Bio-Medical Sensing using Ultra Wideband Communications and Radar Technology: A Feasibility Study

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***Abstract*—The aim of this work is to study the application of Ultra Wideband (UWB) technology to perform biomedical sensing and vital signs monitoring in humans. Among the numerous signals that can be measured, the heart rate (HR) is chosen as the first objective due to its importance. The research is pointed towards the development of a technique that can allow both, radar sensing and communications using the same UWB transceiver. Such a sensor, could use UWB radar principles to measure the heart beat rate and UWB communication standards to transmit these measurements. Readily available commercial transceivers with minor adaptations will be considered as possible to solve for the physical layer. Signal processing for target detection will be done at higher levels. Having sensors with such "duo" properties can make them ideal nodes for wearable computing, as well as sensor and body area networks.**

***Index Terms*— Ultra wideband radar, ultra wideband communications, heart rate, contact-less vital signs monitoring, heart rate variability (HRV).**

I. Motivation

THE motivation behind this topic comes from the interest of the proponent in the area of pervasive computing technologies for healthcare [23], [36] (pervasive healthcare for shortness) and wearable healthcare IT systems [1], [34]. Most of the applications proposed on those areas basically need two components: a sensor of some kind and a communication infrastructure (transceiver and protocols) to share the data gathered by the former. There are many strategies and techniques proposed for the communication among sensors. Plenty of protocols, routing schemes and physical layers are being published regularly. However, after all, the thing that will make these networks valuable is the data they transport. How are the data gathered (i.e. sensed) has not been that popular so far. This is not a trivial problem in the digital healthcare paradigm if one really likes to make it pervasive. The proponent hypothesizes that the bio-sensors needed to boost the idea of pervasive healthcare have to be: non invasive, contactless and wirelessly networkable. Pervasiveness automatically calls for non invasiveness mainly because the paradigm not only involves pathological patients but also healthy people that for the sake of prevention and/or early diagnostics would like to be constantly health monitored. Therefore, an invasive sensor is certainly not going to be popular among healthy people thereby precluding its pervasiveness. Contactless could be also a deterrent to pervasiveness, but it is more related to comfort or wearability of the bio-sensors. Let's say that for long term monitoring it is much better to have contactless bio-sensors. Moreover, if this property remains valid for a certain range, (e.g. one meter, or so) is also useful to assure continuous monitoring even under special conditions (e.g. when a physically challenged old person is being bathed), thus enabling the possibility to gather data that could be of help for diagnostics. Finally, wireless networkability is necessary to transmit and share the monitored data with other systems or central repository due to the inherent limited capacity of the sensor. Networkability is also desired to enable a dialog between the sensors that can enable for example better accuracy due to signal processing several readings of the same parameter obtained throughout two or more distributed sensors. Scenarios in which some sensors remain inactive until they are enabled by other neighbors upon the satisfaction of a certain group condition also require networking among them. Pervasive health will also contribute to context aware environments in which vital signs monitoring would certainly play a major role in one of its main intended applications, that is to watch out for elderlies [22]. Those environments require also networkable sensors to become a reality. In short, wireless telemetry to read data from the sensor is not enough. The sensor should have a stack and the necessary protocols to establish a dialog with, and relay information to, its potential neighbors.

So far, the described sensor is made of two parts: The sensing part and the communications part. From the sensing side, for certain type of variables, such as the heart rate variability (HRV), RADAR sensing seems to meet the requirements of non invasiveness and contactless. RADAR sensing is also robust, another desirable characteristic for a device that will be probably continuously worn or integrated in the garment. From the communications side, it was previously mentioned that there are many possibilities. The decision must be made taking into account the size of the transceiver and the antenna, power consumption, communications standards supported, and to a less degree, data rate. As it will be discussed later there exist radar and communications systems that can fulfill

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the requirements separately. However, to the best of the author knowledge there is no system that integrates both things in one device. It would be highly desirable to have a system that can meet the needs of both systems, that is, perform radar detection and sensing together with communications using the same transceiver.

One technique that satisfies this desire is Ultra Wideband (UWB) technology. Being heavily researched and applied for many years in military radar applications, UWB technology is making its way towards wireless communications networks through the standardization process leading by the IEEE [16], [17]. There are various reasons why UWB seems to satisfy the previously stated requirements, but the most important is that: due to its resolution, it can be used as an accurate radar, and due to its resistance to multipath (which is a consequence of its resolution) it can be used for communications at high speed; and both tasks can be performed using the same design (i.e. same pulse shape, same frequency, transmitted power, etc.). This is key to the motivation of this idea because it opens the possibility to the design of biosensors that can be highly integrated, small and power efficient, something that has been wanted for long in this research community.

There is another motivation that is not at all banal. As it was mentioned before the IEEE is progressing on the standardization of UWB communications. However as it usually happens, companies start to commercialize early versions of the technology in order to gain some market thus influencing the decision. Beyond these strategies, from the point of view of this article, having early UWB communications chipsets enable the possibility to leave for a moment the simulation environment to experiment with real systems. This is a fact of inestimable value to validate the theory and perform affordable tests "in-vivo" that could, at the end, pave the way towards tangible devices that can provide useful results in real scenarios.

Finally, there is also an altruistic motivation due to the many applications that such a device could have to enhance the wellness of the population. An UWB radar/ communications sensor alike, would be small, thus easily portable. This in turn would enable proactive home monitoring of vital signs, which in an aging population could decrease the cost of healthcare by moving some amount of eligible patients from hospital to home. Considering the potential saving this is not a minor thing [19], [14]. The medical applications are numerous and have been devised as early as in 1996 [26]. Apart from what has already been described, an UWB radar can be used to measure cardiac volume; respiration movement detection and diagnostic (e.g. prevention of Sudden Infant Death Syndrome –SIDS–, and Obstructive Sleep Apnea Syndrome –OSAS–); internal blood pressure that can be indirectly derived from a measurement of arterial pulsation; pregnancy monitoring; in general almost any object of adequate size can be monitored (e.g. vocal cords; vessels; bowels; lung; chest; bladder; fetus; etc.)

