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Patient-Care Sensing and Monitoring Systems

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62.1 Introduction

Wireless sensors that have more advantages relative to wired sensors are playing an important role in improving the quality of life in daily indoor space. The applications include home security systems to improve the safety of our home and vital signs monitoring systems to improve our health. The sensor systems can remotely detect the echo reflected from a person and then estimate the state and/or vital signs such as respiration rate and heart rate, for example. Several types of wireless sensor device have thus far been developed such as video camera, passive infrared (IR), and microwave. The video camera is unacceptable for some applications from a privacy protection point of view, although it can monitor a wide area of the indoor space. Passive IR sensors are generally developed to be dedicated to a relatively small area such as the home entrance and toilet area. Microwave sensors such as Doppler and frequency modulation continuous wave (FM-CW), which are capable of penetrating a variety of nonmetallic materials such as inner walls, provide a wider coverage area when compared with video cameras and IR, but it is susceptible to interference from other wireless radio systems, thereby causing false alarms or false detection. Ultrawideband impulse-radio (UWB-IR) has lately attracted considerable attention in short-range remote sensor applications since it offers high-ranging accuracy, multipath reduction, and environmental friendliness due to the very low energy emission [1–4]. However, it requires very-high-speed analog-to-digital converter (ADC) and high-level processors in order to synchronize and detect the received nanosecond pulse. It may also cause interference to existing or future wireless systems using the same or nearby bands because it occupies a bandwidth wider than 500 MHz. Therefore, the UWB device operated in the lower band of 3.4–4.8 GHz is required to implement the detect-and-avoid (DAA) technique in many countries such as Europe, Korea, and Japan [5].
To solve these problems, the use of the stepped-FM scheme has been suggested for the UWB sensor. The scheme has the following main advantages relative to UWB-IR [6-10]:

- **Lower-speed ADC and lower-level processor:** It transmits a series of bursts of narrowband pulses where each burst is a sequence consisting of many pulses shifted in frequency from pulse to pulse with a fixed frequency step. Each received narrowband pulse is phase-detected and then combined into the large effective bandwidth (sequentially over many pulses). Therefore, the hardware requirement is less stringent relative to UWB-IR. The detector bandwidth is smaller, resulting in lower noise bandwidth and higher SN ratio when compared with UWB-IR.
- **Inherent DAA function:** It is capable of coexisting with other narrowband wireless systems operating in the same frequency range. It detects interference potential by searching and is then designed to have some spectrum hole (nonactivated within a portion of the wide radio spectrum) to prevent any conflict and to coexist with the other narrowband wireless systems [11]. For example, the frequency band of interference can be detected by the phase detector, while the spectrum hole is adaptively assigned according to the interference band.

We have fabricated the sensor setup where the algorithm detecting and avoiding the interference previously mentioned has also been developed. Note that the ADC speed is 10 ks/s for the 2 GHz bandwidth. Measurements were conducted for some scenarios and the results are presented. From the results, the scheme is shown to be useful as a wireless sensor and can also coexist with other wireless systems operating in an overlaid frequency band.

### 62.2 Stepped-FM UWB Sensor

#### 62.2.1 UWB-IR Sensor

UWB-IR uses nanosecond pulses spreading out all over a continuous wide bandwidth as shown in Figure 62.1a. It offers many advantages such as low-cost implementation, low transmission power, ranging, multipath immunity, and low interference. Due to the ultrashort-duration pulses, subcentimeter ranging is possible, thereby resulting in the correct identification of the complex-shaped target. It does not require up and down conversion; thus, it may reduce the implementation cost and low power consumption. In spite of the advantages, however, there are several engineering issues that need to be considered. Due to the very short pulses, accurate synchronization and detection may be difficult. Interference to existing or future radio systems using the same band is one of the difficult issues to be solved. Designing wideband RF components is also a difficult challenge, which includes high-speed ADCs.

