Magic Mirrors: Active frequency-selective surface beacons for synchronization, communication, and identification in biomedical radar

Alan Bannon*†, Michael Woollard‡, Matthew Ritchie‡, Timothy Constandinou*†
*Department of Electrical and Electronic Engineering, Imperial College London, London, SW7 2AZ, UK
†UK Dementia Research Institute, Care Research & Technology Centre at Imperial College London and University of Surrey
‡Department of Electrical and Electronic Engineering, University College London, London, WC1E 6BT, UK
Email: a.bannon@imperial.ac.uk

***Abstract*—Radar systems are often considered as pure observation platforms, gathering data on unaware or non-cooperative targets. The options for a target wishing to transmit information back to an observing radar sensor are limited, complex, and often require clock synchronisation. This work presents the design and analysis of a series of active frequency-selective surface (AFSS) based beacons that can modulate their reflectivity in a controllable manner. Using this modulation with an on-off-keying (OOK) scheme and a communications protocol based on reversals and Barker codes, it is shown how these beacons may be located by a radar, and how information may be encoded and transmitted from beacon to radar without the need for clock synchronization. Several practical applications are explored, including identifying individuals and enabling clock synchronization between channel-separated radars.**

***Index Terms*—Biomedical radar, networked radar, SoC radar, UWB, indoor radar, active frequency selective surface, metamaterials, AFSS**

I. INTRODUCTION

Radar systems conventionally analyze reflections directly or indirectly originating from targets of interest - in the case of biomedical radar systems, these targets are generally individual people. Should any additional information be required, such as timestamps or information the target wishes to transmit to the radar system, this must either be sent on a separate channel, or actively transmitted, requiring at minimum a level of clock-synchronization between the active transmitter and the receiving radar [1].

This work introduces a method involving the development of a beacon device using active frequency-selective surfaces (AFSS). These surfaces can modulate their reflectivity to appear as a controllable vacillating target to an observing radar system. Furthermore, this work will demonstrate how, through the implementation of a customized communication scheme, these beacons can effectively modulate data onto the received radar range profiles. While many potential applications exist for this technique, this work will explore potential applications in biomedical radar sensing.

A. *Challenges in biomedical radar systems*

Numerous challenges remain in biomedical radar systems, particularly concerning the synchronization of networked sensors and the robust identification of individuals.

Given the highly individual nature of biomedical data, it is crucial to distinguish between individuals when multiple individuals are within the radar system's view. Currently, most focus lies in utilizing biometric information derived from radar data for this purpose. However, there are scenarios where only a subset of individuals may be of interest; for instance, in situations involving a caregiver or clinician interacting with a patient only the patient's data is of interest. In such cases, there is both a technical and legislative imperative [2] to ensure the exclusion of non-patient data from storage and analysis.

The increasing complexity of biomedical radar systems often necessitates the networking of sensors to provide coverage over larger areas and exploit data fusion across multiple overlapping sensor fields-of-view. However, maintaining sufficient clock synchronicity between multiple radar sensors, particularly when channel-separation may be enforced, is technically challenging. This synchronicity is vital to allow successful data fusion of time-varying signals, such as heart-beat and gait cycles.

B. *Active frequency-selective surface beacons*

AFSS are a sub-category of meta-materials. Frequency-Selective Surfaces (FSS) exhibit diverse responses (absorption, reflection, transmission) to radio frequency (RF) energy across a spectrum of frequencies. AFSS provide in addition the capability to change some or all of these responses and/or the frequency at which they occur. From a radar sensing perspective, an AFSS capable of dynamically changing reflectivity introduces a fluctuating target to a radar sensor. Consequently, changes in reflectivity will be the most visible to an observing radar sensor, regardless of other characteristics.