From all the applications listed before this proposal focuses specially in the Heart Rate Variability (HRV). The HRV, as an indicator for the cardiovascular autonomous nerve system, codifies the activity of the peripheral and central parasympathetic and sympathetic nervous system. For example, through the usage of brain imaging methods it has been confirmed that the high frequency power component contained in the HRV signal, reflects activities seen in some areas of the brain critical to the allocation of resources during stress, such as the medial pre-frontal cortex [20]. As such, the evaluation of HRV is a way to monitor non-invasively neural activity linked to the capacity to stand stressful situations (e.g. threats). Therefore, in this case HRV reveals its utility in the assessment of human performance due to its link with actual cognitive activity. Other studies have identified HRV as an effective diagnostic and prognostic marker for a variety of health conditions [30], [13]. In general, the link between respiration patterns and emotional and mental state has been recognized for many years [5], [2]. It can be said that having the possibility to obtain a long history of HRV measurements can provide physicians with a new variable to consider in their diagnostics, similar to what happen with today's chemical blood analysis, x-ray radiology, and alike. It can be also good for physiopathological research, as it can be used to prove some theories and open new research paths [21].

The rest of the article is organized as follows: Section 2, surveys the state of the art. Section 3, provides a rough calculation of the range that could be theoretically obtained using an already available UWB RF transceiver. And finally section 4, describes a possible research approach.

II. Survey of the State of the Art

The idea described here mix knowledge taken from two research areas: RADAR and wireless communications. Both areas use electromagnetic waves to achieve their respective objectives; however the techniques and the theory behind them can be rather dissimilar at times or name the same things differently in other cases. Therefore, to be consequent with the scope of this section, the state of the art of both technologies will be briefly surveyed. The signal to be measured as well as the operating regulations constitute other related areas that are also reviewed for the sake of completeness.

A. *UWB impulse radars as biomedical sensors*

UWB impulse radars are characterized by very wide bandwidths and a corresponding fine range resolution. UWB radar technology has been heavily researched mainly by the U.S. Army, and unfortunately much of this work remains classified. As the study of the UWB propagation phenomena progressed throughout the years, several claims were rose about its amazing potential performance benefits especially for applications such as terrain profiling through foliage or camouflage, and ground penetration to find buried objects; as well as enhanced capabilities for counter-stealth or low probability of interception. So promising were those claims that in 1990 the U.S. Defense Advance Research Projects Agency (DARPA) commissioned a study to verify them [9].

At that time, the assessment panel concluded that there was no credible evidence of unique phenomenological capabilities related to the claims and that it did not believe impulse radar offers a major new military capability nor correspondingly did it present the threat of a serious technological surprise. It also added that either conventional wideband (i.e. non-impulse) or UWB impulse radars could accomplish the same tasks. Having said that, UWB impulse radar was simple another technique to approach problems whose solution was already known using other conventional methods. However, the report emphasized several times that UWB impulse radar might present substantial advantages in terms of implementation cost, size or weight especially for short range applications, and these are exactly the properties that this proposal aims to exploit.

The idea of monitoring physiologic functions in humans using radars started as early as the 1970s (see [33] and the references therein), but further development was hindered by the cumbersome and costly technology of those years. Microwave radiation safety concerns was another deterrent. Particularly regarding UWB technology, an UWB radar application was first described on a paper in a scientific journal in 1998 [15]. There are also several U.S. patents describing its medical applications. One of the most cited is the one awarded to Thomas McEwan [27]. The patent is the result of a work done at the U. S. Lawrence Livermore National Laboratory (LLNL) [26]. This publication describes promising medical applications already mentioned in the previous section, and it emphasizes that the average emission level used (≈1μW) is about three orders of magnitude lower than most international standards for continuous human exposure to microwaves making the device medically harmless. Aside from LLNL, UWB radar applications in medicine are being or were studied at University of California Davis (breath, speech); University of California Berkeley (speech); University of Iowa (speech). Experimental prototypes were built and tested by Ossberger et al. [31]; Immoreev et al.[18]; Michahelles et al. [28]; and Tor Vergata University of Rome [33]. Particularly this last reference is very interesting because it may be the first attempt to seriously model the phenomena, that is, the scattering of UWB pulses along the path to the heart while the other references focused mostly on the signal processing once the reading is obtained in a more or less empirical manner. However to the best of the author knowledge no commercial device has ever hit the market.

B. *UWB communications*

UWB communications has been receiving a lot of publicity recently because it is regarded as the future technology for high data rate and short range transmission. Since late 2001 the IEEE Wireless Personal Area Networks Group started a standardization process [16], [17], that has received a lot of contributions and research resources from academy and private companies. There are a lot of papers covering almost every aspect as well as very good textbooks and reviews [6], [24].

Moreover, the first applications providing a complete chip-set solution (i.e. Medium Access Controller, Baseband controller and RF transceiver) are hitting the market [10], [11]. This proves that, even though the technology has not yet been standardized, is maturing quickly. This is good because for the sake of this work the UWB communication technology is considered as being given, that is, ready to use. The task is then to discover an efficient way to use the same commercial transceiver and standard protocols to perform radar sensing but without disrupting the communications in order to get an usable sensor that can also participate in a network.

