2024 IEEE Texas Symposium on Wireless and Microwave Circuits and Systems (WMCS) | 979-8-3503-4937-5/24/$31.00 ©2024 IEEE | DOI: 10.1109/WMCS62019.2024.10619042

# Feasibility Study of Employing MIMO SFCW Radar using Doppler Division Multiple Access

Derek Thompson
*Dept. of Electrical and Computer Engineering*
*Texas Tech University*
Lubbock, TX, USA
derek.thompson@ttu.edu

Aaron B. Carman
*Dept. of Electrical and Computer Engineering*
*Texas Tech University*
Lubbock, TX, USA
aaron.b.carman@ttu.edu

Changzhi Li
*Dept. of Electrical and Computer Engineering*
*Texas Tech University*
Lubbock, TX, USA
changzhi.li@ttu.edu

***Abstract*— Multiple input multiple output (MIMO) radar systems have seen considerable use due to their ability to simulate a large antenna array with few physical antenna elements. The performance of microwave sensors can benefit greatly from MIMO techniques. This paper presents a simulation study to determine the feasibility of MIMO radars leveraging the stepped-frequency continuous wave (SFCW) transmit scheme and investigates the possibility of utilizing Doppler division multiple access (DDMA) for MIMO SFCW radar. Although DDMA is a well-known slow-time phase coding method to synthesize frequency division and generate orthogonal MIMO waveforms, it has not been leveraged in the context of SFCW radar. Therefore, this paper compares SFCW with the more common frequency modulated continuous wave (FMCW) technique to compare the merits and demerits of each transmit scheme. A MATLAB simulation is presented to analyze the possibility of DDMA SFCW radars.**

***Keywords — SFCW, MIMO, DDMA, FMCW, slow-time, phase coding, frequency division, simulation, feasibility***

## I. Introduction

Multiple input multiple output (MIMO) techniques are commonly employed in modern radar systems and are especially useful in application requiring high fidelity detection and angular resolution [1]. MIMO radar systems leverage multiple transmitter and receiver chains to improve key factors such as signal-to-noise ratio (SNR) and target resolution. Improvement in such factors leads to more effective detection and improved angular resolution. However, to realize these benefits the individual transmitters must be distinguishable, or orthogonal. Common techniques for achieving orthogonal transmit channels in MIMO radar include time division multiple access (TDMA) [1] and frequency division multiple access (FDMA) [2]. However, a modified version of FDMA, known as Doppler division multiple access (DDMA) combines the advantages of both methods by allowing continuous transmission of each channel while maintaining relatively simple hardware requirements [3]. However, a well-known drawback of DDMA is a reduction in maximum unambiguous velocity through the division of the Doppler spectrum among the number of transmitters ($N_{TX}$).

The authors wish to acknowledge the National Science Foundation (NSF) for funding support under Grant ECCS-2030094.

