

System level considerations for Ultra-low power transmitter-only wireless networks in the indoor environment

Guy Thoonen, Emanuele Lopelli, Johan van der Tang and Arthur van Roermund
Technische Universiteit Eindhoven, Mixed-signal Microelectronics Group, EH 5.10
P.O.Box 513, 5600 MB Eindhoven, The Netherlands
Phone: +31 40 247 2664, email: guy.thoonen@skynet.be

Abstract—Indoor networking applications requiring only low duty cycles and low data rates offer unique opportunities for drastic reductions in power consumption, leading to extended battery lifetimes and at the same time delivering robustness. In order to reach those goals, careful investigation of multiple system level parameters is necessary. A main distinction can be made between applications requiring both a transmitter and a receiver in the wireless devices, and applications in which a transmitter that communicates with a residential gateway suffices. This paper concentrates on the last class of applications, discussing parameters as the data rate, the use of spread spectrum and the modulation scheme. It is shown that a data rate of a few kilobits per second delivers excellent performance in terms of power efficiency. Furthermore, a system test bench is constructed using Simulink, in order to verify theory in the comparison between direct sequence spread spectrum (DSSS), for example used in Zigbee, and frequency hopping spread spectrum (FHSS). Regarding robustness, the results show that FHSS outperforms DSSS in the indoor environment and for low data rates. This situation can be changed by increasing the complexity of the DSSS system, for instance by using equalization techniques. However, doing this may lead to more power consumption. Finally, reference values for the hopping rate and hopping set are also given.

Keywords— Transmitter, Low Power, Low Data Rate, Spread Spectrum

I. INTRODUCTION

Without doubt, it's possible for anyone to come up with applications that would benefit from the absence of wire. Some of these applications may already exist, using wire. Others might have been possible, yet impractical because of the need for excessive wiring. In either case, it's clear that wireless communications can be a solution for a whole range of applications. Consequently, requirements of the wireless link may differ a lot. As a result, multiple standards have emerged, including Bluetooth [1], Zigbee [2], ISO 15693 (for RF ID tags), etc. However, none of these standards are optimized for applications operating at extremely low data rates and requiring only very low duty

cycles, at the same time extending battery life (assuming a battery is needed), reducing size and cost and yet still offering sufficient functionality. Examples of applications with these characteristics are ambient intelligence, sensor networking and indoor control functions. This paper generally focuses on networks of low data rate, low duty cycle wireless devices.

On the road to suitable implementations, optimized for low power consumption, the first stop is on the system level. The most basic question relates to which scenario a certain implementation may follow. Two clear distinguishable scenarios are the one with only a transmitter in the wireless devices, transmitting data to a wired central node (transmitter-only) and the one with both a transmitter and a receiver in the wireless devices (transmitter+receiver). These scenarios are discussed in section II.

II. SCENARIOS

A very important system parameter is the use of a receiver+transmitter or a transmitter-only in the wireless devices. This choice is highly application dependent. Clearly, transmitter-only is not always an option. Many applications that use a wireless interface, need a receiver and a transmitter in the remote units, for instance a wireless headset. In a non-critical sensor network, on the other hand, no information needs to go the other way for functionality, for example in the monitoring of the temperature in a room and passing the data to a central processing unit.

At first glance, implementing a receiver could have some advantages, as it allows for more sophisticated duty-cycle control mechanisms. This way, the wired node of the network could be set to put the wireless sensors into and out of some kind of standby or semi-active state. The controlling events could depend on a combination of various parameters like hour of the day, direct user intervention, etc... Because of this semi-active state, during which power consumption is lower, energy could be saved, making this look like the most-preferred system. Furthermore, transmitter-only poses limitations on other parame-

ters, like network topology and multiple access scheme.