C. *Radar and communications integration*

The integration of radar sensing together with communications equipment has been used in aerospace satellites and exploration vehicles mainly in order to save space, since some components such as the transmitter, receiver and antenna can perform well in either role. Reference [3] is a good example of such integration, where the combination provides the radar eyes and the communications the ears and voice for the NASA's Space Shuttle Orbiter. This *ku* band system integrates a wideband two-way data system and a frequency-hopping, low repetition rate, pulse-Doppler radar. The system has two modes: In the radar mode, it measures range, velocity, angle and angle rate. In the communications mode, it receives and demodulates the spread spectrum forward and return link with the ground station. Frequency diversity is used to integrate both systems assigning 13.775 GHz for communications and a band of 13.8~14.0 GHz for radar. Such closeness in frequency is required to avoid retuning the low noise amplifiers when switching from the radar to the communications mode.

There were also other proposals aimed to integrate radar and communications for automotive systems. Researchers at Mazda Motor Corp. presented a vehicle-to-vehicle communication and ranging system based on the ranging capabilities of spread spectrum (SS) named "SS communication radar" [29], [35]. A car equipped with this system can range others not equipped by measuring the start of the returned PN code as given by the correlation peak. In case the other car has a similar system they can exchange information. The range resolution was about 1 meter and the data rate about 12.6 kbps, either values fairly low for the application envisioned by this article.

With the same application in mind DaimlerChrysler AG along with the Technische Universität München [38], designed a system in which the communication band is located in the first null of the radar pulse spectrum. This could be done because the frequency band of the communication transceiver is small compared to the pulse spectrum (i.e. 1.5 vs. 250 MHz). Because the bands overlapped, the same RF front-end could be used thus decreasing the cost. The pulse radar was designed to allow simultaneous sensing and communications reaching a range of 40 meters for the former and 200 meters for the latter.

For the army, multifunction RF systems can reduce military costs while minimize radar cross section and probability of detection thus enabling them to work simultaneously with tolerable co-site interference. This has motivated Roberton et al. at UCLA to develop a Chirped Spread-Spectrum Integrated Radar and Communication [32], allowing the elements of the antenna array to simultaneously transmit and receive communications and radar data. During transmission radar pulses are combined (overlapped) with communications bits. The quasi-orthogonality between "up-chirps" (frequency increasing with time) and "down-chirps" (frequency decreasing with time), is used to solve for self-jamming. The radar and communications signals occupy the same frequency band, but have opposite polarity in their respective frequency sweeps.

Finally, from the medical side researchers at Bell Labs, have proposed a system in which a commercial 2.4GHz cordless phone together with a simple add-on module is used to detect human respiration and heart activity [25]. The module puts together an antenna and a mixer to receive direct and back-scattered transmissions from the wireless terminal. Then it uses the principles of Doppler radar to output a signal proportional to the motion of the person's heart and chest.

However, to the best of this author's knowledge no integrated UWB radar/communication system has been published yet.

D. Regulations

Communications systems that are not respectful of current regulation can be conceived for the sake of research, however medical monitoring systems in that condition can be harmful for people's health and will be of no practical interest. Therefore there is no other choice but to design something that can be compatible with actual legislation on electromagnetic emission. In the field of UWB transmission, regulations are recent in some countries, and still missing in others. That immaturity calls for a revision of its current state. However, for the sake of brevity the legislation on UWB communications systems can be consulted on reference [6] and references therein. Only the medical side of it will be described here.

Currently, the most widely known emission masks for UWB radio are those issued by the FCC in the U.S. [8]. The FCC's regulation established three types of UWB devices based on their potential to cause interference: 1) imaging systems including Ground Penetrating Radars (GPRs); wall-through-wall surveillance, and medical imaging devices, 2) vehicular radar systems, and 3) communications and measurement systems. The following comment reflects the youth of this legislation: *"This combination of technical standards and operational restrictions will ensure that UWB devices coexist with the authorized radio services without the risk of harmful interference while we gain experience with this new technology. In the meantime, we plan to expedite enforcement action for any UWB products found to be in violation of the rules we are adopting and will act promptly to eliminate any reported harmful interference from UWB devices."* [8]. According to this, chances are it will change.

The regulation mentions that medical systems must be operated in the frequency band 3.1~10.6 GHz. and describes it as a system that *"may be used for a variety of health applications to 'see' inside the body of a person or animal"*. And it specifically adds: *"Operation must be at the direction of, or under the supervision of, a licensed care practitioner."* Regarding communications, such as high-speed home and business networking devices, it also sets the range of frequencies between 3.1~10.6 GHz, thus allowing simultaneous operation of radar sensing and communications in the same band, which is in the interest of this application. In that range, the average power spectral density should not go over -41.3 dBm/MHz in either operation mode. This is equivalent to approximately 0.55 mW over 7.5 GHz range. As it will be shown later, commercial UWB devices rarely use more than 2 GHz bandwidth, which under the rules mentioned above gives approximately 0.16 mW that, according to [33] and the references therein, is intrinsically safe for humans even under chronic monitoring conditions.

Finally, in March 2005 the FCC granted a waiver which basically enables the usage of direct sequence UWB as gated system to achieve a power spreading effect similar to frequency hopping. This means gated UWB systems can also transmit at higher power levels and then sit quiet, as long as they still meet the same limits for average power density during the certification testing. The effect of this waiver is two-fold: from the communication point of view it translates into higher data rates, and from the radar side it allows better range.