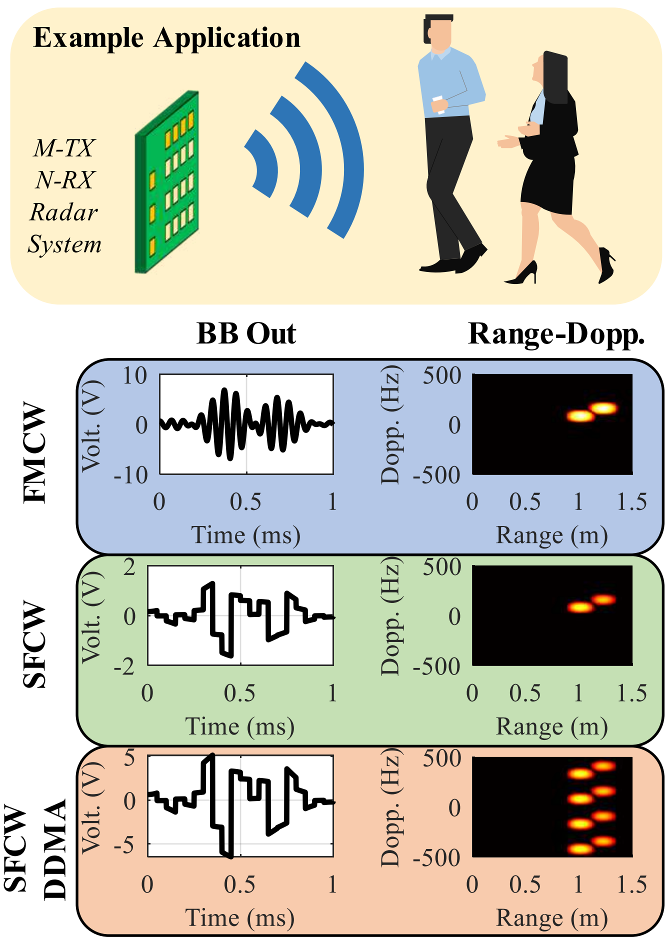


Fig. 1. A graphical comparison of induced baseband responses and correcsponding range-Doppler maps for FMCW, SFCW and SFCW leveraging DDMA.

In typical MIMO radar systems, FMCW is the preferred transmit scheme due to its 2-D signal structure. This means, FMCW radar can intrinsically detect range and velocity through range-Doppler processing [4]. However, the wide continuous bandwidth of FMCW contributes to spectral congestion, and causes radar to radar interference [5]. Therefore, the investigation of other transmit schemes such as stepped-frequency continuous wave (SFCW) can help to mitigate the

979-8-3503-4937-5/24/$31.00 ©2024 IEEE

drawbacks of FMCW radar. Nevertheless, there are currently a limited number of MIMO radars leveraging SFCW [6]. Fig. 1 shows an example SFCW response in a MIMO DDMA system and a graphical comparison with FMCW. To analyze the feasibility of the SFCW transmit scheme in DDMA MIMO radar systems and combat the drawbacks of FMCW, this paper presents a simulation study of the feasibility of SFCW DDMA radar and analyzes the merits and demerits of SFCW and FMCW radar to leverage the potential benefits of SFCW in the context of MIMO radar.

## II. SFCW DDMA Radar Theory and Simulation

### A. SFCW Radar Theory and FMCW Comparisons

SFCW radar is an architecture commonly used for applications including ground penetrating radar [7], [8], and through the wall imaging radar systems [9], but is rarely leveraged for other applications, including MIMO systems [6]. SFCW radar is akin to the more commonly used FMCW radar. FMCW radar transmits a linearly increasing frequency ramp to induce a baseband beat frequency directly related to target range. SFCW radar, on the other hand, utilizes $N$ equally spaced frequency steps which creates a discretized frequency ramp. Since both share a 2-D signal structure, they can be processed similarly using typical range-Doppler processing techniques. Fig. 2(a) illustrates the difference between the transmit schemes in the frequency domain, with the resulting time-domain baseband signals shown in Fig. 2(b). The instantaneous frequency transmitted by the $n^{th}$ frequency step of a generalized SFCW radar is given by (3) where $f_0$ is the initial transmission frequency at $n = 0$ and $\Delta f$ is the frequency step.

$$f_i(n) = f_0 + n\Delta f \tag{1}$$

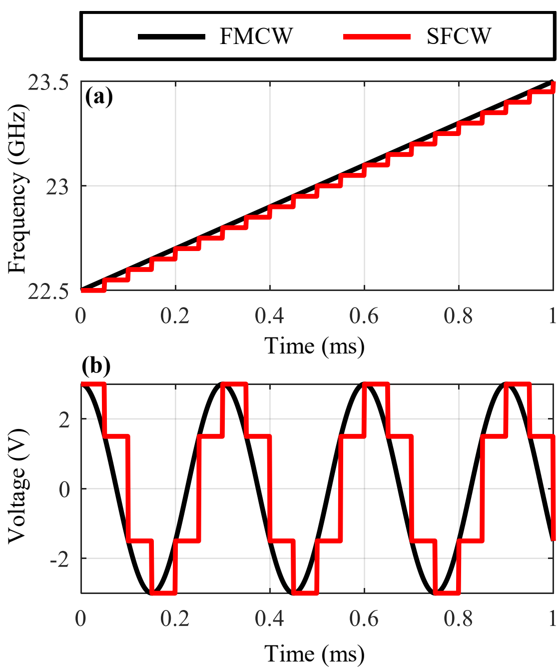


Fig. 2. FMCW/SFCW chirp (a) and baseband (b) signal comparison. From the graphs, the SFCW signals (red) can be treated as discrete FMCW waves (black).