Yet, there are some counterarguments:

- Evidently, a transmitter-only system is less complex, cheaper and the individual nodes consume less power. In addition, a simple duty-cycle control algorithm in the wireless sensor is possible as well. For instance, the transmitters may send a new value every 10 minutes, and go into standby-mode in between.

- Between transmissions, the power consumption of receiver+transmitter will be higher than transmitter-only. To be advantageous, the number of transmissions and receptions has to be significantly lower for a transmitter+receiver system compared with the number of transmissions for a similar transmitter-only system.

- Having a receiver in the remote sensors, implies that it has to listen whether it should go into semi-active state. When already in this state, it should listen whether it should become active again (hence the term semi-active). This means the receiver should check periodically with the wired node. How often these checks occur determines quality of service and additional power consumption.

Of course, given the right assumptions, scenarios can be brought up for which both methods are justified.

Consider for instance a transmitter-only system which consumes power P_t while sending. The duty cycle is 0.1% and, between transmissions, power consumption is $k \cdot P$, with k respectively 0.1%, 0.01% and 0. At the same time, consider a transmitter+receiver system that is set to go into semi-active mode at night. During a transmission, the transmitter consumes P_t and the receiver P_r . The duty cycle of transmissions and receptions¹ is 0.2% during 16h per day. The remaining 8h, the duty cycle is reduced to 0.02%. Between transmissions, power consumption is $k \cdot P_t + k \cdot P_r$, with k again 0.1%, 0.01% and 0 respectively. Figure 1 compares the energy consumption of transmitter+receiver system and the transmitter-only system in function of the power relation between transmitter and receiver. As can be seen, the transmitter-only system seems to outperform the transmitter+receiver system.

Now, on the other hand, consider the same system as above. Only this time, assume the transmitter-only system sends the same information three times per transmission to improve the chance the data arrives correctly. The transmitter+receiver system can use an acknowledge signal. Therefore, it is not necessary to send each data stream twice. Assume that, in 1% of the cases a retransmit is needed. Figure 2 compares the energy consumption of these two systems in function of the power relation between transmitter and receiver for three values of k .

¹i.e. reception of acknowledge and commands that can put the system into or out of semi-active state

Clearly, under these assumptions, the power requirements to break even are less harsh and the use of a receiver seems more justifiable.

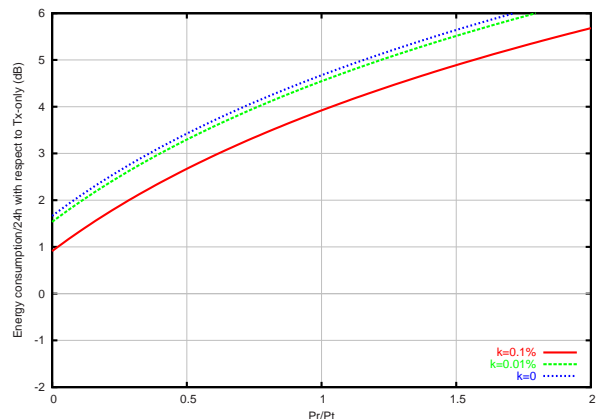


Fig. 1. Energy consumption for a transmitter+receiver system in comparison with a transmitter-only system

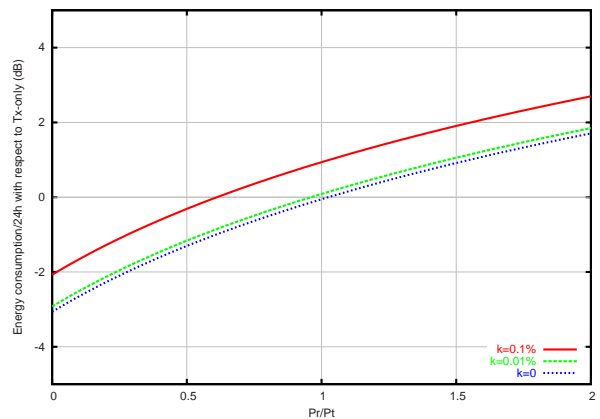


Fig. 2. Energy consumption for a transmitter+receiver system in comparison with a transmitter-only system including retransmissions

In spite of these speculations, and considering the earlier arguments, the transmitter-only system may still be a valid choice for the wireless sensor network. When possible, leaving out a transmitter in the wireless devices means less hardware, hence the costs are lower. However, in the development trajectory, to save money, best would be to follow a single general approach, that focuses on the more limited transmitter-only case, but always keeping in mind the transmitter+receiver scenario for reusability.

