Forward Scatter Radar for Remote Intelligence of Building Interiors

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ABSTRACT

Through-wall radar allows for remote intelligence of building interiors, including stand-off detection and tracking of persons inside a building. However, reliable radar tracking of people inside a building is not trivial. Conventional, monostatic through-wall radar measures the backscatter of moving people. The backscatter from a human is relatively low compared to the scattering from building features or furniture. In this paper, the Forward Scatter Radar (FSR) concept is proposed to detect and possibly track moving people in specific areas of a building. The FSR concept exploits the forward scatter of objects, which is typically larger than their backscatter; for humans a factor of 20 is possible. In this paper it is shown that stand-off detection of moving people inside a building can be performed reliably and consistently based on their forward scatter.

1.0 INTRODUCTION

At present, the means to covertly obtain inside-building awareness are limited. Most technology reported in open sources is still in the early stages of development (in particular active acoustic surveillance and X-ray imaging), does not allow stand-off operation or surveys only a small portion of the building at a time [1]. Small hand-held through-wall radar is probably the most mature technology for inside building surveillance. Typically these systems need to be pressed against the wall and monitor only the room directly behind the wall. This type of systems is therefore unsuited for covert, long-term surveillance of an entire building.

Larger through-wall radar systems can be used to survey and monitor an entire building while maintaining a certain stand-off distance. These larger radar systems are commonly used in a drive-by fashion to map the building, but in a stationary position they may be used to detect and track moving people inside the building. In addition, through-wall radar may support capabilities such as communication, emitter direction finding, transponder interrogation and navigation support. Thus in principle, (large) through-wall radar systems fulfil a significant part of the information needs for inside building awareness. Radar propagation is however hampered by walls, in particular walls of dense materials (such as concrete) attenuate radar waves considerably. In general, the cluttered inside of a building is a difficult environment for radar. The objects and walls inside a building lead to many, relatively strong, multipath reflections. Due to the multipath reflections, the rather weak reflections from (moving) people may be wrongly positioned or not be detected at all. Thus by deploying a large through-wall radar system (on a single side of the building), some parts of the building cannot be surveyed due to blocking and in other parts the information quality may be poor due to clutter. Therefore, a through-wall radar system should always be a part of a multisensor suite including other sensors with ‘gap filling’ capabilities.

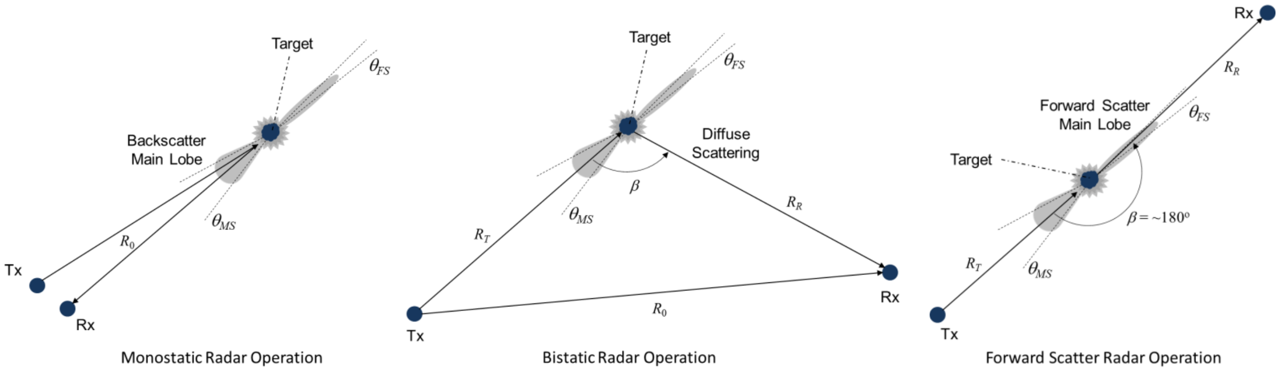
In this paper, the Forward Scatter Radar (FSR) concept is proposed as a ‘gap filling’ sensor for detection of moving people in specific parts of a building. The FSR concept makes use of small transmitters and receivers placed on different sides of the building. Each transmitter on one side of the building forms an FSR system with each receiver on the opposite side of the building. In this way, multiple FSR baselines are formed covering a specific area of the building. People moving within that part of the building will cross the FSR baselines and then their presence will be detected.