Some key observations can be made from Fig. 2 and (1) that differentiate SFCW from FMCW in terms of practical applications. The first is that while both architectures utilize an overall bandwidth of $B$, the instantaneous bandwidth of SFCW radar is narrower than FMCW because each discrete frequency step is constant [10]. At a given instant, SFCW looks like a simple continuous wave radar, providing an advantage compared to the continuous bandwidth of FMCW. Another advantage of SFCW radar manifests in the requirements for supporting hardware. Because only one analog-to-digital converter (ADC) sample is required per $\Delta f$, the required sampling rate of a system leveraging SFCW is lower than an FMCW system [10]. Furthermore, the baseband signal can be used alongside range-Doppler processing to extract target velocity via the Doppler effect [3]. As noted in [10], under the assumption of negligible target movement in a pulse repetition interval (PRI), the discrete frequency steps of SFCW radar act as a CW radar when reconstructed along the slow time axis.

The frequency steps of an SFCW system also provide disadvantages compared with FMCW, primarily in the form of new ambiguities introduced. The baseband beat frequency of an FMCW radar is only limited by ADC sampling frequency. According to the Nyquist sampling theorem, if the sampling frequency of the ADC is at least twice that of the recovered beat frequency, the target range can be recovered unambiguously assuming the propagation time does not exceed the PRI. However, SFCW radar's unambiguous range is inversely related to the frequency step $\Delta f$ by (2) where $c$ is the speed of light [10].

$$R_{unambigous} = \frac{c}{2\Delta f} \tag{2}$$

The unambiguous range described by (2) assumes that the SFCW radar system leverages both in-phase and quadrature ($I/Q$) channels, however. The maximum unambiguous range of an SFCW radar using scalar baseband outputs is half that of its $I/Q$ counterpart. Intuitively, this can be understood by considering that the $I$ and $Q$ channel information can be placed on a unit circle. If only the $I$ channel is considered, it is not possible to distinguish between a point at $\pi/2$ and a point at $3\pi/2$ since the real component is equal in both cases. As such, while complex baseband data can support up to a $2\pi$ phase difference between frequency steps, scalar baseband data can only support up to a $\pi$ phase difference, further limiting the unambiguous range of a practical or low-cost radar system using scalar baseband data. This is implemented in simulation with results shown in Fig. 3. From Fig. 3(a). The impact of the scalar unambiguous range can be clearly seen, with a mirror image present across the unambiguous range. If, however, complex baseband data is considered while all other radar parameters are left equal, the unambiguous range is effectively doubled. These results are shown in Fig. 3(b), where, in contrast to Fig. 3(a) only the real target remains.

Despite sharing a similar 2-D signal structure, single channel FMCW radar systems do not suffer from the same range ambiguity. Although each transmit scheme presents its own design tradeoffs, SFCW has merit in certain wireless sensing environments. TABLE I presents a direct comparison of key features of both SFCW and FMCW as it relates to design considerations in a wireless sensing application.