III. DATA RATE

The data rate is a critical factor in radio systems that aim at low power consumption. Indeed, low power dissipation requires that complex signal processing such as adaptive equalization should be avoided when possible. From an application point of view, there is no tight requirement on

the data rate due to the low amount of information that each node should send more or less periodically. Equalization will fix the upper bound for the data rate.

The indoor environment is greatly affected by fading due to multipath caused by reflections. A channel can be frequency selective if $f_0 < \frac{1}{T_s}$ or flat-fading in the opposite condition, where T_s is the symbol period and f_0 is the coherence bandwidth, that can be approximated, in the most pessimistic case, as follows [3]

$$f_0 \approx \frac{1}{50\sigma_\tau} \quad (1)$$

where σ_τ is the rms delay spread. Frequency-selective fading causes distortion because not all of the signal's spectral components are equally affected by the channel. The signal's spectral component, falling outside the coherence bandwidth, will be affected differently compared to the components contained within the coherence bandwidth. In the flat-fading condition, all the spectral components will be affected in the same way by the channel and therefore, unlike frequency-selective fading, flat-fading does not introduce channel induced Inter-Symbol Interference (ISI). However, performance degradation has to be expected whenever the signal experiences narrowband fading due to large reduction of the SNR. To avoid the use of equalization techniques and thus save power, the channel should exhibit a flat-fading response. Taking in account a $\sigma_\tau = 100\text{ns}$ [4], which is a typical measured value for an indoor environment, the coherence bandwidth is approximately 200kHz. Therefore, to avoid induced ISI, the data rate should be less than about 40ksymbol/s, assuming the signal bandwidth equals the symbol rate.

The lower bound of the data rate comes from power consumption considerations. Considering a fixed bandwidth B , a data rate D and a packet length L_{packet} , and supposing that, at each transmission, the node sends one full packet, the overall average power consumption P_d of the transmitter node can be approximated as

$$P_d = P_{\text{tx}} \frac{T_{\text{tx}}}{T} + \frac{P_{\text{diss}}}{T} (T_{\text{tx}} + T_{\text{wu}}) + \frac{P_{\text{idle}}}{T} (T - T_{\text{tx}} - T_{\text{wu}}) \quad (2)$$

where P_{tx} is the power radiated from the antenna, T_{tx} is the time required for each transmission, T_{wu} is the wake-up time of the transmitter (i.e. the time required to start up the circuitry), P_{idle} is the power dissipated in the idle mode when most of the transmitter functions are off, P_{diss} is the non-radiated power dissipated by the transmitter and T is the time interval between two consecutive transmissions. From the Shannon-Hartley theorem it is known that

$$D = B \log_2 \left(1 + \frac{P_{\text{in,dem}}}{N_{\text{tot,dem}}} \right) \quad (3)$$

where D is the maximum data rate achievable on an additive white Gaussian noise channel, $P_{\text{in,dem}}$ is the received signal power at the demodulator side and $N_{\text{tot,dem}}$ is the total noise power at the input of the demodulator. The term $\frac{P_{\text{in,dem}}}{N_{\text{tot,dem}}}$ is the signal to noise ratio at the demodulator side ($SNR_{\text{in,dem}}$) and can be related to the signal to noise ratio at the input of the receiver by