E. Heart Rate Variability

The interest in the Heart Rate Variability (HRV) as a non invasive diagnostic indicator has been constantly high through the last 30 years. A very recent number of the IEEE transactions on biomedical engineering included a special issue on the latest advances in HRV signal processing and interpretation which constitutes a good example of its contemporaneity [4]. The state of the art about the study of this physiological variable has been reviewed there and the references therein. Particularly, the usage of HRV has been proposed as a useful signal in a number of medical areas as diverse as: cardiovascular modeling; sleep studies; detection of apnea episodes in preterm infants; classification of pregnancy disorders; vaso-vagal syncope; bedside monitoring and early diagnosis of sepsis in premature infants in neonatal intensive care units; autonomic dysfunction and related pathologies, just to mention a few.

Among the myriad of applications envisioned for HRV measurements, the proponent is particularly interesting in two: Aging detection and identification of arrhythmias in postmyocardial infarcted patients. In an aging society where the healthcare costs are trying to be cut by moving eligible patients from hospital to home, it is important to have instruments that can monitor ambulatory patients at home. Autonomic aging detection is important when dealing with neurodegenerative diseases like Alzheimer and Parkinson. The heart rate dynamics (e.g. HRV) give clues on the aging evolution of the elder. This in turn, can feed a context sensitive system which could then adjust the level of support that the elder requires to continue living alone (e.g. check the status of appliances more frequently, increase the number of vocal reminders, etc.), and/or send adequate warnings to their relatives and physicians. Regarding postmyocardial infarcted patients, pervasive HRV monitoring can be used to early detect fatal ventricular arrhythmias which are one of the main causes of death in survivors of acute myocardial infarction. These are applications that could clearly contribute to the well being of the society.

III. Feasibility Study

This section aims to test, in a very roughly and approximated way, if the power available from one commercial UWB communication system is enough to perform radar sensing at a reasonable range. For the sake of brevity, the analysis is done in the far field. However, the distances being envisioned (i.e. between 15 cm and 1 m) are rather short with respect to λ. Therefore, only a full wave analysis could give a more reliable estimate of the phenomena. Another thing that is not being considered is the fact that an UWB antenna will perform differently in free space than at the interface with the tissue.

A. Power budget of a monostatic radar based on a commercial UWB communications transceiver

As UWB communications technology matures, chipsets will start hitting the market. One such example comes from Motorola's Freescale Semiconductor which provides an UWB transceiver as a part of its XS110 chipset for UWB communications [10]. This work intends to check if this transceiver "as is" could be used as radar for HR sensing.

The datasheet of the MC270113 UWB RF transceiver specifies:

- Transmit output power: $P_t = -8$ [dBm]
- Center frequency: $f = 4.104$ [GHz]
- RF frequency range: $3.1 \le f \le 5.1$ [GHz]
- Bandwidth: $B = 2$ [GHz]

The FCC's rules limits the indoor PSD to the values showed in TABLE I, where the measured bandwidth is $mb = 1$ [MHz].

TABLE I
AVERAGE POWER LIMITS SET BY THE FCC IN THE U.S. FOR INDOR UWB DEVICES [6]

Frequency [MHz]	$EIRP_{mb}$ [dBm]
0–960	-41.3
960–1610	-75.3
1610–1990	-53.3
1990–3100	-51.3
3100–10600	-41.3
Above 10600	-51.3

Thus, for the RF frequency range being considered, the maximum allowed power spectral density is $PSD = -41.3$ [dBm/MHz]. Having a bandwidth of $B = 2$ [GHz], the effective isotropic radiated power is limited to:

$$EIRP = PSD \cdot B$$
$$EIRP\,|_{dB} = PSD \text{ [dBm/MHz]} + B \text{ [dBMHz]}$$
$$EIRP\,|_{dB} = -41.3 + 33.01 = -8.29 \text{ [dBm]}$$

It can be seen that the transmitted output power P_t of the Freescale's transceiver is approximately equal to FCC's maximum allowed $EIRP$ for the frequency range. This leaves no room for transmitting antenna gain G_t, since $EIRP = P_t \cdot G_t$. Therefore, as it is the usual practice in UWB communications systems, it is chosen an isotropic antenna with $G_t = 0$ [dBi].

Given that, the transmitter power density uniformly distributed at a distance R from the source is

$$P_\Delta = \frac{P_t \cdot G_t}{4\pi R^2}$$

and the fraction intercepted by the target is

$$P_i = \frac{P_t \cdot G_t}{4\pi R^2} \cdot \sigma$$

where σ is the radar cross-section (RCS) of the target.

The estimation of σ requires special care, but for the sake of this approximate power budget, the following is assumed:

"The heart is spherical and it behaves as an isotropic radiator sending back a spherical wave with the same polarization as the transmitted signal."

B. RCS components

Radar cross-section is made up of three components: the area of the target, its reflectivity at the polarization of the radar's receiver antenna, and the antenna-like "gain" of the target [7].

$$\sigma = \left| A_{tgt} \cdot \Gamma_{tgt} \cdot G_{tgt} \right| \text{ [m}^2\text{]};\ \Gamma_{tgt} = \frac{P_{Refl(tgt)}}{P_{Impg(tgt)}}$$

where:

A_{tgt} = The projected area of the target as viewed from the radar

Γ_{tgt} = The reflectivity of the target at the polarization of the radar

G_{tgt} = The antenna-like "gain" of the target in the direction of the radar

$P_{Refl(tgt)}$ = The power reflected by the target (in all directions)

$P_{Impg(tgt)}$ = The illuminating power impinging on the target (within its projected area)

The heart, in the adult, measures about 12 cm in length, 8~9 cm in breadth at the broadest part, and 6 cm in thickness [12]. Thus from the assumption made before, the target can be considered as a sphere of 12 cm diameter.

Since the wavelength $\lambda = \frac{c}{f} = 0.073$ [m] is not strictly much shorter than the circumference $2\pi a = 2\pi \cdot 0.06 = 0.377$ [m] (≈ 5 times bigger => not much greater); the area cannot be taken as the optical cross-section [7].