Given the intricate topology and tight tolerances required in the design of high-performance AFSS devices, this work opts to use a proven and well-understood AFSS design based on planar circular elements and PIN diodes [3] as a proof

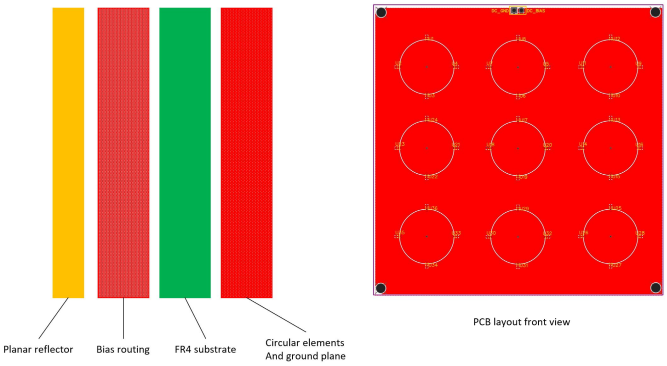

Fig. 1. Structural diagram of the proposed AFSS beacon device: R - front view generated by PCB layout software. L - side view of layers.

of concept. The original design presented in [3] is optimised to function around the 2.4 GHz band, and will require modification to function at other frequency ranges. In addition, the existing design is intended to act as an isolator and as such relies on the modulation of absorption as its active component. Thus to form the beacon device, an additional reflector is required behind the AFSS to enable the modulation of absorbency to manifest as modulation in reflection. A graphical representation of this configuration, along with the proposed structure of an AFSS beacon device, is depicted in Fig. 1.

II. METHODS

This work will cover the design and analysis of several experimental AFSS beacons. As has been discussed, the AFSS design selected for this work requires an additional reflector to maximise visibility to radar. For most of the designs considered, a simple planar reflector has been used, however a chaotic polyhedral reflector has also been briefly considered.

The radar system used in this work is a networked radar system based on the Novelda X4 sensor [4]. The X4 is a pulsed sensor that uses swept-threshold sampling (STS) to directly capture RF reflections [5], [6]. Unfortunately, due to the implementation of STS with a chaotically dithered sampler, channel separation is enforced, with no method available to synchronise radar clocks or samplers. This limitation means that many of the contemporary methods of synchronization or registration of networked radar systems are not possible to implement; forcing the system to operate in a multi-static-like mode of independent-but-networked sensors. The networked radar system used in this work produces data at 500 range-profiles per second from an internal direct-RF sampling rate of approximately 24 GHz.

Finally, in order for meaningful information to be conveyed between beacon and radar sensor, a communications and encoding scheme will be designed and implemented using on-off-keying (OOK) as the fundamental modulation.

A. Devices

As shown graphically in Fig. 2, the PIN diode-based AFSS design chosen for this work has a fairly simple topology of 4 diodes connecting circular elements to a surrounding ground plane. Bias to the diodes is supplied by traces on the reverse of the manufactured PCBs to the center of each circular element. To operate the AFSS and change the absorbency of the surface the diode bias voltage is increased to place the diodes into a forward-biased conducting state. Element size is driven by the center frequency of the radar system, in this case approximately 8 GHz. Multiple AFSS PCBs were designed and manufactured with element sizes of $\frac{1}{4}$, $\frac{1}{8}$ and $\frac{1}{16}$ λ. These designs are shown in Fig. 2

B. Communications and encoding scheme

Consider the AFSS hardware as an amplitude modulation (AM) system, where the carrier is the radar cross-section (RCS) of the backing reflector. The modulation is imposed by varying the absorbency of the frequency-selective layer, which results in an observable change in returned power to the interrogating radar system.

This approach is constrained by a number of adversarial factors. Firstly, the system is entirely passive with respect to transmitted energy; the interrogating radar must provide sufficient illumination for the backscattered energy to be detectable under the inherent constraints of the radar waveform and theory of operation. Secondly, as a result of the carrier being RCS, all other targets which the radar is interested in detecting are noise from the perspective of the communication channel. This includes any target which may be wearing/carrying/manipulating a beacon. A human target may present a large RCS relative to that of a wearable beacon, posing a challenge to the detection of the beacon.