$$\frac{SNR_{\text{in,rec}}}{SNR_{\text{in,dem}}} = NF \quad (4)$$

where NF is the noise factor of the receiver and $SNR_{\text{in,rec}}$ is the signal to noise ratio at the input of the receiver. Suppose that the received signal arrives attenuated by a factor α (path loss), considering an additive white Gaussian noise channel only, then

$$SNR_{\text{in,dem}} = \frac{P_{\text{tx}}}{N_{\text{AWGN}} B \cdot NF \cdot \alpha} \quad (5)$$

where N_{AWGN} is the power spectral density of an additive white Gaussian noise channel (which is equal to $k \cdot T$ where k is the Boltzmann constant and T is the temperature in Kelvin). Substituting (3) in (5), yields an expression for the transmitted power as a function of all the other parameters

$$P_{\text{tx}} = N_{\text{AWGN}} \cdot B \cdot NF \cdot \alpha \cdot \left(2^{\frac{D}{B}} - 1 \right) \quad (6)$$

Now the transmission time is defined as

$$T_{\text{tx}} = \frac{L_{\text{packet}}}{D} \quad (7)$$

Substituting (6) and (7) in (2), an approximated formula is obtained for the power dissipated by the transmitter as a function of the data rate.

Suppose that each node transmits every ten minutes, with a bandwidth of 10kHz, a channel attenuation of 85dB, a wake-up time of a few milliseconds, and a P_{idle} of $10\mu\text{W}$. If the receiver has a noise factor of 10dB, then the overall power consumption as a function of the data rate and the power used by the transmitter circuitry (excluding the radiated power)² to transmit data appears as shown in Fig. 3 for a packet length of 1000 bits.

From this figure, it is clear that the data rate can be lowered till a certain value. Below some hundreds of bits per second the duty cycle will increase to a point for which

²The transmitted power affects the Signal to Noise ratio at the input of the receiver and therefore, from the Shannon-Hartley theorem, the capability of the link to support a certain data-rate. The power consumption of the buildings blocks of the transmitter is somehow a "wasted" power consumption and therefore it has been decoupled to analyze how it influences the choice on the optimum data rate.

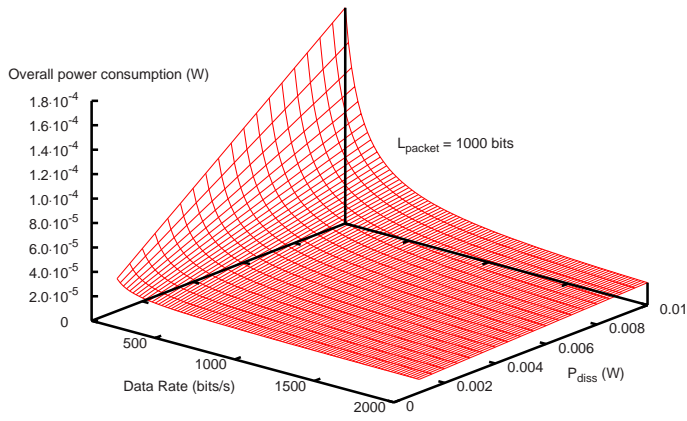


Fig. 3. Power consumption as a function of data rate and power dissipated by transmitter circuitry

the power spent in the transmitter circuitry will dominate, increasing the overall power consumption. This effect is greater when the power consumption of the transmitter (excluding the radiated power) increases from one to ten milliwatt. Raising the data rate above a few kilobits per second is not useful, since for a fixed bandwidth the advantage from duty cycle reduction is spoiled by the increase of transmitted power to keep the same performances at the receiver side (Shannon-Hartley theorem).

IV. SPREAD SPECTRUM

The term spread spectrum is used to describe any technique in which the bandwidth of the transmitted signal is much wider than the bandwidth of the information signal. Spread spectrum techniques are useful for a number of reasons, which include:

- Low power spectral density, so the information signal looks like noise to other radios.
- High immunity to jamming and interference.
- High resolution ranging.
- Possibility for Code Division Multiple Access (CDMA).
- Effective measure against narrowband fading.

