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Theoretical Study on Detection Distance for Chipless RFID Systems According to Transmit Power Regulation Standards

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Abstract—This paper address the problematic of estimating the performance of chipless RFID systems operating in the UWB band from 3.1GHz to 10.6GHz. For this purpose, a model which takes into account chipless tags' characteristics such as RCS and quality factor is proposed to better estimate the theoretical detection distances. Chart showing theoretical detection distances as a function of the frequency and for various RCS levels are derivate from radar equation according to the radiated emission limit set by transmit power regulation authorities. Detection ranges are estimated according to two different approaches, the continuous wave based radar technique, and the impulse radio based radar technique.

Index Terms—chipless RFID, UWB, read range, radar.

I. INTRODUCTION

Research activity around chipless RFID technology [1-7] is getting more intense every year. Researchers are motivated by key features that could make this technology really attractive from the side of major actors of the consumer market, as well as the internet of things (IoT). In the world of identification, the current situation is that industrials see the passive RFID [8] as a great technology but still too young to propose a true global system able to compete with the optical barcode, which is today the biggest market of identification worldwide with tens of trillion units sold per annum. Indeed, a conventional RFID tag contains an antenna connected to an IC. The estimated unit cost is close to 0.1\$. Even if it is low, this price is still too expensive for most of the goods sold in the consumer market. That is why chipless RFID has a key role to play in the coming years. As an alternative to chipped tags, a chipless tag is made of an antenna or scatterer only, so that it can be realized with a single step process, using roll to roll industrial printing techniques. In this case, the achieved unit cost has been recently estimated at 0.004\$ with flexography printing technique [4]. But the weak point of this technology is the reading system which is still not properly defined, and not standardized. In the state of the art it is very hard to find a study addressing clearly the following points:

- What is the expected read range of a specific chipless system?
- What it the operating bandwidth? And does it fit the specific power emission limit for these specific operating frequencies so that we could potentially sell this product?

For example, most of chipless tag designs encoded in the frequency domain require an ultra large bandwidth (above 500 MHz) to operate. However, it is quite difficult to develop a reader based on the emission of continuous waves (see Fig. 1 (a)) in the frequency band between 3.1 and 10.6 GHz because we face hurdles regarding the authorized transmitting power for frequencies located outside the ISM bands. These power values are very weak (below -41.3dBm/MHz in the best case). Alternatively, a temporal approach based on impulse radio radar as shown in Fig. 1 (b) has the major advantage of spreading the power over the entire band of interest so that it is possible to detect the whole frequency response of a remote chipless tag with a short single pulse. In this case, the energy is concentrated in a very short time, resulting in a high instantaneous radiated power but a very low average power compatible with usual standards.

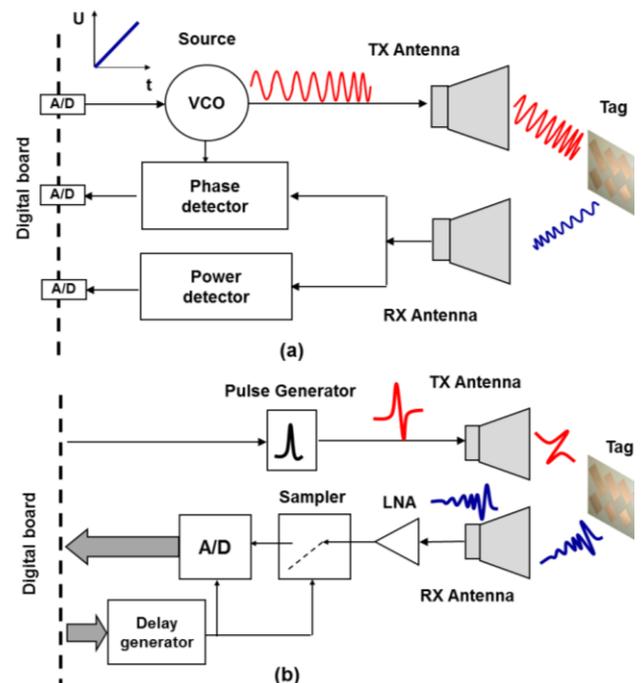


Fig. 1 Basic principle of chipless RFID system based on (a) Frequency Stepped CW based radar (b) Impulse radio based radar.