To successfully communicate under such constraints whilst satisfying the goal of near-realtime processing, a robust yet efficient communication protocol is required. As alluded to earlier, the use of RCS as a carrier where the beacon may be in close proximity to large targets precludes the use of “tone on” to signal the start of a transmission. Instead, we apply reversals to induce a strong vacillating signal at the baud rate of the channel. This is both analytically trivial and computationally efficient to detect simultaneously across all range bins using a temporally windowed method such as the short-time Fourier transform.

Once a bin containing a possible beacon signal is identified, frame synchronisation is achieved through a leading Barker code. One bit of null padding follows to maintain even bit alignment; this prevents phase inversion between the current transmission and those immediately preceding/following, a situation which would adversely impact the detection of the transmissions across temporal windows containing multiple data frames. A fixed-width byte-aligned data payload follows; for the experiments described in this paper, 32 bits of payload are present unless otherwise specified. As is typical in wireless communications, forward error correcting schemes can be applied at this stage to mitigate the impact of noise on the channel.

The overall length of each transmitted frame is determined by a couple of fundamental design tradeoffs. The accurate

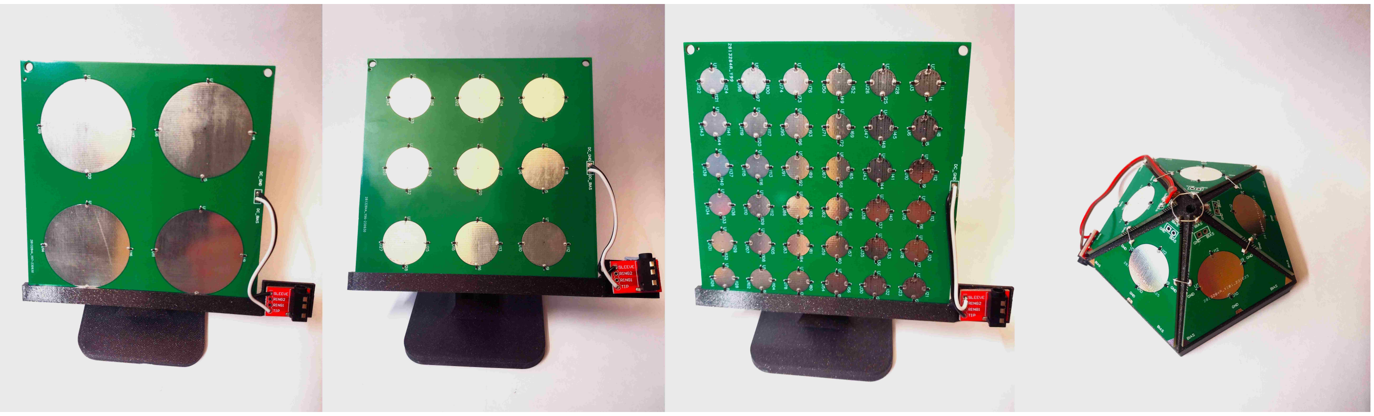

Fig. 2. Front views of AFSS beacon designs. From right: 1/4 λ, 1/8 λ, 1/16 λ, 1/8 λ tessellated. Note the 3.5mm audio connectors used to manage bias signals.

detection and demodulation of the modulated signal in a single range bin requires that range profiles must be available at at least the Nyquist rate for the chosen baud rate. In the current experimental system, range profiles are available at a frequency of 500 Hz for a maximum baud rate of 250 symbols/second. Next, we must consider that the detectability of the signal is improved by decreasing the baud rate; however, the beacon may be mobile within the scene. Range migration will increase the number of confuser targets (in this context, sources of noise power) within the range gate occupied by the beacon and decrease SNR.

For the purposes of this proof-of-concept, parameters have been chosen as shown in Table I

Baud period	Reversal count	Barker code	Payload Length
36ms	64	7 bits + 1 padding	32 bits

TABLE I
COMMUNICATIONS SCHEME PARAMETERS USED FOR TESTING.

III. RESULTS AND PERFORMANCE

A. *Characterization of devices*

Several variations of the proposed AFSS beacon design were fabricated and tested. To simplify logistics and testing, devices under test were connected via standard 3.5mm TRRS audio connectors and cables to a custom built controller based on the Raspberry Pi Pico development board which was used to generate square-wave bias signals to drive the AFSS devices.