The FSR signature of a human results from the interference between the signal received directly from the transmitter and the signal scattered forward by the human. The forward scatter of objects is typically much larger than their backscatter; for humans the forward scatter may be a factor twenty higher than the backscatter. As a consequence, the interference signature exhibits large variations if a person crosses the FSR baseline. Detection of these large signal variations is expected to be more robust than detection based on a person's radar backscatter.

In this study, the feasibility of using the FSR concept for detection of moving people inside buildings has been evaluated. The forward scatter signature of humans has been assessed based on information from literature (Section 2) and free-space simulations and measurements. Finally, the FSR concept was evaluated in a more realistic, through-building measurement scenario. By using these measurements, a comparison is made between the FSR signature and the conventional backscatter signature (Section 3). The conclusions are summarized in Section 4.

2.0 FORWARD SCATTER RADAR

Three different radar operating regimes can be distinguished; monostatic radar operation, bistatic radar operation and FSR operation. As schematically illustrated in Fig. 1. Note that the regimes are determined by the scatter characteristics of the target. Therefore, the actual bistatic angles for which regime transitions occur, depend on the target's size and shape together with the radar wavelength. A radar system operates in forward scatter mode when the bistatic angle β is close to 180°. There is extended literature on scattering effects, Forward Scatter Cross Section (FSCS) for FSR and backscatter Radar Cross Section (RCS) for monostatic an bistatic radar, e.g., [2-8].



Monostatic Radar Operation

Bistatic Radar Operation

Forward Scatter Radar Operation

Figure 1: The three radar operating regimes; monostatic operation (left), bistatic operation (middle) and forward scatter operation (right). The position of the transmit antenna is indicated by "Tx," whereas the position of the receive antenna is indicated by "Rx".

In forward scatter mode, the amount of energy scattered by a target in the direction of the receiver is given by the FSCS. The FSCS can be obtained from Babinet's principle and is given as [2]:

$$\sigma_{FS} = \frac{4\pi A^2}{\lambda^2}, \tag{2.1}$$

in which A is the area of the target's silhouette and λ is the radar wavelength. This expression is valid when the bistatic angle is indeed close to 180°, the target's dimensions are larger than the radar wavelength and the target is in the far field of both the transmitter and receiver. This equation embodies an important result: it states that, if a target is opaque for radar frequencies, its FSCS is determined by its area and radar frequency only. As a result, the use of Radar Absorbent Materials (RAM) or stealth designs does not reduce the FSCS. Traditionally, FSR has therefore been applied as perimeter defense against stealth targets.

In literature, analyses of the FSCS of different target types and shapes have been presented, based on both simulations and measurements. However, only few results with respect to the FSCS of humans have been reported [7, 8]. The FSCSs reported for humans follow from electromagnetic simulations in which a human is modeled as a perfectly conducting cylinder. In these simulations, primarily low radar frequencies have been used. For frequency bands relevant for through-wall radar applications, only two human FSCSs are mentioned: 22.0 dBm^2 for 1 GHz frequency and 33.2 dBm^2 for 3 GHz frequency. These values are based on simulations in which a human is modeled as a perfectly conducting cylinder of 0.5 m diameter and 1.8 m length.