In our case, the second and the last within these characteristics are the most important. Knowing that it is useful to apply spread spectrum to handle interferences, the next step deals with the choice (from a power consumption point of view) between the two most important spread spectrum techniques, Frequency Hopping (FHSS) and Direct Sequence Spread Spectrum (DSSS).

A. Modulation

The type of modulation greatly affects the power consumption. It is known from communications theory that a BPSK modulation technique is optimum in terms of power consumption. DS spreads its energy by rapidly chopping the signal in such a way that it is continuous only for a time

intervals ten or more times smaller than the data period. In this way, the energy of the signal is spread in a bandwidth ten or more times wider than the data bandwidth. In a FH system, the spectral power is lowered by hopping over many channels. During each hop, however, the FHSS signal appears as a narrowband signal. Normally, FSK modulation is used in FHSS systems while BPSK is used in DSSS systems [5]. Moreover, while in a DSSS system a coherent detection is conventionally employed, in a FHSS system it is very hard to achieve and a non-coherent one is used. Indeed, it is very difficult to maintain phase coherence when the system jumps from a frequency bin to another frequency bin. Therefore, the FHSS system normally requires a SNR 6dB greater than a DSSS system (3dB because BPSK is more energy efficient than BFSK and 3dB from the non-coherent detection employed). Considering the same noise floor the conclusion is that a FHSS system would require 6dB more transmitted power than a DSSS system to achieve the same BER. On the other hand, using FSK modulation gives the possibility to use non-linear amplification, which is more power-efficient than linear amplification.

A BPSK modulation technique would be constant envelope if no pulse shaping was applied. In the real case, pulse shaping is needed to avoid ISI due to the limited bandwidth of the channel. In this case, it happens that the waveform is not constant envelope anymore and linear amplification is needed. This limitation translates directly in larger power consumption due to low efficiency of linear amplifiers like class A or AB.

B. Interference susceptibility

A way to reduce the amount of interference between different channels is to lower the power spectral density of the transmitted signal, which is accomplished in both FHSS and DSSS, but in different ways. Therefore, the capabilities to reject an interferer vary, depending on the choice between FHSS and DSSS.

A DSSS system spreads the data energy over a larger bandwidth, decreasing the spectral power density over the entire bandwidth. At the receiver side, the spread signal is correlated with a replica of the spreading code synchronized with the transmitted code. Therefore, the desired signal collapses in the data bandwidth, while all other interfering signals will be spread over the larger bandwidth. After despreading, the signal is filtered to the data bandwidth, and therefore most of the noise will be outside this narrower band, hence it will be rejected.

This principle is helpful against narrowband interferers, which will be spread over a much larger bandwidth, but not against wideband interferers such as the microwave oven.

As shown in table I, an FHSS system has a stronger resistance against wideband interference compared to DSSS.

TABLE I
PERFORMANCE OF DSSS AND FHSS IN THE PRESENCE OF
A WIDEBAND INTERFERER

$BW_{\text{interferer}}/BW_{\text{total}}$	BER_{DSSS}	BER_{FHSS}
1/8	46.5%	7.7%
1/4	48%	12.5%
1/2	49%	23.0%

The results from this table have been obtained by considering an interferer with a spectral power density 20dB above the wanted signal. The processing gain of the DSSS system is not high enough to spread the interferer spectral power to a level considerably lower than the spectral power of the wanted signal. Therefore, the bit-error rate approaches 50%. On the other hand, in a FHSS system, even when the interferer is very strong, there are still enough unjammed channels to assure reliable communication. When half of the bandwidth is occupied by the interferer, the BER of the FHSS system approaches 25% because in the other half of the channels, reliable communication is still possible.