1) Azimuth modulation amplitude: The original AFSS design [3] noted that a drawback of the design was a relatively narrow effective azimuth. Given that most of the designs presented in this work use planar reflectors it can reasonably be expected that the effective azimuth may be similarly narrow or even narrower.

Measurements were performed manually using a Novelda X4 sensor illuminating the AFSS beacons which were turned in azimuth between measurements. A square-wave was used to bias the AFSS, and the difference in reflected amplitude between forward-bias and reverse-bias states was measured. The results of these measurements are shown graphically in Fig. 3.

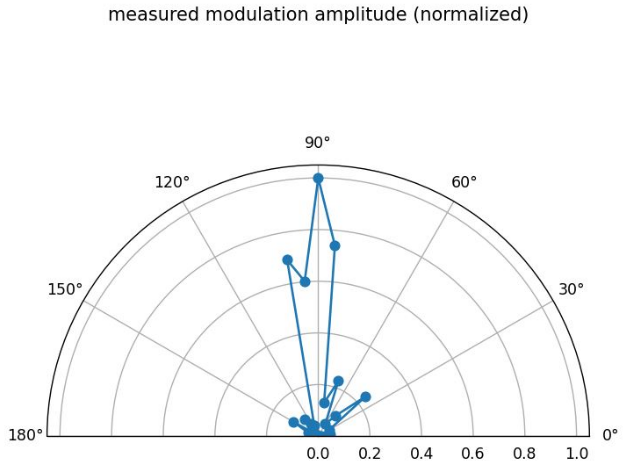

Fig. 3. Manually measured azimuth modulation amplitude of a 1/16 λ AFSS beacon (normalised).

As expected the azimuth amplitude response is narrow, and off-bore-sight modulation may have significantly reduced amplitude.

2) Element size modulation amplitude: Several AFSS beacons were fabricated with element sizes of $\frac{1}{4}$, $\frac{1}{8}$ and $\frac{1}{16}$ λ of the center frequency of 8 GHz. To investigate how element sizing may effect the modulation amplitude, each AFSS was placed 750 mm away from a Novelda X4 sensor, square-wave was used to bias the AFSS, and the difference in reflected amplitude between forward-bias and reverse-bias states was measured. The results of this experiment are shown in Fig.4.

There appears to be a significant positive correlation between element size and modulation amplitude response. While

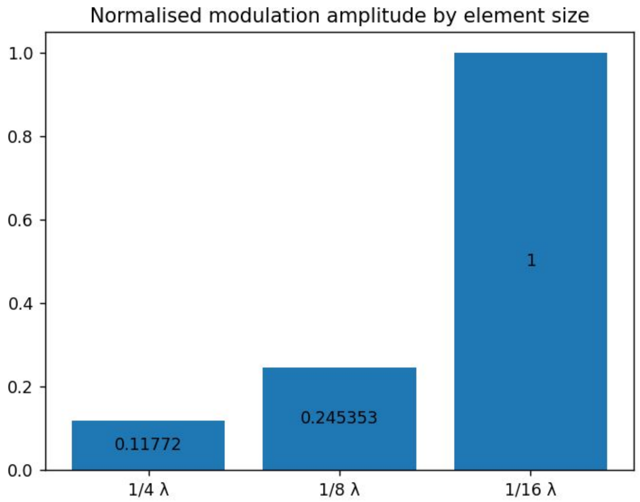

Fig. 4. Element size vs modulation amplitude. Measurements taken at 750mm. 8GHz center frequency.