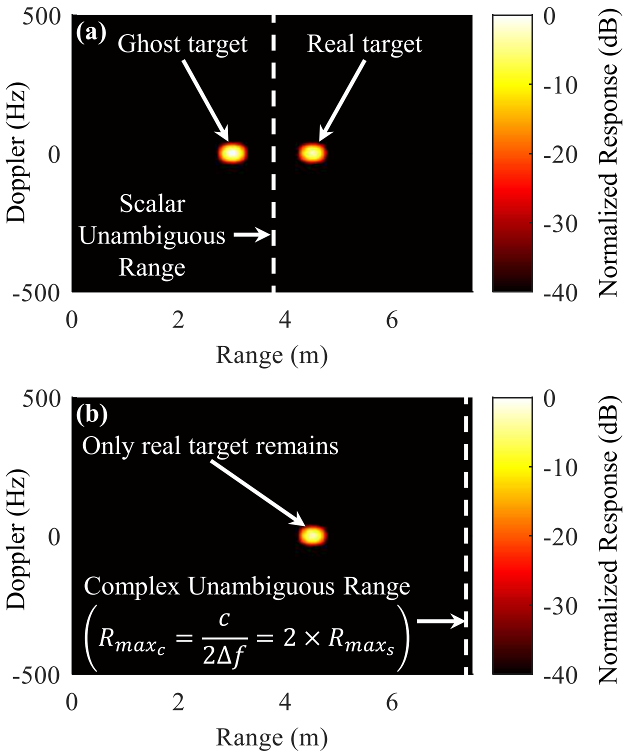


Fig. 3. SFCW radars leveraging scalar (a) and complex (b) baseband outputs. The results in (a) show an unambiguous range reduction due to the scalar output, while using complex *I/Q* data (b) gives the full unambiguous range.

TABLE I
COMPARISON OF SFCW AND FMCW

| **Parameters** | **Transmit Scheme** | |
|---|---|---|
| | *SFCW* | *FMCW* |
| *Chirp* | Discretized frequency ramp | Continuous frequency ramp |
| *Signal Structure* | 2-D for fast and slow time processing | 2-D for fast and slow time processing |
| *Maximum Unambiguous Range* | Requires *I/Q* demodulation to maximize, limited by frequency step, $\Delta f$ | Only limited by Nyquist sampling and pulse repetition frequency PRF |
| *Baseband Output* | Series of direct Doppler responses, discretized response | Beat frequency related to target range, continuous response |
| *ADC sampling* | Lower rates required, one sample per $\Delta f$ | Higher rates required to accurately reconstruct |
| *Instantaneous Bandwidth* | Narrow, like CW radar in given time instant | Wider, continuous bandwidth |

## B. Simulation Setup

A simulation platform is developed to evaluate the theory developed in this work using well-known signal models for FMCW/SFCW radar and DDMA. The simulation platform uses a user-defined chirp waveform and solves for the output baseband signals in both scalar and complex domains created by a variable number of targets with user-defined ranges and velocities. Furthermore, a periodic phase shift is applied to each TX signal to simulate DDMA, allowing for the impacts of DDMA parameters to be evaluated. The closed-form expression for the baseband signal generated by the $i^{th}$ target and $k^{th}$ transmitter is given by (3), where $f_c(t)$ is the time-varying transmit frequency, $\tau_i(t)$ is the time-varying distance to the $i^{th}$ target, and $\varphi_k(t)$ is the time-dependent DDMA phase shift applied to the $k^{th}$ transmit signal. The resulting baseband signal is then the sum of the individual signals given by (3) for every transmitter-target combination and is represented in (4) where $N_T$ is the number of targets and $N_{TX}$ is the number of transmitters.

$$x_{i,k}(t) \propto \exp\big(j2\pi f_c(t)\tau_i(t) + \phi_k(t)\big) \tag{3}$$

$$x_{BB}(t) = \sum_{i=1}^{N_T} \sum_{k=1}^{N_{TX}} x_{i,k}(t) \tag{4}$$

After calculating the time-domain baseband signal for a user-defined number of chirps, the simulation then uses traditional range-Doppler processing to visualize the response of each target using range-time and range-Doppler graphs. This allows for the rapid evaluation of the effects of parameters such as frequency step in SFCW radar, number of chirps per frame, and periodic phase shifts for DDMA systems.

## C. Dopper-Division Multiple Access Simulation

To generate orthogonal transmit signals and use MIMO techniques to synthesize a large virtual antenna array, DDMA may be used. The motivation of this study is not to analyze the benefits of DDMA compared with other MIMO schemes but rather to investigate the feasibility of DDMA for SFCW radar in potential wireless sensing applications. However, when compared to other techniques such as TDMA or FDMA, DDMA offers several advantages by allowing all transmitters to be enabled continuously with a relatively simple architecture [3]. By providing a unique progressive phase shift on each transmit channel, DDMA effectively synthesizes the response of a moving target. The applied phase shift isolates the contribution of each transmitter in the Doppler domain after range-Doppler processing by allocating a sub-band of the Doppler spectrum to each transmit chain that is directly related to the applied phase coding.

