
ZigBee	-12.2 dB	$\mathbf{10^{-1}}$	**-0.4 dB**	-0.4 dB
ISO (NC)	0 dB	10^{-4}	12.3 dB	-0.9 dB
ISO, post-filt (NC)	**3.24 dB**	10^{-4}	12.3 dB	2.34 dB

Table 2.4c: Comparison of SNR and probability of error among solutions, factoring in the relative noise power. ISO 18000-7 has the best performance in the presence of noise, even quite respectable when using non-coherent (NC) receivers.

$$P_E = \left(\frac{1}{\sqrt{2\pi}}\right) \int_{\sqrt{SNR}}^{\infty} \left(e^{-\frac{t^2}{2}}\right) dt \quad \text{eq. 2.6}$$

$$P_E = \left(\frac{1}{\sqrt{2\pi}}\right) \int_{\sqrt{2SNR}}^{\infty} \left(e^{-\frac{t^2}{2}}\right) dt \quad \text{eq. 2.7}$$

$$P_E = \frac{1}{2} e^{\left(-\frac{SNR}{2}\right)} \quad \text{eq. 2.8}$$

Equations 2.6, 2.7, and 2.8 show the relationship between P_E and SNR for Coherent FSK, PSK/QPSK, and Noncoherent FSK.

2.4.4 Power Requirements for Major Wireless Standards

Approximating the power requirements for any wireless standard is never a one-size-fits-all process. The claims made in table 2.2a are based on the following, basic assumptions:

- Best-in-breed silicon is used
- Where possible, data provided by best-in-breed silicon developer is used to analyze its power requirement.
- A connection model roughly similar to that used by ISO 18000-7 is employed. That is, the system is expected to achieve roughly 2.4 second detection latency.

ISO 18000-7 can be analyzed rather easily, due to its simplicity. For low energy Bluetooth and WiFi, data provided by the chip developer was used exclusively. For ZigBee, more analysis was necessary.

ISO 18000-7

Despite the advantage of having the implementation with by far the lowest RX power, ISO 18000-7 must spend the most time in receive: roughly 36 seconds per day of wakeup detection plus 30 seconds after each successful, received command. Intelligent ISO 18000-7 implementations can force superfluous devices to sleep at these times, but we assume a naive implementation.

In total, for ten data transmissions the time spent in receive is 336 seconds per day, which at 7.5 mW averages to 29.2 μW over the day. The total time spent in transmit is roughly 1 second, which is negligible. The expected time for collections performed at any times during the day is 100 seconds, also at 7.5 mW, averaging 8.8μW. The sleep power is 4 μW. Thus the total power per day is:

$$29.2\ \mu W + 8.8\ \mu W + 4\ \mu W = 42\ \mu W$$

This is, as mentioned, a naive or worst-case implementation. The term that resolves to 29.2 μW can be brought to nearly 0 by basic system design principles, as devices requesting data from other devices should instruct them to sleep immediately after fetching data.

Low Energy Bluetooth

It can be difficult to obtain fully tested, validated data on low energy Bluetooth silicon because the standard is so new. There is not a plethora of compliant silicon in the market yet. Nonetheless, data from Nordic Semiconductor that is publicly available on the low energy Bluetooth website [4] does provide some useful information, and we have used it to empirically approximate the average power consumption of a known, low energy Bluetooth solution.

The time spent transmitting data on a low energy Bluetooth system is negligible. The gating factor is the time a chip spends in advertising mode. Assuming three packets per burst, which is typical for low energy Bluetooth, a series of charts shows us that we can expect a device discovery time in the ballpark of 2.4 seconds if the advertising interval is between 26.7 ms and 651 ms. Assuming 300 ms, we can refer to another chart to find that a 300 ms advertising rate will run on a 300 mAh cell for about 0.66 of a year. The resultant, average power consumption thus approximates to 50 μW. We expect this figure is realiable because the source exemplifies 320 ms as a useful advertising rate.

WiFi

As with low energy Bluetooth, the average power consumption and performance for a known, low power WiFi component was leveraged to approximate the figure from table 2.2a. Again, transmission time is negligible.

The performance quotation of the surveyed component is 15 ms from sleep mode to having a WiFi connection, at least in some sense. Assuming no major time is spent maintaining or enabling the network connection (which is admittedly optimistic) the device must spend 540 seconds per day in receive mode, at 90 mW, if it is to achieve 2.4 second latency. This behavior approximates to 570 μW per day.

While the WiFi approximation may be naive, it is also optimistic, in that it assumes that the active radio components, RX and TX, are on for such short time spans that they are negligible. In reality this is probably not a safe assumption, and thus I expect the approximated power is optimistic at 2.4 second latency. A chart below shows the model for the surveyed WiFi component's power per day as a function of latency.