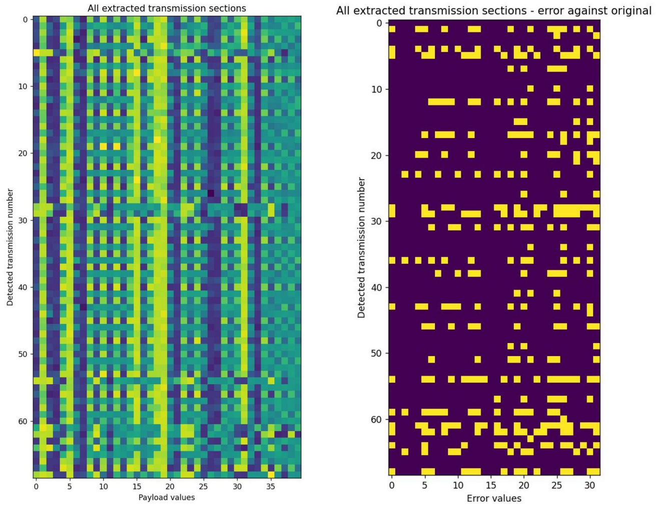

Fig. 5. Example output of a BER test. L - extracted payload sections. R - bit errors compared to expected payload.

this effect could be purely related to the size of the element, another explanation could be the different ratios of element area to diode count. Even as element size was changed the diodes per element was constant at 4 diodes per element, meaning that as element size was reduce the conductance available per square millimeter of element. Further investigation with multiple diode counts on consistently size elements is needed to determine the exact cause of this relation.

3) Tessellated design: As shown in Fig. 2, to attempt to mitigate the narrow effective azimuth of the AFSS, a tessellated design was fabricated to reduce the incident azimuth for as many possible sensor location as possible. Unfortunately, this design has not yet been well evaluated, and detailed investigation of this approach will be conducted in future.

B. Characterization of communications channel

To evaluate the use of the proposed communication scheme, a millisecond UNIX timestamp was used as a sample payload, along with the communications scheme parameters given in table I. An AFSS beacon was placed at various distances from an X4 sensor and the resulting bit-error-rate (BER) is shown in Fig. 6. An example of the extracted payload sections and a comparison to the expected payload is shown in Fig. 5.

It was observed that below 1m the BER remained stable at 0, and increased very rapidly to around 50% past 1.5m. At present the authors believe this very sharp change may be driven by a failure in the barker code detection step of the communications scheme, however further testing is required to confirm this.

C. Synchronization of networked radar systems

In the case of the Novelda X4, and many other low-cost system-on-chip (SoC) radar sensors, channel separation is enforced using a chaotic dither in the sampler ADC. While this simplifies operating multiple radars in the same space, it also makes conventional techniques for synchronization impossible. However, an AFSS beacon visible to multiple sensors will present a common event that can be used to determine the slow-time clock offsets between multiple sensors.

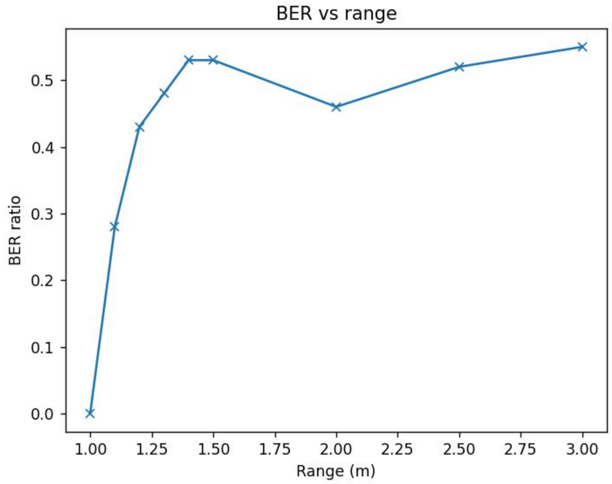

Fig. 6. Manually measured BER as a function of range for a 1/8 λ AFSS beacon

In some circumstance, such as the design and validation of networked radar systems, this information is used as a testing method to ensure the existing clock synchronization method - for example NTP - is providing sufficient synchronicity. In other conditions, a consistent shared slow-time clock could be vital to ensure synchronization is maintained during analysis of high-frequency period signals, such as individual section of a heart-beat rhythm

To explore this application, two networked X4 sensors were placed to view a single AFSS beacon. The networked sensors used NTP from a local network server to set and synchronize their internal clocks. After data recording had