To intuitively examine the results of a periodic phase shift on the resulting range-Doppler graph, an SFCW DDMA system is simulated. The simulated radar system consists of 3 transmit channels leveraging a 1 GHz bandwidth, with a chirp-to-chirp phase shift of 0, π/2, and -π/2 for each transmitter. A single stationary target is present in the sensing environment at 2.5m from the radar. The results of this simulation can be found in Fig. 4. From the range-time results shown in Fig. 4(a), the effects of the cyclical phase shifts can be seen in the form of a periodic response in a single range bin, where periods of constructive interference (i.e., all TX channels transmitting at the same phase)), and destructive interference induce a periodic response. The periods of constructive interference occur every 4 chirps, which corresponds to the previously mentioned periodic phase shifts (i.e., after 4 chirps each TX channel completes a ±2π revolution). After performing range-Doppler processing, the resulting range-Doppler graph shown in Fig. 4(b) shows that the applied phase shifts create a separation in the Doppler domain, allowing each transmission channel to be resolved.

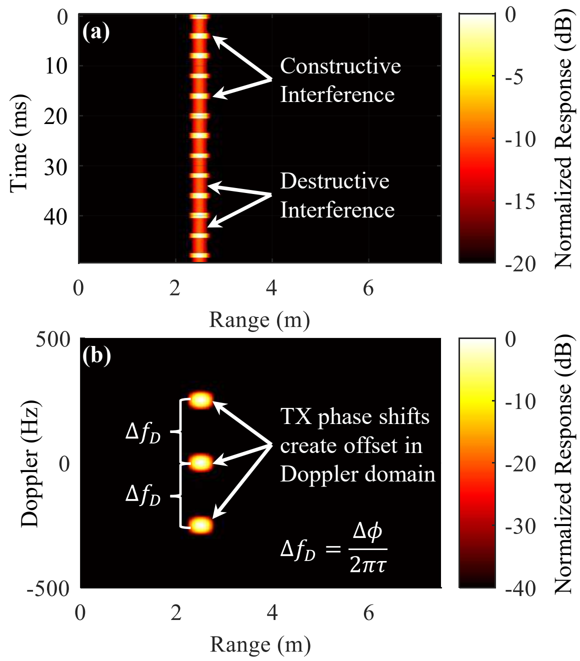


Fig. 4. SFCW DDMA radar simulation results showing the range-time (a) and range-Doppler (b) results of the simulation in test case with a single target illuminated by three transmitters at a 2.5 m distance in the sensing environment

Fig. 5 provides an example of a situation where, due to a the velocity ambiguity of DDMA, the targets radial velocity cannot be accurately resolved. The velocity of the third object exeeds the maximum unambiguous velocity of the DDMA system and the resultant Doppler frequencies are equivalent to that of a stationary target. The maximum unabiguous velocity of a generic FCMW/SCFW radar with a given pulse repitition frequency (PRF) is given by (5). Where the assumption is that both positive and negative radial velocities are observed.

$$V_{max} = \frac{PRF * \lambda}{4} \tag{5}$$

$$V_{max,DDMA} = \frac{PRF * \lambda}{4 * N_{TX}} \tag{6}$$

It is trivial to see how (6) can be derived from (5) beacuase standard DDMA allots an even amount of the Doppler spectrum to each tranmistter. Therefore, the maximum unambiguous velocity, $V_{max}$, and resultant maximum observable Doppler frequency, $f_D$, is further limited by the total number of tranmsmitters denoted by $N_{TX}$. Doppler frequency and velocity are linearly related through (7). (8) can easily be inferred from (7) as the maximum velocity and maximum Doppler frequency are then also linearly related.

$$f_D = \frac{2 * V * f_c}{c} \tag{7}$$

$$f_{D,max} = \frac{2 * V_{max} * f_c}{c} \tag{8}$$

The simulation leverages a maximum carrier frequency of 24 GHz and a PRF of 2 kHz. Using (5) and (6) the maximum unambigous velocity in the test case presented in fig. 5, when $c$ is the speed of light in m/s, is 1.25 m/s which corresponds to an $f_{D,max}$ of 200 Hz. Through (7), the velocities of the three targets shown in fig. 5 can be recovered. The velocities of targets 1, 2 and 3 respectively are 0 m/s, .625 m/s and 1.25 m/s. Due to the velocity ambiguity, target 3 appears to be moving 0 m/s and therefore cannot be resolved accurately with standard DDMA systems or processing methods.