The $\frac{circumference}{wavelength} = \frac{2\pi a}{\lambda} \cong 5$ which according to Fig. 1 belongs to the resonance region and thus

$$\frac{A_{tgt}}{\pi a^2} = 0.9 \Rightarrow A_{tgt} = 0.9 \cdot \pi \cdot 0.06^2 = 0.01 \ [\mathrm{m}^2]$$

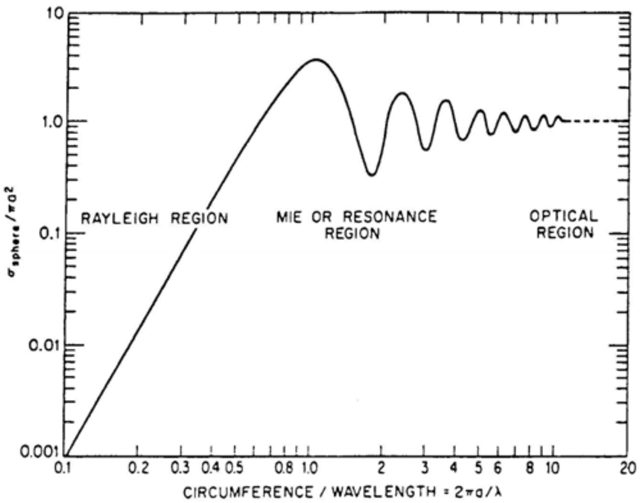

Fig. 1. Sphere RCS versus frequency [7].

As for Γ_{tgt}, there exists a measurable difference in reflection magnitude between the heart muscle and the blood it pushes into the vascular tree, thus following the approach in [27] (i.e. one dimensional analogy to propagation along a transmission line, similar to time domain reflectometry (TDR)), one gets:

$\Gamma_{tgt} = \frac{Y-1}{Y+1}$ where $Y = \frac{Z_{heart}}{Z_{blood}}$ and Z_{heart}, Z_{blood} are the propagation impedances of the heart muscle and the blood for the center frequency f.

Reference [27] gives $\varepsilon_{r_{muscle}} = 40$ and $\varepsilon_{r_{blood}} = 60$ without mentioning the frequency, but since the pulse utilized there has duration of 200ps, that is, a frequency of 5 GHz, it can be assumed that $\varepsilon_{r_{muscle}}$ and $\varepsilon_{r_{blood}}$ where taken at that frequency. However, this is a point that needs further clarification to be done in future works.

Using these values and the fact that $Z = \sqrt{\frac{\mu_0}{\varepsilon_r \varepsilon_0}}$ $[\Omega]$, $Z_{heart} = 60$ $[\Omega]$, and $Z_{blood} = 49$ $[\Omega]$ one gets:

$\Gamma_{tgt} = \frac{\frac{60}{49} - 1}{\frac{60}{49} + 1} = 0.1 \Rightarrow 10\%$ reflection magnitude between the presence and absence of heart muscle, probably measured at 5GHz whereas the intended system operates at approximately 4GHz, this introduces an error that must be accounted in further refinements of this power budget.

Finally, the worst case of $G_{tgt} = 1$ is assumed.

Computing the RCS with these values gives:

$$\sigma = |0.01 \cdot 0.1 \cdot 1| = 0.001 \ [\mathrm{m}^2]$$

Therefore the fraction of the effective radiated power intercepted and backscattered by the target of spherical cross-section is $\frac{\sigma}{4\pi R^2}$

Some amount of this power will be captured by the receiving aperture $A_e = \frac{G_r \cdot \lambda^2}{4\pi}$ where $G_r = G_t = 0$ [dBi]

So far the received power can be recast into a product of three factors:

$$P_r = (P_t G_t) \cdot \left[\frac{\sigma}{4\pi R^2}\right] \cdot \left\{\frac{A_e}{4\pi R^2}\right\} \qquad (1)$$

where:

$(P_t G_t) =$ Effective radiated power ($EIRP$) of the radar transmission in the direction of the heart. Constringent to be ≈ -8 [dBm] by the FCC's regulations for the given system bandwidth.

$\left[\frac{\sigma}{4\pi R^2}\right] =$ Fraction of the effective radiated power intercepted and backscattered by the heart assuming it has a spherical cross-section.

$\left\{\frac{A_e}{4\pi R^2}\right\} =$ Fraction of the resulting scattered power captured by the receiving aperture.

The expression (1) is basically the radar equation assuming a lossless propagation medium.

C. Propagation loss

For the sake of this approximation two values can be referenced. Staderini [33] putted together a model (Fig. 2) with data obtained from the Visible Human Project and the Gabriel's data book of dielectric properties of tissues. This model shows a 20 dB round trip loss for the signal to reach the heart and come back (aside from the loss due to reflectivity which in this work is modeled by $\Gamma_{tgt} = 0.1$ equivalent to 10dB loss). The critic to this model is that it has been done considering a continuous wave at 1.5GHz which is significantly lower than the 4.1GHz that is being considered here. Moreover, the characterization was done using a narrowband approach instead of the ultra wide-band dielectric properties required for this project, and it is generally accepted in the UWB community that UWB signals, due to their ultra-wide frequency range, are not affected in the same way as equivalent narrow signals are for the same center frequency.