Now, the received 1D signal, which is referred to as range profile, is generally presented by multiple impulses with gains $\{\beta_k\}$ and propagation delays $\{\tau_k\}$, where $k$ is the impulse index. Suppose for a nanosecond pulse of $s(t)$, the range profile $y(\tau,t)$ is the time convolution of $s(t)$ and the impulse echo response $\sum \beta_k \delta(t - \tau_k)$ is as follows:

$$y(\tau,t) = \sum_k \beta_k s(t - \tau_k)$$  \hspace{1cm} (62.1)

Figure 62.1b shows an example of received power range profile for a bandwidth of 1 GHz in a room (corresponding to 1 ns pulse).

#### 62.2.2 Stepped-FM UWB Sensor

A different approach of UWB, which solves the previous problems, is the use of stepped-FM pulse sequences instead of transmitting a nanosecond short pulse. We have fabricated an experimental setup of a stepped-FM UWB sensor. The block diagram is illustrated in Figure 62.2a. Waveforms at each stage and the external photo are given in Figure 62.2b and c, respectively. The sensor transmits a series of bursts of narrowband pulses, where each burst is a sequence consisting of $N$ narrowband pulses shifted...
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in frequency from pulse to pulse with a fixed frequency step $\Delta f$ [4]. As shown in Figure 62.2a through c, the received echo from an object is phase-detected with the transmitted stepped signal (homodyne detection) and is then I-n-phase and quadrature-phase (I-Q) sampled by a relaxed speed of ADC.

Then, the $n$th complex sample $R_n$ is given by

$$R_n = A_n \exp(-j\theta_n)$$  \hspace{1cm} (62.2)

$$\theta_n = 2\pi (f_c + (n-1)\Delta f) \cdot \frac{2d}{c}$$  \hspace{1cm} (62.3)

where

- $A_n$ is the amplitude of $n$th pulse ($A_n$ can be approximated by $A$ for a stationary object)
- $f_c$ is the fundamental frequency
- $c$ is the velocity of light

Next, each complex sample is applied to the inverse discrete Fourier transformation (IDFT) device in order to obtain an $N$-element synthetic range profile, which is called range spectrum. The $N$-element range spectrum is given by

$$R(\phi) = \sum_{n=1}^{N} R_n \cdot \exp\left(-j \frac{2\pi}{N} (n-1) \cdot \phi \right)$$

$$= N \cdot A \cdot \frac{\sin[\pi(\phi - N\Delta f(2d/c))] - \sin[\pi/N(\phi - N\Delta f(2d/c))]}{\sin[\pi/N(\phi - N\Delta f(2d/c))] - \sin[\pi(\phi - N\Delta f(2d/c))] }$$  \hspace{1cm} (62.4)
\[ \phi = \frac{2dN\Delta f}{c} \]  

(62.5)

It is clear that the range resolution \( \Delta R \) is approximately \( 1/N\Delta f \). For example, suppose \( \Delta f = 34.5 \text{ MHz} \) and \( N = 30 \), the resolution is approximately 30 cm, which is equivalent to a UWB-IR with 1 GHz. Hence, it does not require high-speed ADC devices and a high-level processor at the receiver. Note that the unambiguous range (maximum detectable range) \( R_{\text{max}} \) is given by \( c/2\Delta f \).

An example of the range spectrum is shown in Figure 62.3 where \( \Delta f = 34.5 \text{ MHz} \) and \( N = 30 \) and zero-padding was also used for the IDFT operation. The phase detector should be generally AD sampled by 10 times of stepped pulse repetition rate or more. For example, when the pulse repetition rate of the setup is 1 kHz, the used ADC is 10 kS/s. Therefore, the hardware requirements become less stringent when compared with UWB-IR.
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62.2.3 DAA and Spectrum Hole

The stepped-FM UWB sensor can detect radio interference by monitoring the phase detector output in passive mode (transmitter power off, receiver on) and is then designed to have some spectrum hole (nonactivated within a portion of the wide radio spectrum) at the transmitter in order to prevent any conflict and to coexist with the other narrowband wireless systems. Note that the transmit radio consists of independent narrowband pulses with a different frequency. As such, it provides flexibility to support regulatory measures in different areas of the world and ease concerns about interference. This section describes an interference avoidance technology called spectrum hole.