By exploiting (2.1), the FSCS of an opaque cylinder follows as:

$$\sigma_{FS} = \frac{4\pi L^2 D^2}{\lambda^2}, \tag{2.2}$$

in which D and L are the cylinder's diameter and length respectively. By considering an opaque cylinder of 0.5 m diameter and 1.8 m length, the FSCS is 20.5 dBm^2 for 1 GHz frequency and 30.1 dBm^2 for 3 GHz frequency. These FSCS values are well in line with the values as reported in literature, which are obtained with electromagnetic simulations. The backscatter RCS of a similarly-sized cylinder can be computed with the aid of [9]:

$$\sigma_{RCS} = \frac{\pi L^2 D}{\lambda}. \tag{2.3}$$

By using (2.3), the corresponding RCS of a human follows as 12.3 dBm^2 for 1 GHz frequency and 17.1 dBm^2 for 3 GHz frequency. Thus the FSCS of a human is indeed higher than the RCS.

The width of the forward scattering main lobe is given as:

$$\theta_{FS} = \frac{\alpha\lambda}{D}, \tag{2.4}$$

in which D is the target dimension. The factor α is around one for rectangular and spheroidal targets and may vary from one to four for complex targets [8]. As can be seen, the 'beamwidth' in FSR is independent of the actual antenna beamwidth. The width of the forward scattering main lobe depends on the width of the first Fresnel zone, thus on the geometry of the transmitter and receiver pair. Consequently, in FSR there is no need for a large antenna to confine detections in angle, i.e., to accurately determine the moment a person actually crosses the baseline between the FSR transmitter and receiver.

3.0 FSR SIGNATURE SIMULATIONS AND MEASUREMENTS

In this section, the signature of a target crossing the FSR baseline is assessed. This assessment is performed using free-space simulations based on Huygens-Fresnel wave propagation, including Kirchhoff's obliquity factor and the application of Babinet's principle. The result is compared to a free space measurement, see Fig. 2. The simulation consists of a large metal sheet moving along a track perpendicular to a 12-m FSR baseline and it crosses this baseline halfway between the transmitter and receiver. The same setup was used for the measurements, although in the measurements a person was carrying the sheet, moving fairly slow (hence the difference in time scale). The radar frequency is 2.4 GHz.

The characteristic W-shaped signature (see for instance Fig. 7 in [8]) is clearly visible in both the simulation and measurement. Also the drop in power due to the interference is of the same order. The noisy structure of the measurement (and the separate noise measurements shown in red in the right panel) is due to interference, probably from a Wireless Fidelity (WiFi) access point. From these results it was concluded that the forward scatter signature of a human is indeed prominent and suitable for reliable detection of people crossing the FSR baseline. The large constant signal (indicated as free space in the simulation) can be subtracted from the measured signal. The resulting signal is then purely the forward scattering from the metal sheet. This forward scatter component can be compared to the related backscatter component, to assess whether the forward scatter signature level is indeed higher than the backscatter signature level.