In section II, we are doing a review of the transmit power regulation standards for UWB devices. Then, in section III, we give a method to estimate the read range of a chipless tag for reading system operating in the frequency domain. Before concluding, in section IV we focus on a mean to estimate detection distance in case of an impulse-radio based approach, in respect of the regulation standards.

II. REVIEW ON THE TRANSMIT POWER REGULATION STANDARDS

The growth of the chipless RFID is conditioned by the development of a reader meeting the standards. We need to fit the power mask within the bandwidth of interest, that is, from 3.1GHz to 10.6GHz. This mask refers to the level of power one can radiate into space, and without any special authorization. Fig. 2 shows the mask for the authorized transmit powers defined by the regulatory authorities: the FCC (Federal Communications Commission) in the United States; the European Telecommunications Standards Institute (ETSI) in Europe. ISM bands whose use is not subject to licensing and for which relatively high power are available may not be suitable for our application because they are very narrow. On the other hand, to detect typical largely spread electromagnetic chipless tags' signatures over the frequencies, it seems to be judicious to use the Ultra Wide Band (UWB). In this case, the FCC mask defines a transmit power limit of -41.3 dBm / MHz between 3.1 GHz and 10.6 GHz. The Electronic Communication Committee (ECC) mask in Europe is much more restrictive and imposes a very low emission level between 4.8 and 6 GHz, as well as beyond 9 GHz. So we have a bandwidth of 7500 MHz with the FCC, and 4700 MHz with ECC. It is to be noted that for a hypothetical signal for which, the spectral content spreads throughout the full band, that is 7500 MHz, the average power is -2.54 dBm.

If the UWB standard is applied to continuous-wave based radar as that described in the next section, the transmit power is extremely low, namely -41.3dBm for a "monochromatic" wave with a bandwidth of 1MHz. It is true that, the level

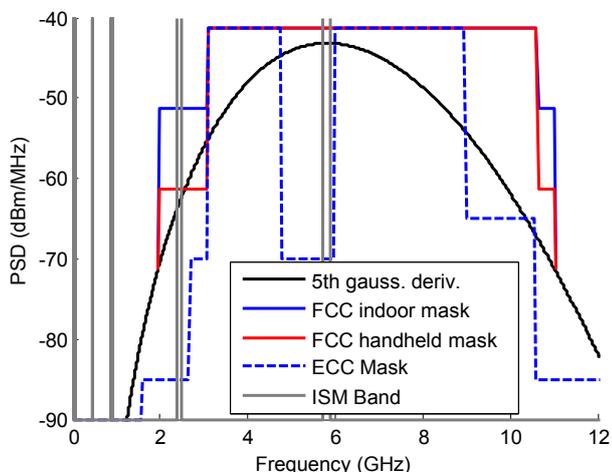


Fig. 2 Emission mask defined by the FCC and the ECC and power spectral density of the 5th derivative of a Gaussian pulse.

defined in ETSI EN 302 065 standard [9] for UWB short distance devices give a limit of -41.3dBm / MHz for the calculation of average power spectral density. However, the maximum peak power (EIRP) authorizes a value below or equal to -24.4 dBm, when measured with a spectrum analyzer having a resolution bandwidth of 3MHz.