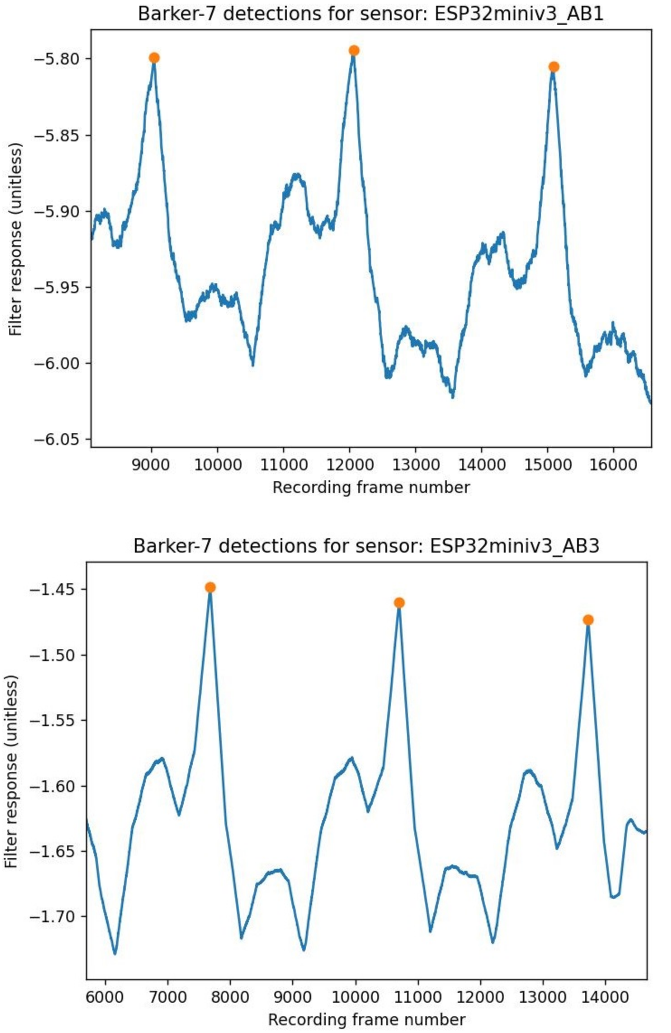

Fig. 7. Detected barker-7 codes from 2 networked radar sensors observing the same AFSS beacon. Note that x-axis is recording frame number from each sensor, not timestamp. Actual clock-skew was in the 50-100ms range.

run for approximately 30 seconds the beacon was activated with reversal modulations followed by a barker-7 code and no following data payload. The modulation scheme was repeated periodically until the end of the recording. For each sensor the beacon was located in range using the reversal frequency, and the time-offsets between the barker-7 codes were established. The output of the barker code detection stage is shown in Fig. 7. The two sensors were determined to have a clock-skew of approximately 70ms +/- 4ms - an error roughly aligned with the Nyquist frequency of the radar sampling.

D. *Identification of individuals*

As a proof-of-principle test, a dataset was collected using a single radar sensor observing two individuals, A and B, seated at different distances from the sensor. For the proposes of the test, individual A acted as a ”researcher” of no interest to a hypothetical study, while person B acted as a “subject” whose data should be recorded. For the 30s duration of the test both individuals remained seated and breathed normally. Classically, without additional information or some previous recognition training dataset identifying either individual from such limited data would be extremely challenging [7]. However, individual A was wearing an AFSS beacon attached to their shirt pocket configured with a simplified modulation scheme of reversals followed by a Barker-7 code.

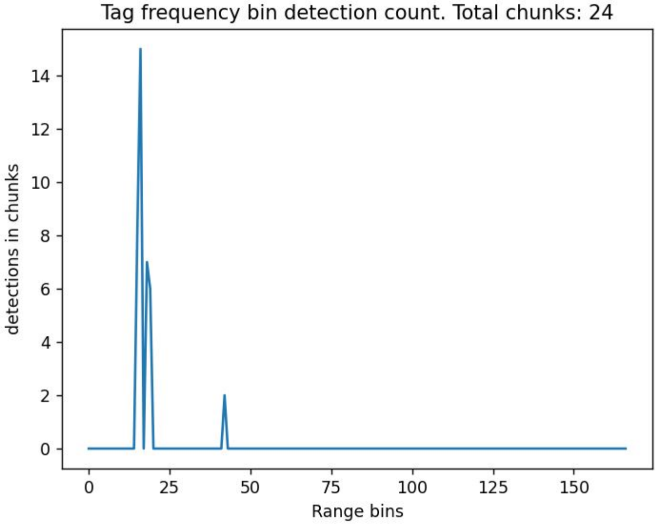

Fig. 8. Detection count of tag reversal frequency vs range showing tag located at the range occupied by individual A.