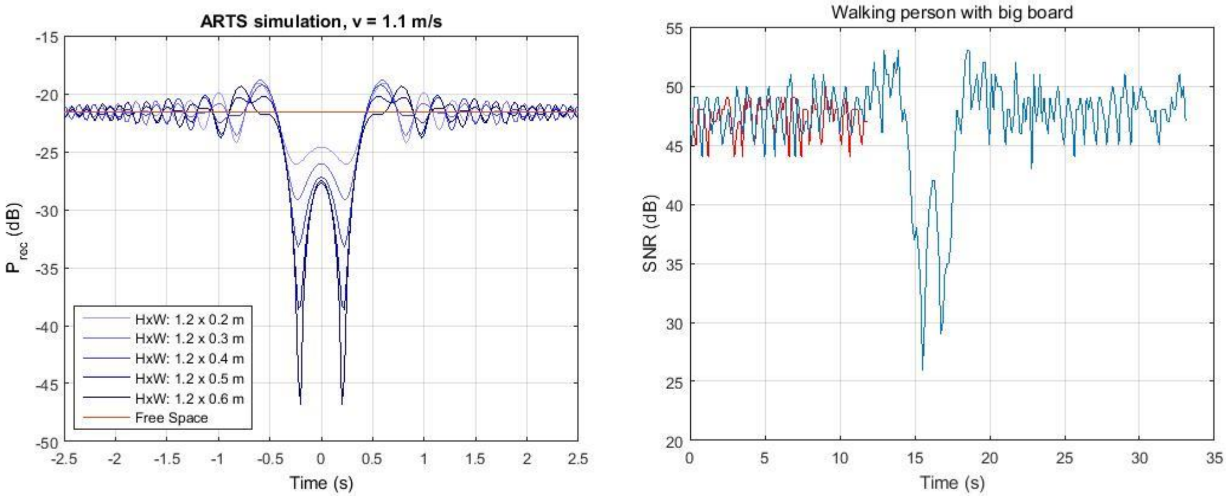


Figure 2: FSR signature of a person carrying a large metal sheet. Left: simulations for different sizes of sheets. Right: measurement of a person carrying a metal sheet of 1.2 m by 0.6 m.

For the comparison of the FSR and backscatter signatures, a realistic measurement scenario was selected, taking into account the effects of propagation through walls, multipath reflections and blocking. The measurement scenario is depicted in Fig. 3. During these measurements the transmitter was placed in the courtyard of a small bungalow facing the brick wall of a storage room. The receiver was placed at the other side of this room, facing a brick wall with three small windows just below the roof. Along the walls and in the middle of the storage room a total of four metal shelving units were located, packed with crates, boxes, and various metal objects. Consequently, severe blocking and multipath effects were expected. Note that the forward scattering signal travels through two brick walls and all four shelving units, whereas the backscatter signal travels through a single brick wall and a single shelving unit, but in two directions.

The measurements have been conducted with the SAPPHIRE radar system. SAPPHIRE is an experimental 2.4 GHz through-wall radar system, designed to be operated from a vehicle [10]. While driving past a building, 3D measurements are obtained enabling the generation of a map of the building structure and extraction of building features [11]. It was shown that SAPPHIRE is capable of penetrating up to four walls. In a stationary setup, through-wall detection and tracking of moving persons was demonstrated in the same bungalow as shown in Fig. 3. The SAPPHIRE system comprises a Multiple Input/Multiple Output (MIMO) array of four transmit elements and eight receive elements. For the FSR measurements, a single transmit/receive channel was used: the radar front-end including the transmit element was placed in the courtyard, whereas one of the receive elements was brought to the other side of the storage room using an extension cable as is illustrated in Fig. 3.

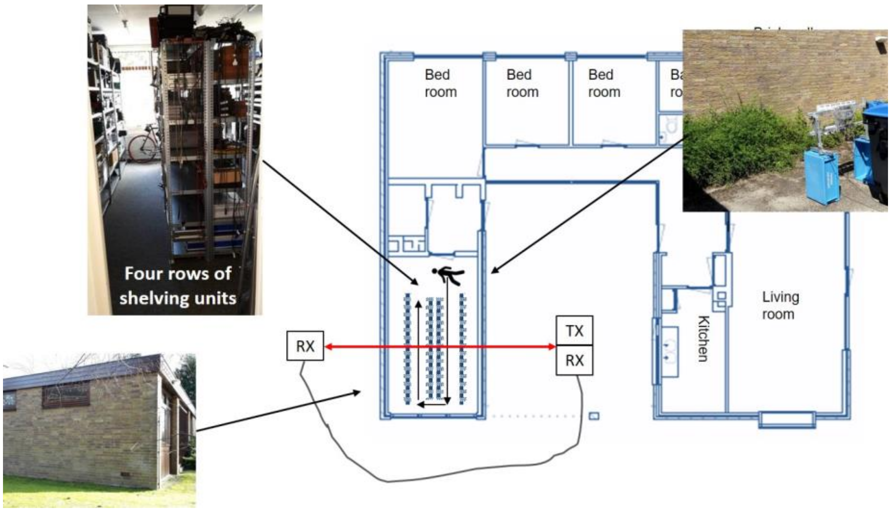


Figure 3: The geometry of the stand-off through-building measurements.