III. FREQUENCY-DOMAIN BASED RADAR SYSTEMS

According to most of the chipless systems, the frequency band of interest is spread between 2 GHz and 10 GHz. Thus, we have to make a power budget for several frequencies within this band. Given the operating frequencies, and the dimensions of the tags, we can assume that the chipless tags operate in far-field zone. Therefore we can use the radar equation to estimate the received power reflected from the tag. This power is correlated with the radar cross section (RCS) of the tag as in (1) [10]. It is noteworthy that RCS is a value independent of the distance of detection. An estimation of the detection range can be calculated with (2) derivate from (1).

$$\frac{P_{rx}}{P_{tx}} = \frac{G_{tx} G_{rx} \lambda^2}{(4\pi)^3 R^4} \sigma \quad (1)$$

$$R = \sqrt[4]{\frac{P_{tx \max} G_{tx} G_{rx} \lambda^2}{P_{rx \min} (4\pi)^3} \sigma} \quad (2)$$

For systems encoding information in the frequency domain, the information is correlated with the variation of the RCS as a function of the frequency. In all cases the receiver must be able to detect a minimum value of the RCS. This is the limiting value that fix, for a given frequency and a given distance, the transmitting power and the reception sensitivity. If the noise level is above the receiver sensitivity, it is necessary to readjust the transmit power value. From (2) we can plot the relationship (see Fig. 3) giving the theoretical detection range as a function of the frequency for several RCS values between -60 and -30 dBm². As aforementioned in previous section, with a CW based detection approach which consists in scanning the overall frequency bandwidth (several GHz), the maximum peak power (EIRP) authorized has to be equal or below -24.4 dBm for a resolution bandwidth of 3MHz. This value is much lower than usual communication systems limits operating in the ISM bands. The power sensitivity P_{rx} is chosen to be equal to the noise floor, measured at -80 dBm for a commonly used radiofrequency receiver. The gain or the receiving antenna is $G_{rx}=10$, whereas the gain of the transmitting antenna is supposed to be $G_{tx}=1$ when dealing with EIRP power.

For a usual chipless tag [1-7], the peak magnitude of resonant modes is above -35 dBsm in the worst case. In order to distinguish clearly a peak, a dynamic of 10dB from the maximum level is necessary. Thus, we have to detect a minimum RCS level of -45 dBsm. According to Fig. 3, at 2 GHz, the maximum detection range is close to 0.3 m for a RCS=-45 dBsm. At 10GHz, the detection range is reduced to

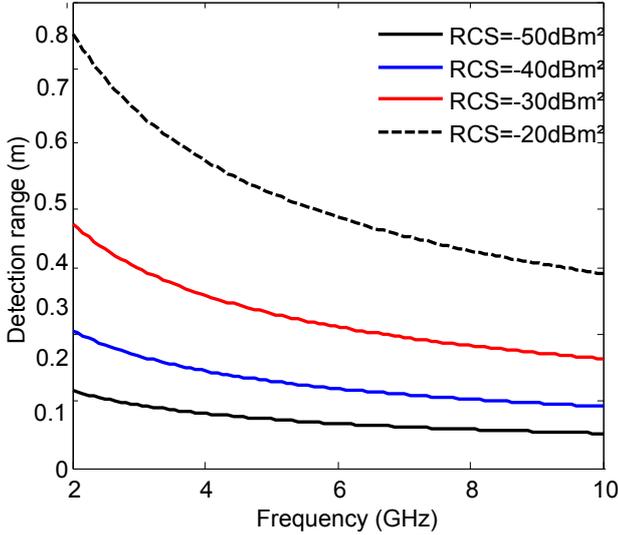


Fig. 3 Theoretical detection range chart calculated with (2) as a function of the frequency, and for RCS values set to -50, -40, -30, and -20 dBsm. The output power is set to $P_{txeirpmax}=-24.4$ dBm, and the power sensitivity is $P_{rxmin}=-80$ dBm. The gain of the receiving antenna G_{rx} is equal to 10.

0.15 m. In the best case, when the peak magnitude is close to -20 dBsm so that we need to detect a minimum RCS level of -30 dBsm, things are better, but still, the read range is not very large. At 2GHz, we obtain a detection distance of 0.47m, whereas at 10GHz we obtain 0.2m. These values give us an idea on the read range that we are expected to have according to an interpretation of the ETSI standard on UWB systems for continuous waves based radar. We will see in next section that detection systems based on the emission of picosecond pulses, may help to achieve larger reading distance with the same constraints.