The other value comes for Ossberger *et al.* [31] that briefly mentions that the sum of forward and backward attenuation is about 50 dB along the signal path from the air/skin interface to the heart at a frequency of 2 GHz. The 25 dB difference between the two references is may be due to the fact that the latter is also including A_{tgt} in the calculation. Adding A_{tgt} to Staderini's model results in a total round trip loss of $A_{tgt}|_{dB} - 35dB = -20 - 35 = -55dB$ which is similar to Ossberger's comment. Thus based on Staderini's model of Fig. 2, again for the sake of this power budget, it is assumed a round trip path loss $L = 20$ [dB]

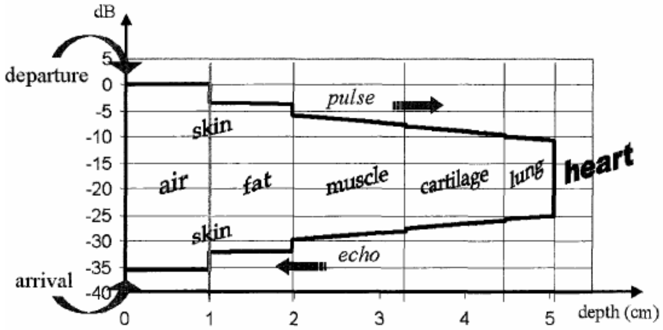

Fig. 2. This figure reproduced from [33] is the Staderini's model predicting the attenuation of pulse-echo intensity traveling from the transmitting antenna to the receiving antenna. Each step accounts for echo at the boundary. Decreasing of the curve accounts for linear attenuation in the tissue (imaginary part of reflection coefficient and multiple reflections are ignored).

Accounting for the propagation loss the received signal power becomes:

$$P_r = (P_t G_t) \cdot \left[\frac{\sigma}{4\pi R^2} \right] \cdot \left\{ \frac{A_e}{4\pi R^2} \right\} \cdot \frac{1}{L} \qquad (2)$$

D. The effect of noise

To estimate the maximum range $R_{\max}$ beyond where the heart cannot be sensed, the received signal power P_r in (2) must equate to the minimum receiver sensitivity $S_{\min}$. According to reference [37] the minimum sensitivity for a system like the one considered here is -85.5 dBm at 28Mbps.
Rearranging and expressing R in terms of other variables:

$$R^4 = \frac{P_t G_t}{S_{\min}} \cdot \left[\frac{\sigma}{4\pi} \right] \cdot \left\{ \frac{1}{4\pi} \cdot \frac{G_r \lambda^2}{4\pi} \right\} \cdot \frac{1}{L}$$

since $G_r = G_t = 1 \Rightarrow 0$ [dBi] and $\lambda = \frac{c}{f}$ one gets:

$$R = \left(\frac{c^2}{64\pi^3} \cdot \frac{P_t}{S_{\min}} \cdot \frac{\sigma}{f^2} \cdot \frac{1}{L} \right)^{\frac{1}{4}}$$

Given that:

$Pt = -8$ [dBm] $= 158.49$ [μW]

$S_{\min} = -85.5$ [dBm] $= 2.82$ [pW]

$\sigma = 0.001$ [m^2]

$f = 4.104$ [GHz]

$L = 20$ [dB] $= 100$

$c = 299.79 \times 10^6$ [$\frac{\text{m}}{\text{s}}$]

Replacing the values and computing: $R \cong 20$ [cm]

Since according to Fig. 2 the heart is approximately 4 cm under the skin, this means that with this system based on the freescale's MC270113 UWB RF transceiver "as is", that is, without any modification, one can be able to detect the heart at approximately 15 cm away from the body which is quite good for a contact-less sensor with the functions envisioned here.

As it is, the sensor would benefit from the small size, highly integrated electronics and antenna of the standard embodiment provided from factory. This will in turn make communications with peer sensors effortless, freeing the designer of this problem to concentrate on the signal processing and protocol functions needed to obtain a meaningful reading.

E. Possible improvements to increase range

Aside from the elemental calculation showed before, there is still room for improvement of range. Here are some possibilities:

- Transmitted power: It was mentioned that the indoor maximum transmitted power is regulated by FCC UWB masks approved in 2002 [8]. However under the waiver approved on March 10, 2005, gated UWB systems can also transmit at higher power levels and then sit quiet, as long as they still meet the same limits for average power density. Gated is exactly the way in which this radar will work, thus the waiver open the possibility to an increase in transmitted power.
- Antenna Gain: Here it was assumed an isotropic unity gain transmitting/receiving antenna. This can also be manipulated to increase range as long as the $EIRP$ is kept under the FCC limits. Care must be taken with directivity since this could affect the communication capabilities sensor with neighbor nodes.
- Data rate: Receiver sensitivity $S_{\min}$ is directly proportional to the required SNR for a given data rate. The previous range was obtained assuming 28 Mbps rate which is quite fast either for radar sensing and data transmission. SNR requirements can be lowered and thus $S_{\min}$ improved by lowering the data rate. This possibility is suggested in [11] where it is mentioned that *"synchronization can be performed at a reduced data rate to increase the probability of acquisition in poor signal-to-noise ratio environments"*. This characteristic of the communication system can be useful to increase the range of the radar system.
- Frequency range: As can be seen from TABLE I the range $0 \le f \le 960$ [MHz] also has a power spectral density of -41.3 [dBm/MHz]. This is a very interesting range because a signal with low frequency components suffers less attenuation when penetrating human tissues, thus improving range. Maybe without much effort and by just introducing minor modifications (i.e. dynamically adjusting external circuits like the clock and output filters) the chipset can be made to work in these frequencies for radar sensing, clocking it back to 4 GHz for communications.
- Heart model: The assumption used to model the heart is clearly too coarse. An accurate model could probably offer better results hopefully increasing the range. To start with, a model similar to Fig. 2 has to be calculated but considering the frequencies and the UWB characteristics of the radiated signals considered here. The reflection must be recomputed with the right impedances measured at the right frequencies.