During the measurements, a single person walked into the storage room, turned around at the back of the room and then left the room again. The measured forward scatter and backscatter signatures of a walking person are present in Fig. 4. For detection, a fixed-threshold detector is used on the background subtracted forward scatter signal (left panel) and background subtracted backscatter signal (right panel). The detection threshold is indicated by the dotted line in each panel. In both cases, the person crossing the radar baseline (the red arrow in Fig. 3) is detected twice; going into the room and subsequently leaving the room.

From Fig. 4 it is clear that the signature level is higher for backscatter then for forward scatter. This is likely due to the geometry; a different geometry might be required to validate the assertion that backscatter signature levels are higher on average. Another noticeable difference is the width of the signature. As stated in Section 2, the width of the forward scatter signature depends on the width of the first Fresnel zone and is independent of the actual antenna beamwidth. The width of the backscatter signature, on the other hand, depends on the antenna beamwidth. Since single elements were used for these measurements the antenna beam, and thus the measured backscatter signature, is relatively wide. Clearly, the FSR signatures are narrower. Both signatures exhibit multiple threshold crossings over a broad interval, which could lead to the erroneous conclusion that several people were moving around the room.

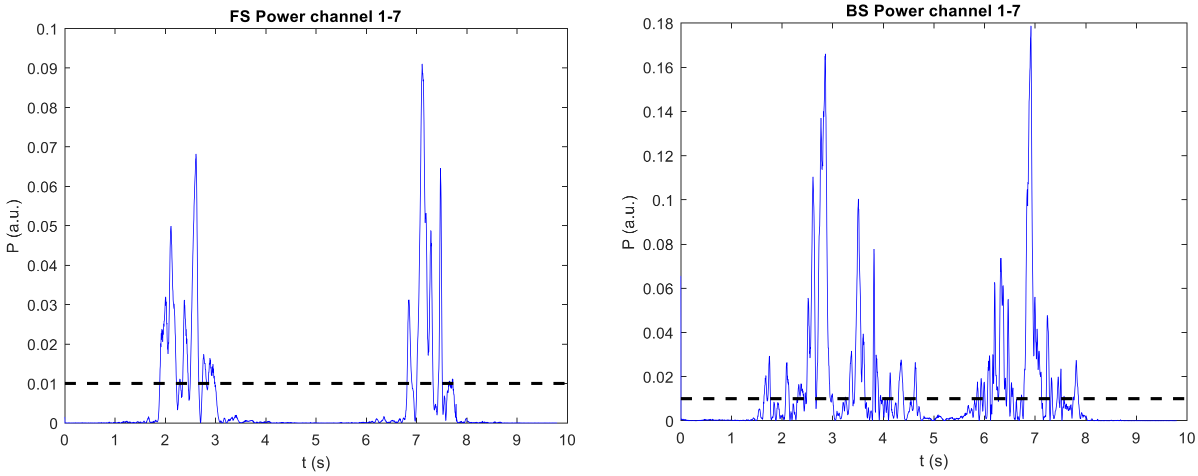


Figure 4: Comparison of the forward scatter (left) and backscatter (right) signatures of a human.

4.0 CONCLUSION

In this paper a novel application for FSR is introduced, namely detection of motion inside buildings. Due to the increase in cross section it was expected that the forward scatter of a person would yield a larger probability of detection than the related backscatter. Furthermore, due to the narrower 'beamwidth' in case of FSR, it was expected that the moment a person actually crosses the radar baseline can be determined more accurately than in case of backscatter radar. Measurements of the forward scatter and backscatter signature of a person, using a stand-off through-wall radar, demonstrated that the baseline crossing can indeed be better pinpointed, but it did not show the expected improvement in signature level. More measurements are required for a true assessment of the detection performance of FSR with respect to backscatter radar.

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