IV. TIME-DOMAIN BASED RADAR SYSTEMS

An impulse radio based radar approach has the major advantage of sensing the entire frequency response of the tag with a single pulse. In this case, the energy is concentrated in a very short time, which provides a high instantaneous transmit power while maintaining a low average power, compatible with regulation standards for UWB communication.

A minimum repetition rate, or pulse repetition frequency (PRF) is set at 1 MHz by the ETSI and 400 kHz by the FCC to limit the instantaneous power. If we use a PRF of 1 MHz, that is one pulse per μs , we can find that a power of -2.54 dBm during $1\mu s$ gives energy of 557 pJ. It is therefore necessary to optimize the distribution of this energy to fit the transmit power mask shown in Fig. 2. Specific pulse shapes such as the 5th derivative of a Gaussian pulse (see Fig. 4) can be used to fit the FCC indoor mask dedicated to systems inside the buildings. This waveform covers the whole bandwidth of 7500MHz centered at 6.85 GHz. The amplitude of the peak is 8 V, which corresponds to energy of 113.7pJ that is much lower than the maximum authorized value of 557 pJ.

As shown in Fig. 4, this signal spreads over a time $T_p=600$ ps. The duty cycle is 600ps/ $1\mu s$ that is 1 per 1667. In terms of power, this gives a gain G_{RC} (3) of 32.2dB within this

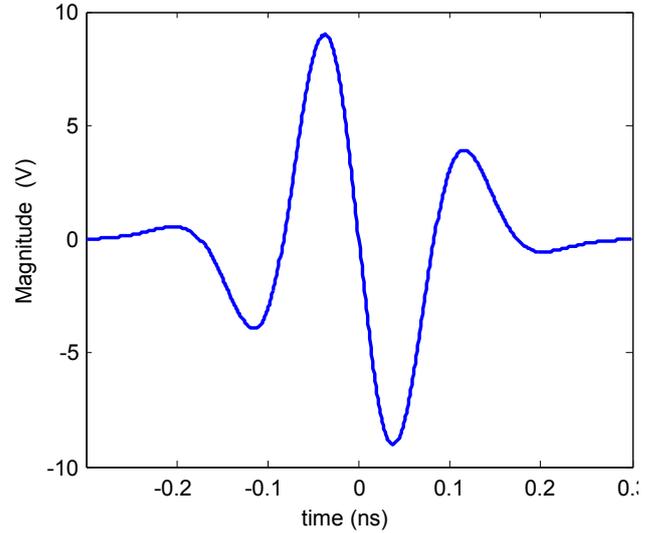


Fig. 4 Waveform of the fifth temporal derivative of a Gaussian pulse.

short duration of 600ps to compare with the same energy consumed in $1\mu s$.

$$G_{RC} = \frac{1}{PRF \cdot T_p} \quad (3)$$

However, we should consider that the response of the tag is not instantaneous so that we need to sample its response for a longer time than 600 ps. To estimate this duration, we need to consider quality factor (4) of tag's resonant modes. First we can say that the response time is longer when the resonance frequency is low. Thus, the longest response time is obtained for the lowest frequency for a given chipless tag. We consider the minimum frequency at 3.1 GHz to operate in the UWB. A resonant mode with a bandwidth of 50 MHz (which is conventionally used in chipless RFID) gives a quality factor equal to 62 at 3.1 GHz according to (4). As stated in [11], resonant modes can be modeled by second order transfer functions. For a second order resonant system, using (5) we obtain the response time $Trep_{n\%}$ at n% for a given center frequency f_0 and a quality factor Q . For example, for a resonance frequency of 3.1GHz and a quality factor of 62, we obtain a response time of 19 ns. We can therefore conclude that most of resonant modes created by chipless tags operating in the UWB band release most of their energy in less than 20 ns.