Figure 62.4a shows the power spectrum for \( \Delta f = 34.5 \text{ MHz} \) and \( N = 30 \) where some stepped pulses from 3.655 to 3.724 GHz are not transmitted corresponding to the spectrum hole of 6.6% (simulation result). The band is seen to be suppressed less than -13 dB. Consider the federal communications commission (FCC)

![Image](image_url)

**Figure 62.3** Example of range spectrum with zero padding (\( \Delta f = 34.5 \text{ MHz} \) and \( N = 30 \)).

![Image](image_url)

**Figure 62.4** Power spectrums of transmit signal with spectrum hole: (a) Spectrum hole of 6.6% (b) spectrum hole of 16.6%.
regulation of $-41.3$ dBm/MHz, the band is suppressed to less than $-55$ dBm. Therefore, it does not interfere with existing radios. Figure 62.4b also shows the power spectrum against three narrowband interferences where we assumed three spectrum holes of 3.310-3.379 GHz, 3.621-3.655 GHz, and 3.897-3.966 GHz (corresponding to 16.6%) as shown in Figure 62.4b. Figure 62.5 shows the range spectrums for 6.6% and 16.6% where a zero-padding was used for the IDFT processing (1024 points).

### 62.3 Detection and Avoid Technology

The UWB device operating in the 3.1–4.2 GHz band is required to implement a DAA technology (narrowband signal detection and avoidance function) that allows it to detect an active wireless system operating in the same frequency range. The stepped-FM UWB sensor has inherently a DAA function unlike UWB-IR.

The flowchart of the suggested DAA algorithm is shown in Figure 62.6. Prior to transmitting the UWB radio, the receiver is activated (passive mode) and detects some narrowband radios such as

![Flowchart of DAA algorithm](image)

**FIGURE 62.5** Range spectrums with and without spectrum hole.

**FIGURE 62.6** Flowchart of DAA algorithm.
communications and broadcast signals. Figure 62.7a shows the output of the phase detector where a narrowband radio of 3.84–3.85 GHz is assumed. In the measurement, the radio was generated by an Agilent E8254A signal generator. It is seen that the radio is detected corresponding to the step number of 23 and 24 where \( \Delta f = 14.5 \) MHz and \( N = 70 \). Based on the result, the transmitter is then activated. Figure 62.7b shows the power spectrum where 7 stepped pulses from 3.76 to 3.85 GHz are not transmitted. Figure 62.7c shows the transmit signal together with the interference in frequency domain. It is seen that the UWB radio can coexist with the radio.

**FIGURE 62.7** DAA technology: (a) Phase detector output, (b) power spectrum of transmit signal, and (c) power spectrum of received signal.
62.4 Patient-Care Sensing and Monitoring System

A patient-care sensing and monitoring system has been developed using the stepped-FM UWB sensor. The measurements were conducted and the results are presented.

62.4.1 Sensing and Monitoring Algorithm

The requirement for monitoring the state of the elderly person in care facilities and hospitals is increasing year by year since the increase in accidents involving the elderly persons is of great concern. When the elderly attempt to leave the bed alone, for example, it has been reported that the fall accident occurs frequently. Therefore, it is important to monitor the state of the person. The flow chart is shown in Figure 62.8 where the sensor detects various states or state in a room. The received range spectrum consists of echoes from various obstructions such as the bed, person, and walls where the state should be estimated by employing a “ranging filter” and a “motion filter.”

The ranging filter \( \Delta R_p(\phi) \) is to detect the range from the sensor to a person, which is given by

\[
\Delta R_p(\phi) = |R_i(\phi) - R_0(\phi)|
\]

where

- \( R_0(\phi) \) is a reference range spectrum that represents the range spectrum in a static room without a person.
- \( R_i(\phi) \) is the range spectrum of \( i \)th frame.