C. Near-far problem

The near-far problem is the major limitation in DSSS systems and increases the complexity of the transceiver due to the need for power control circuitry. Without any power control the performances of a DSSS system in an environment in which other DSSS systems are present can be heavily spoiled. However, FHSS systems are affected as well.

Thanks to the processing gain, it may seem that a DS system has large advantages over a FH system (that is narrowband in a single frequency slot and therefore it does not have any processing gain). On the other hand, a FH system has the capability to jump between frequency slots. Therefore, the probability that a near-far problem occurs in a DSSS system is proportional to the probability that the two nodes (one very near to the receiver and one very far away from it) decide to communicate at the same time.

In FHSS systems, there is one more condition to respect: they must use the same frequency slot at the same time. It is easy to imagine that this extra condition lowers the probability that the phenomenon occurs giving an advantage to the FHSS system with respect to a DSSS system.

As shown in figure 4 for a FHSS system, when *User 1* is 5 times further away from the receiver, the BER is still below 5%.

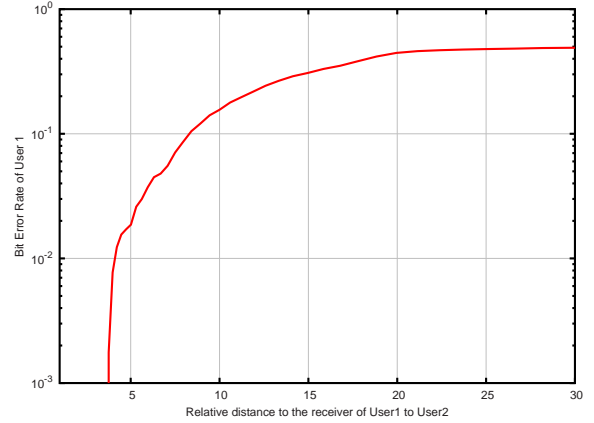


Fig. 4. Near-far sensitivity for a FHSS system

At the same relative distance, the DSSS system has already a BER of about 50%, as shown in figure 5.

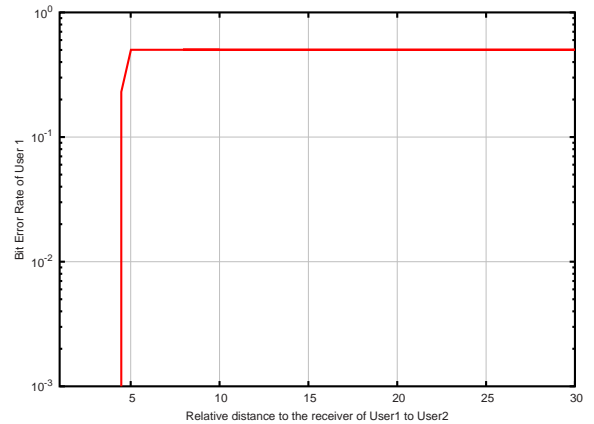


Fig. 5. Near-far sensitivity for a DSSS system

The results shown in the previous plots have been obtained using Simulink models, in which the users were interfering continuously with each other and only an additive white gaussian noise (AWGN) channel has been considered. In reality, thanks to the low data rates, the probability that 2 or more users will communicate simultaneously, is in the order of a few percent. Therefore, the average bit error rate should be scaled down accordingly. For example, a BER of 10% will translate to a BER in the order of 0.1%.

In conclusion, there is a high probability that in a DSSS

system, Automatic Gain Control (AGC) should be used, while in a FHSS system, it can be easily avoided, reducing the complexity of the system and therefore the overall power consumption.