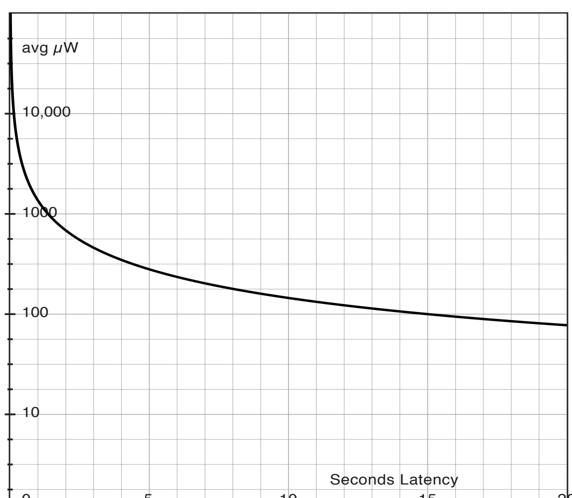


Figure 2.4e: Low Power WiFi can't compete with low power standards unless it deprecates two-way traffic.

ZigBee

ZigBee and 802.15.4 on which it is based require a more in-depth assessment of power averages than do the other, surveyed wireless standards. ZigBee's protocol allows for so much customization that it is virtually impossible to nail down a power estimate that can compare to applications using other technologies: there will always be a way to trade-off network performance for some degree of power savings. Nonetheless, the following analysis considers what we believe to be very typical protocol configurations.

Also worth noting is the nomenclature. The following several paragraphs are rich with 802.15.4 jargon readers may want to familiarize themselves if they seek an iron-clad understanding of the power estimation technique.

The 802.15.4 MAC is responsible for six, specific duties (the seventh, providing a reliable link, could be considered implicit). The minimal set of MAC requirements of any given device may be summarized as follows [8]:

- Generating network beacons if a coordinator
- Synchronizing to the beacons if not a coordinator
- Supporting PAN (personal area network) association and disassociation
- Supporting device discovery
- Employing the CSMA-CA (carrier sensce multiple access) mechanism for channel access
- Handling and maintaining the GTS (guaranteed time slot) mechanism
- Providing a reliable link between two peer MAC entities

The MACs complexity comes especially from the fact that it must support so many different types of behavior: non-synchronized and synchronized, acknowledged and unacknowledged, time-slotted and CSMA-CA, etc. In order to narrow down the otherwise massive list of device configuration options, we will pick three basic modes to evaluate:

- Coordinator beacons with superframe, Devices use guaranteed time slot for communication. The downside here is that the size of the PAN is relatively small.
- Coordinator beacons with superfame, Devices do not use guaranteed time slots, but rather use CSMA-CA in the contention access period (CAP) of a superframe. The downside here is the plausibility of collision.
- Coordinator does not use beacons, but listens at all times for transmissions from Devices (send via CSMA-CA), and Devices listen periodically for commands from the coordinator.

The third option is most like the ISO 18000-7 model, except that the Coordinator must be on at all times because 802.15.4 defines that Reduced Function Devices (RFD) are not capable of receiving or processing requests for data from the Coordinator. In other words, the base level of functionality for 802.15.4 cannot efficiently accomplish an asynchronous data upload without using superframes.

For the beacon enabled modes we assume that, in maintaining the PAN, the Device must conduct a passive scan of the band space at least once a day. We find that the passive scan time per day is ~395 seconds by assuming the following:

- Base superframe duration is 0.384 seconds, a moderate length.
- Superframe duration is 49.152 seconds
- Passive scan duration of 98.688 seconds per channel, which is also a moderate figure
- Only four channels out of sixteen are scanned [16]

In addition, the amount of time spent watching for Coordinator beacons is significant. We'll assume here that the Device has good timing and only needs to receive and listen for each beacon for 50 ms each superframe. The time spent listening for superframe beacons thus equals ~88 seconds.

Finally, we assume that transmission of data in the GTS or via slotted CSMA is negligible time spent. Altogether, for beacon enabled networks (the kind that can be used with battery powered Coordinators for meshing) the approximate power per day at 84 mW for RX is: 473 µW!

The second treatment requires Coordinators that are capable of running continuously, usually prohibiting battery powered or mobile application. We will assume the following:

- Devices will poll a single channel, at 2.4s interval
- Device poll time will be 10 ms
- Data frames will be transmitted, as needed, via unslotted CSMA.