$$Q = \frac{\Delta f}{f_0} \quad (4)$$

$$Trep_{n\%} = \frac{Q}{\pi f_0} \log_e(100/n) \quad (5)$$

Using (3) with a time $T_p=20$ ns, we obtain a power gain of 50, that is 17 dB in log scale. Then, in order to extract the received power $P_{rx}(f)$ associated with each spectral component, we multiply the received PSD by the bandwidth (equal to the

frequency resolution of the system), and by the duty cycle gain introduced in (3). We obtain (6) replacing the resolution frequency df by its equivalent expression (7) which corresponds to the inverse of the observation time T_{rx} . Using (7) with $T_{rx} = 20\text{ns}$, we find a frequency resolution of 50 MHz.

$$P_{rx}(f) = \frac{DSP \cdot df}{PRF \cdot T_{rx}} = \frac{DSP}{PRF \cdot T_{rx}^2} \quad (6)$$

$$df = \frac{1}{T_{rx}} \quad (7)$$

A power budget can be calculated injecting the PSD and the frequency resolution into the expression of the radar equation (1) to obtain a novel equation (8). In this equation, we use directly the power spectral density EIRP term $PSDeirp$ so that the gain of the transmitting antenna no longer appears. However the gain of the receiving antenna G_{rx} is still present.

$$R = \sqrt[4]{\frac{DSP_{eirpmax} \cdot Grx \cdot \lambda^2}{P_{rxmin} (4\pi)^3 PRF \cdot T_{rx}^2 \sigma}} \quad (8)$$

With the pulse previously defined, that is to say compatible with the FCC indoor mask, using (8) we plotted in Fig. 5, the theoretical detection distance as a function of the frequency for several RCS levels. The gain of the receiving antenna is set to 10 dB.

We can observe that ranges between 0.5 m and 1.5 m can be achieved over the entire frequency band for an object with a minimum RCS value of -45 dBm^2 . For a minimum RCS value of -30 dBm^2 , this range rises up to 1m to 2.7m. This is a very interesting result, because it shows that impulse radio UWB based radar, whose transmit power fit the FCC indoor mask, achieves larger detection ranges than continuous wave based greater than 0.5 m.

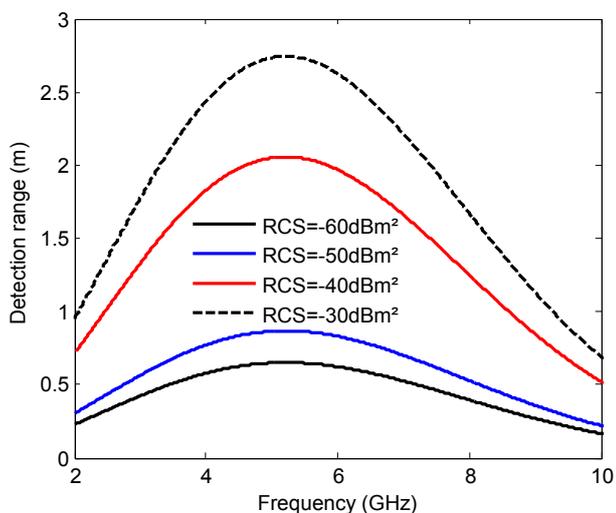


Fig. 5 (a) Theoretical detection range chart calculated with (8) as a function of the frequency, and for RCS values set to -60, -50, -40, and -30 dBsm. The pulse shown in Fig. 4 is transmitted to the tag. The noise floor is set at $P_{rxmin} = -80 \text{ dBm}$.

V. CONCLUSION

We presented a theoretical study on the determination of theoretical detection ranges that we can achieved for chipless RFID systems operating from 3.1 GHz to 10.6GHz, while considering the transmitting power limit values defined by the ETSI and the FCC regulation authorities. We find out, that continuous wave based radar systems can achieved detection range up to 0.47 m in the best case, that is for a tag's RCS of -20 dBsm , whereas a detection range up to 2.7 m is possible for an impulse radio based radar system. This better performance is correlated with the high instantaneous power permitted by a picosecond pulse while keeping a low average power. In a future work the proposed theoretical model will be verified by practical measurements for both radar approaches.

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