For example, when a person moves, the range spectrum would also fluctuate. Also, some motion in a room is expected to be detected by the motion filter \( \Delta R_m(\phi) \), which is given by

\[
\Delta R_m(\phi) = |R_i(\phi) - R_{i-1}(\phi)|
\]

Note that \( R_i(\phi) \) and \( R_{i-1}(\phi) \) represent the range spectrum of \( i \)th and \((i - 1)\)th frame, respectively.

![Flow chart of monitoring algorithm.](image-url)
The motion filter is to detect some motion in a room, while the ranging filter is to estimate the range of a person. The trajectory of a moving person can also be estimated; thereby the state should be estimated such as “walk in room” and “fall.” It is also possible to observe his state in bed such as “tossing about in bed” and “sitting up in bed” using the motion filter without invasion of privacy. Therefore, the state of a person can be detected that includes “out of room,” “static,” “walk in room,” “sleep in bed,” “tossing about in bed,” “sitting up in bed,” and “fall” in this algorithm.

62.4.2 Measurement Results

The measurements were conducted in a care room shown in Figure 62.9 and the results are presented. The specification is shown in Table 62.1. The algorithm has been developed for six states of “out of room (‘out’ for short),” “walk in room (walk),” “sleep in bed (sleep),” “tossing about in bed (toss about),” “sitting up in bed (sit up),” and “fall.” Figure 62.10 represents an example of the measured results where the solid line is the sensor’s estimated state, while the dashed line is the actual state identified by a video camera as shown in Figure 62.9. The measurements were conducted for different subjects and the detection rate was investigated. Next, it is important to investigate the detection performance for spectrum hole. The result of “fall,” “sit up,” “sleep,” and “out” is shown in Figure 62.11. Table 62.2 summarizes the results. A detection rate of more than 88% is seen to be attained for a spectrum hole of 10%. Note that the rate is approximately 100% without a spectrum hole.

![Scene for measurement environment.](image)

**FIGURE 62.9** Scene for measurement environment.

<table>
<thead>
<tr>
<th>TABLE 62.1 Measurement Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit power</td>
</tr>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>Stepped bandwidth $\Delta f$</td>
</tr>
<tr>
<td>Number of steps $N$</td>
</tr>
<tr>
<td>Frame period</td>
</tr>
<tr>
<td>ADC device</td>
</tr>
<tr>
<td>Antenna</td>
</tr>
</tbody>
</table>
62.5 Conclusions

The increase in accidents involving the elderly patient becomes a great concern, and the requirement for monitoring their activity and state is especially increasing in care facilities. This chapter presents a bed state monitoring sensor of the elderly patient using a stepped-FM UWB scheme, and the performance has been investigated for each spectrum by measurements in care facilities. The sensor provides the following advantages:

- **Lower-speed ADC and lower-level processor:** It transmits a series of bursts of narrowband pulses where each burst is a sequence consisting of many pulses shifted in frequency from pulse to pulse with a fixed frequency step. Each received narrowband pulse is phase-detected and then combined with the large effective bandwidth (sequentially over many pulses). Therefore, the hardware requirement is less stringent relative to UWB-IR.
• **Inherent DAA function**: It is capable of coexisting with other narrowband wireless systems operating in an overlaid frequency band. It can be designed to have any spectrum hole that does not cause interference with other wireless systems and medical equipment. For example, the location of the spectrum hole can be adaptively assigned according to the interference band detected by the DAA.

From the results, the scheme has been found to be useful and can also coexist with other wireless systems operating in the overlaid frequency band. Also, it has been shown that various states of the patient can be detected including “sleeping in bed,” “sitting up in bed,” “fall,” “walk in room,” “static,” and “going out and in at the door.”

**References**

5. Electronic Communications Committee (ECC), ECC REPORT 120, Technical requirements for UWB DAA devices to ensure the protection of radiolocation services in the bands 3.1–3.4 GHz and 8.5–9 GHz and BWA terminals in the band 3.4–4.2 GHz, Kristiansand, Norway, June 2008.