The data from this test was high-pass filtered in slow-time to show visually the contributions made by the breathing movements of each individual. This visualization is presented in Fig. 9.

Searching for the expected reversal frequency resulted in a strong detection at range bin 16 - the expected location for individual A. This frequency search and detection is shown in Fig. 8. From this, searching for the Barker-7 with a matched filter resulted in a high-confidence detection, indicating that the beacon was highly likely present in bin 16. Of note, this detection was made despite the beacon being directly attached to individual A’s clothing, and thus itself moving with their chest motion during the test.

IV. DISCUSSION AND FUTURE WORK

This work has shown how AFSS beacons may be practically designed and fabricated to function with existing radar systems. Further, the performance of these AFSS beacons has been evaluated, and a encoding and communications scheme explored. Finally, some practical applications have been demonstrated.

While some aspects of the performance of the design are somewhat challenging, particularly the narrow azimuth response, the basic principles of the technique have been established, and hopefully future work will address these issues.

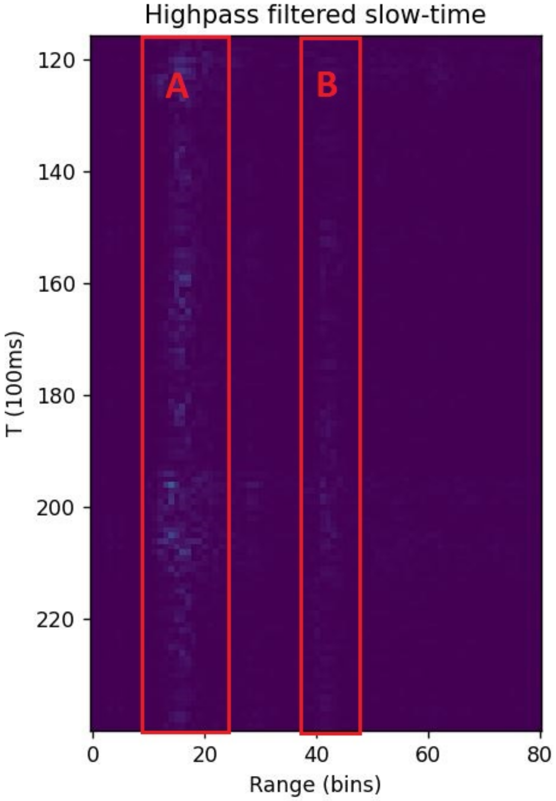

Fig. 9. High-pass filtered slow-time range profiles showing individuals A and B at different ranges from the radar sensor

The results presented were at times limited by reliance on manual measurement. This particularly effected the azimuth response characterization. In future, the use of a motorised turntable and automatic data capture will allow results with much higher granularity.

In addition to better experimental data, simulating the proposed designs using RF or EDA software could allow a better understanding of the frequency-response of the AFSS and might suggest changes to improve magnitude and azimuth responses.

One of the key contributors to the narrow azimuth modulation response is very likely the design of AFSS chosen. AFSS designs with a wider azimuth response would almost certainly improve performance, and further work to explore this possibility is ongoing.

Moreover, while some proof-of-principle experiments have been conducted to showcase potentially real-world applications, there remains work to conduct testing in complex uncontrolled real-world environments.

Finally, while this work has considered applications of AFSS beacons to biomedical radar sensing, many other areas could potentially use the same techniques for a variety of purposes. For example, an automotive application could conceivably be encoding unique ID’s or maneuvering information onto reflections from each vehicle.

ACKNOWLEDGEMENTS

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