The lack of a proper wake-up detection paradigm forces the 802.15.4 Device to stay awake longer during each poll longer than comparable ISO 18000-7 devices have to (10ms may be hopelessly optimistic, in actuality). Thus the total time spent receiving per day becomes at least 360 seconds, yielding an average power of 354 µW. The term used in table 2.2a is an average of the results determined above from the beacon-enabled and nonbeacon-enabled methods: 414 µW.

2.4.5 Modeling Helical Antennas

Practical experience indicates that aside from applications in the low frequencies, helical antennas are seldom used in today's low power wireless products. In cases where the bandwidth requirements are relatively small (like DASH7 applications), helical antennas can provide excellent performance in compact packages. This section models the radiation efficiency of a few helical designs using standard methods [3]. Some common constants are defined below.

$\mu = 4\pi \times 10^{-7}$ Permeability constant (free space value)	$\varepsilon = 8.85419 \times 10^{-12}$ Permittivity constant (free space value)
$\eta = \sqrt{\frac{\mu}{\varepsilon}}$	Intrinsic impedance of the medium
$k = \sqrt{\mu\varepsilon\omega^2}$	dummy variable

Antenna Efficiency

We measure the efficiency of an antenna design by the following relationship between radiation resistance (R_R) and loss resistance (R_L) [6]. For the helical antenna, radiation resistance and loss resistance have been mathematically modeled in [6] and [7], and we interchangeably denote these as R_{RH} and R_{LH}.

$$E_A = \frac{R_R}{R_R + R_L} \quad \text{eq 2.9}$$

$$R_{RH} = \eta\left(\frac{2\pi N^2}{3}\right)\left(\frac{kA}{\lambda}\right)^2 \quad \text{eq 2.10}$$

$$R_{LH} = \frac{Nr_l}{r_w}\left(\frac{R_p}{R_0} + 1\right)\sqrt{\frac{\omega\mu_0}{2\sigma}} \quad \text{eq 2.11}$$

$$R_p = 2r_w R_s \sum_{m=1}^{N} \int_0^{\pi} K_m^2\left(\theta, \frac{r_c}{r_w}\right) d\theta \ - \ 1 \quad \text{eq 2.12}$$

$$R_s = \sqrt{\frac{\omega\mu}{2\sigma}} \qquad R_0 = \frac{NR_s}{2\pi r_w} \quad \text{eqs 2.13, 2.14}$$

The battery of equations above relate to radiation resistance and loss resistance of a helical antenna, as described in [6] and [7]. The nomenclature is defined as follows: R_p is the resistance per unit length due to the proximity effect of one loop onto another, R_0 is the skin effect resistance per unit length, R_s is the surface impedance of the conductor (of which σ is the conductivity of the conductor). The relationships between these should make basic sense in the loss equations. The other nomenclature relates to the dimensions of the helix: N is the number of loops, r_w the wire radius, r_l the loop radius, and r_c is half the lateral distance between loops of the helix. K_m is a charge distribution function relating these dimensional constants with the charge per radian of each of the m=N loops: it is way beyond the scope of this paper but is covered in detail in [7]. For our models we will use tabular values calculated for K_m.

Modeling the Designs

The results below consider three designs of different sizes, all operating at 433.92 MHz. We can observe that the large antenna model is so efficient that most loss will take place in the matching circuit, not the antenna itself. Further analysis of the mathematics will also show that loop efficiency improves markedly at this frequency as loop radius increases beyond 10 mm.

Bounding Dimensions	N	r_l	r_w	r_c	E_A
63 x 63 x 72	6	30	1.5	6	~98%
25 x 25 x 37	6	12	0.6	3	~60%
9 x 9 x 38	14	3.8	0.6	1.3	~7%

Table 2.4d: Three helical antenna models at 433.92 MHz that may be suitable for different DASH7 applications. All units are mm.

Optimal Design

The optimal antenna is the one that provides the best antenna efficiency for acceptable dimensions. As we can see from the described model, due to the A^4 term increasing the loop radius has a greater influence on radiation resistance (eq 2.10) than does adding loops to the helix ($A = \pi r^2$). In eq 2.12 we also see that, given a set of dimensions, adding loops also increases the loss resistance (although to a lesser extent than it increases radiation resistance).

Unlike higher frequency platforms that can utilize half-wave dipoles of fixed dimensions, at 433 MHz the size of the helical antenna is not more-or-less fixed, and usually the optimal antenna is the biggest one that can fit. Care should be taken during the product development process to find the middle ground between building the antenna around the device and the device around the antenna. Ultimately, through clever engineering it is possible to realize excellent antenna performance at 433 MHz even when using electrically small helical antennas.

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