In conclusion, the actual range is quite good but it would be nice to increase it to about 1 m because this would provide more flexibility to the application. Tweaking the parameters mentioned before seems to be an affordable and easy way to approximate to that objective. The solution is definitely not impossible because there were some prototypes that achieved sensing distances of 3 m [27]; 1 m behind a 20 cm thick brick wall or 5 m without obstacles [31]; and 0.1~3 m in [18]. However there are big differences between these systems and the one proposed here: First, they are not modulated, that is, they radiate the pulse in baseband, therefore including low frequency components that are less attenuated in tissues. Second, they use directional antennas, typically some kind of horn with gain > 1. Third, they were not thought to respect the FCC rules, thus they do not respect emission levels of the FCC and cannot be commercialized. Four, and the most important for the sake of this work, they do not provide communications capabilities, therefore they cannot be part of a sensor network, nor they increase detection accuracy by processing multiple signals coming from nearby peer neighbors.

IV. Research Approach & Conclusion

The research could start by refining the radar propagation model used before to adjust it to the frequencies and to the ultra wide bandwidth signals that will be utilized here.

The next step is to work on the determination of the radar cross section or scattering model of the heart. Previously, for the sake of simplicity, the heart was considered a spherical isotropic scatterer in the far field. Such approximation is clearly too coarse and has to be revised in order to clearly know what will be measured. In other words, as it was reviewed, it is rather easy to aim an UWB radar to the thorax and obtain a signal which is somehow related to heart motion. However it is not at all easy to know what is actually being measured, and this calls for an accurate model of the object being monitored.

Another point to investigate is how the performance of a communication antenna is affected when placed at the interface with tissue. With the help of the refined propagation and the antenna model, the power budget will be recomputed to asses the feasibility and/or the possible alternatives.

Then follows a study of what are the modifications needed to perform radar sensing with commercially available UWB communications devices such as [10] and [11]. Also, due to the availability in the market of UWB USB evaluation kits, it would be nice to conclude this part with the construction of a prototype to perform several in vivo tests in order to finally assess the feasibility.

Once the signals are available either from simulation or from the prototype the work could continue studying the signal processing techniques necessary to successfully recover the HRV.

Finally, in the case a working prototype could have been built, it would be nice to demonstrate the communication capabilities of the sensor, showing the transmission of HRV measurements to nearby neighbors or to a central repository as a proof of the networkability.

References

[1] Binkley, P.F.; “Predicting the potential of wearable technology”; *IEEE engineering in medicine and biology magazine*; may/june 2003.

[2] Boiten, F.; Frijda, N. H.; and Wientjes, C.J.E.; “Emotions and Respiratory Patterns: Review and Critical Analysis,” *International Journal of Psychophysiology,* 17, pp. 103-128; 1994.

[3] Cager, R.; LaFlame, D.; Parode, L.; “Orbiter Ku-Band Integrated Radar and Communications Subsystem”; *Communications, IEEE Transactions on;* Vol. 26, Issue 11, Part 2, pp. 1604 – 1619; Nov 1978.

[4] Cerutti, S.; Goldberger, A.L.; Yamamoto, Y.; “Recent Advances in Heart Rate Variability Signal Processing and Interpretation”; *IEEE Transactions on Biomedical Engineering;* vol. 53, Issue 1, pp. 1 – 3; Jan. 2006.

[5] Clausen, J.; “Respiration Movement in Normal, Neurotic, and Psychotic Subjects”; *Facta Psychiamka Et Neurologica:* Supplementum 68, 1951.

[6] Di Benedetto, M.-G., Giancola, G.; *“Understanding Ultra Wide Band Radio Fundamentals”;* Prentice Hall PTR; Upper Saddel River, NJ, USA; 2004.

[7] Edde, Byron.; *“RADAR: Principles, technology, applications”;* Prentice Hall; 1995.

[8] Federal Communications Commission; “Revision of Part 15 of the Commission’s Rules Regarding Ultra-Wideband Transmission Systems”; ET Docket 98-153; Washington, D.C., U.S.A; April 22, 2002.

[9] Fowler, C.; Entzminger, J.; Corum, J.; “Assessment of ultra-wideband (UWB) technology”; *Aerospace and Electronic Systems Magazine, IEEE,* Vol. 5, Issue 11, pp. 45 – 49; Nov. 1990.

[10] Freescale Semiconductor; “MC270113 Ultra-Wideband RF Transceiver”; MC270113/D Rev. 1.6, 10/2004.

[11] Freescale Semiconductor; “MC270123 Ultra-Wideband Baseband Controller”; MC270123/D Rev. 2.1, 10/2004.

[12] Gray, Henry; *“Anatomy of the Human Body”.* Philadelphia: Lea & Febiger, 1918; Bartleby.com, 2000. www.bartleby.com/107/. May 2000 by Bartleby.com

[13] Hilton MF; Bates RA; Godfrey KR; et al.; “Evaluation of Frequency and Time-Frequency Spectral Analysis of Heart Rate Variability as a Diagnostic Marker of the Sleep Apnea Syndrome,” *Med. Biol. Eng. Comput.,* 37, (6), pp. 760-769; Nov. 1999.

[14] Hoffman, C.; Rice, D.; Sung, H.; “Persons with chronic conditions: their prevalence and costs,” *Journal of the American Medical Association,* vol. 276, pp. 1473- 1479, Nov. 13, 1996.

[15] Holzrichter, J.F., Burnett, G.C.; Ng LC; Lea, W.A.; “Speech articulator measurements using low power EM-wave sensors”; *The Journal of the Acoustical Society of America;* 103(1):622-5; Jan. 1998.