D. Multipath

In a DSSS system, the capability to suppress multipath interference is related to the correlation process. The multipath ray will arrive at the receiver side delayed with respect to the direct path. If the multipath ray is delayed more than one chip, then the two sequences may be fully uncorrelated and it will be rejected by the correlation process at the receiver side. Otherwise, the two sequences will be partially correlated and the fading effect will be present. This effect will be more evident in an indoor environment, because of the shorter delay between the direct ray and the various multipath rays. To avoid these problems, a higher chip rate is required (and therefore a higher processing gain), at the cost of a higher working frequency of the baseband circuitry. As a consequence, the power consumption of the baseband blocks will increase linearly with the increase of the chip rate (it is proportional to $f \cdot C \cdot V^2$ where f is the operating frequency of the baseband digital circuitry, V is the supply voltage and C is the load capacitance).

For FH, the multipath signals always arrive within the signal's coherence interval causing fading. However, FHSS has an advantage with respect to DSSS. It is an avoidance system and therefore a multipath environment, that can be destructive in a certain frequency slot, will not be the same in another frequency slot. This advantage is even stronger if the slots are not adjacent in frequency.

The previous comparison clearly shows that it is not possible to decide between Direct Sequence and Frequency Hopping techniques without referring to a target application field. This article focuses on indoor ultra-low power applications. Analyzing the two systems from this point of view, a FHSS system seems to outperform a DSSS system, allowing also for a simpler architecture and therefore saving power.

E. Hop rate and set

In a FHSS system, there are various parameters to be chosen. First of all, it is necessary to understand how big the set of frequencies needs to be and how fast the system has to hop. These parameters are strictly dependent on the performances required from the system in terms of data rate and *BER*.

Consider for example the 902–928MHz and 2400–2483.5MHz unlicensed ISM (Industrial, scientific and medical) frequency bands. The minimum number of fre-

quency bins is set by FCC rules to 50 in the 902–928MHz band and to 75 in the 2400–2483.5MHz band, when avoiding intelligent hopping techniques. Increasing the number of frequency slots will decrease the collision probability, improving the *BER* performance. However, more frequency bands imply longer codes and therefore, baseband circuitry complexity and power consumption rises. Therefore, a number of slots, larger than the minimum required by FCC has to be used only if strictly necessary.

A fast-hopping system, using a majority bit decision, gives an inherent advantage in terms of *BER* with respect to a slow-hopping system at the expense of a higher hopping rate. The main drawback of such a technique, is that the system needs to hop faster, which may result in higher power dissipation in the synthesizer due to the lower settling times required. The gap between the two systems may be filled using techniques like forward error-correction for slow-hopping systems.

V. CONCLUSION

In this paper, different scenarios have been analyzed from a power consumption point of view. The choice between a transmitter-only and a transceiver scenario does not only depend on the particular application, but also on whether a more advanced protocol (a protocol that allows for an acknowledgement signal) can be used to improve power consumption performances. Furthermore, it has been demonstrated that an optimum data rate exists for the minimization of the power consumption. Here, the data rate is lower bounded by the power dissipated in the transmitter (excluding the radiated power) as well as in the receiver and upper bounded by the need for equalization at the receiver side.

The indoor environment forces the use of spread spectrum techniques to cope with fading and interferences. From the comparison between spread spectrum methods, it has been shown that, for low data rate applications, FHSS outperforms DSSS, providing a simpler and more robust architecture which leads to lower power consumption, also thanks to the possibility to use a low hopping rate, relaxing the power requirements of the hopping synthesizer.

REFERENCES

- [1] Specification of the bluetooth system. [Online]. Available: <https://www.bluetooth.org>
- [2] The zigbee alliance. [Online]. Available: <http://www.zigbee.org>
- [3] *IEEE Commun. Mag.*, *Rayleigh Fading Channels in Mobile Digital communication systems part I: Characterization*, July 1997.
- [4] J. Chang. Summary of delay profiles for mbwa. [Online]. Available: grouper.ieee.org/groups/802/20/Contribs/C802.20-03-77.ppt
- [5] M. Simon, J. Omure, R. Sholtz, and B. Levitt, *Spread Spectrum Communications Handbook*. New York, NY: McGraw-Hill, 1994.