[16] IEEE 802.15 WPAN High Rate Alternative PHY Task Group 3a (TG3a); http://www.ieee802.org/15/pub/TG3a.html

[17] IEEE 802.15 WPAN Low Rate Alternative PHY Task Group 4a (TG4a); http://www.ieee802.org/15/pub/TG4a.html

[18] Immoreev, I.Y.; Samkov, S.; Teh-Ho Tao; “Short-distance ultra wideband radars”; *Aerospace and Electronic Systems Magazine, IEEE,* Volume 20, Issue 6, pp. 9 – 14; June 2005.

[19] Intel Corporation; “Digital Home Technologies for Aging in Place”; Available online: http://www.intel.com/research/print/overview_digital_home.pdf; Feb. 2004.

[20] Jovanov, E.; O'Donnel, A.; Morgan, A.; Priddy, B.; Hormigo, R.; “Prolonged telemetric monitoring of heart rate variability using wire-less intelligent sensors and a mobile gateway”; *EMBSBMES Conference, 2002. Proceedings of the Second Joint;* Vol. 3, pp. 1875 - 1876 vol.3; 23-26 Oct. 2002.

[21] Jovanov, E.; O'Donnell Lords, A.; Raskovic, D.; Cox, P.G.; Adhami, R.; Andrasik, F.; “Stress monitoring using a distributed wireless intelligent sensor system”; *Engineering in Medicine and Biology Magazine, IEEE* Vol. 22, Issue 3, pp. 49 – 55; May-June 2003.

[22] Korhonen, I.; Parkka, J.; Van Gils, M.; “Health monitoring in the home of the future”, *IEEE engineering in medicine and biology magazine;* May/June 2003.

[23] Korhonen, Ilkka; Bardram, Jakob E.; “Guest editorial introduction to the special section on pervasive healthcare”; *IEEE transactions on information technology in biomedicine,* vol. 8, No., Sept. 2004.

[24] Liuqing Yang; Giannakis, G.B.; “Ultra-wideband communications: an idea whose time has come” *Signal Processing Magazine, IEEE,* vol. 21, Issue 6, pp. 26 – 54, Nov. 2004.

[25] Lubecke, V.; Boric-Lubecke, O.; Beck, E.; "A compact low-cost add-on module for Doppler radar sensing of vital signs using a wireless communications terminal"; *Microwave Symposium Digest, 2002 IEEE MTT-S International;* Vol. 3, pp. 1767 – 17; 2-7 June 2002.

[26] McEwan, T.; Azevedo, S.; "Micropower Impulse Radar"; Science & Technology Review; Lawrence Livermore National Laboratory, US; Jan./Feb. 1996; Available online: http://www.llnl.gov/str/pdfs/01_96.2.pdf.

[27] McEwan, Thomas E.; "Body monitoring and imaging apparatus and method"; United States Patent 5,766,208; June 16, 1998.

[28] Michahelles, Florian; Wicki, Ramon; Schiele, Bernt; "Less Contact: Heart rate detection without even touching the user"; In *Proc. 8th IEEE International Symposium on Wearable Computers,* Arlington, USA 2004.

[29] Mizui, K.; Uchida, M.; Nakagawa, M.; "Vehicle-to-vehicle communication and ranging system using spread spectrum technique (Proposal of Boomerang Transmission System)"; *Vehicular Technology Conference, 1993 IEEE 43rd;* pp. 335 – 338; 18-20 May 1993.

[30] Nunes Amaral, L. A.; Goldberger,A.L.; Ivanov, P. Ch.; Stanley, H. E.; "Scale Independent Measures and Pathologic Cardiac Dynam-ics," Physical Review Letters, Vol. 81, No. 11, Sep. 1998.

[31] Ossberger, G. Buchegger, T. Schimback, E. Stelzer, A. Weigel, R; "Non-invasive respiratory movement detection and monitoring of hidden humans using ultra wideband pulse radar"; Linz Center of Mechatronics GmbH, Austria; *Ultra Wideband Systems, 2004. Joint with Conference on Ultrawideband Systems and Technologies. Joint UWBST & IWUWBS. 2004 International Workshop on.* Publication Date 18-21 May 2004; On page(s) 395- 399.

[32] Roberton, M.; Brown, E.R.; "Integrated radar and communications based on chirped spread-spectrum techniques"; *Microwave Symposium Digest, 2003 IEEE MTT-S International;* Vol. 1, pp. 611 - 614 vol.1; 8-13 June 2003.

[33] Staderini, E.M.; "UWB radars in medicine"; *Aerospace and Electronic Systems Magazine, IEEE,* Volume 17, Issue 1, Jan. 2002 Page(s)13 – 18.

[34] Tröster, G.; "The Agenda of Wearable Healthcare." *IMIA Yearbook of Medical Informatics 2005: Ubiquitous Health Care Systems;* Stuttgart: Schattauer; p.125-138; 2004.

[35] Uchida, M.; Kagawa, Y.; Okuno, A.; "A vehicle-to-vehicle communication and ranging system based on spread spectrum technique-SS communication radar"; *Vehicle Navigation and Information Systems Conference, 1994. Proceedings.,* 1994; pp. 169 – 174; 31 Aug.~2 Sept. 1994.

[36] Varshney, U.; "Pervasive healthcare"; *Computer* vol. 36, Issue 12, pp. 138 – 140; Dec. 2003.

[37] Welborn, M., Kohno, R., Mc Laughlin, M.;"DS-UWB Physical Layer Submission to 802.15 Task Group 3a"; IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs); IEEE P802.15-04/0137r3; July 2004.

[38] Winkler, V.; Detlefsen, J.; Siart, U.; Buchler, J.; Wagner, M.; "Automotive radar sensor with communication capability"; *Wireless Technology, 2004. 7th European Conference on;* pp. 305 – 308; 2004.