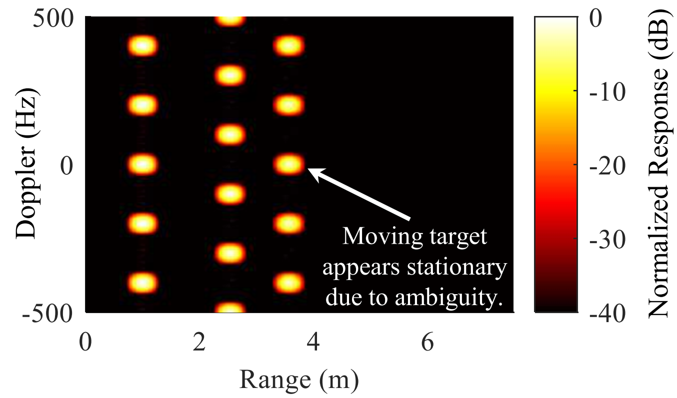


Fig. 5. SFCW DDMA simulation showing potential velocity ambiguity in a test case with 3 targets illuminated by 5 transmitters at 1 m, 2.5m and 3.75 m ranges in the sensing area moving at 0 m/s, .625 m/s and 1.25 m/s respectively.

### D. *Key Results*

As seen by the simulation results in Fig. 3 and Fig. 5, it is feasible for future MIMO radar systems to effectively leverage DDMA with an SFCW transmit scheme. The similarities of SFCW and FMCW radar, such as the 2-D signal structure allows for similar range-Doppler processing and therefore the computational load of SFCW and FMCW are fundamentally the same. Each of the schemes has potential merits and demerits as discussed in Section II. and in TABLE I. Therefore, choosing a transmit scheme requires careful evaluation of the application and sensing environment.

The results of the simulation confirm that MIMO DDMA SFCW radars are feasible and have potential applications in modern sensing environments. The similarities between SFCW and FMCW allow similar implementation and the unique advantages of SFCW, such as reduced ADC sampling requirements, can be used to overcome some prohibitive challenges in low-cost MIMO radar sensors. As noted in [11] these challenges include increasingly exorbitant amounts of data and high ADC sampling rates. Similarly, leveraging the narrow instantaneous bandwidth of SFCW [10] can relieve the well-known issue of electromagnetic spectrum congestion [12] and can find use cases in applications such as [5] where radar to radar interference can decrease the performance of wireless sensors.

## III. Conclusion

This paper presented a feasibility study of MIMO SFCW radars using DDMA and a comparative analysis of the design tradeoffs of the FMCW and SFCW transmit schemes. The simulation results show merit in leveraging SFCW and DDMA together for certain wireless sensing environments and verified the applicability of MIMO SFCW radars in localization applications. Future work will focus on an experimental study on the performance comparison between FMCW and SFCW radar systems employing DDMA for emerging applications.

## REFERENCES


[1] M. Farhadi *et al.*, “Automotive Synthetic Aperture Radar Imaging using TDM-MIMO,” in *2021 IEEE Radar Conference (RadarConf21)*, May 2021, pp. 1–6.

[2] M. Q. Nguyen *et al.*, “A Fast-Chirp MIMO Radar System Using Beat Frequency FDMA With Single-Sideband Modulation,” in *2020 IEEE/MTT-S International Microwave Symposium (IMS)*, Aug. 2020, pp. 1015–1018.

[3] M. Q. Nguyen *et al.*, “Fast-Chirp FDMA MIMO Radar System Using Range-Division Multiple-Access and Doppler-Division Multiple-Access,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 69, no. 1, pp. 1136–1148, Jan. 2021.

[4] S. Peter and V. V. Reddy, “Extraction and Analysis of Micro-Doppler Signature in FMCW Radar,” in *2021 IEEE Radar Conference (RadarConf21)*, May 2021, pp. 1–6.

[5] M. Umehira *et al.*, “Inter-radar interference in automotive FMCW radars and its mitigation challenges,” in *2020 IEEE International Symposium on Radio-Frequency Integration Technology (RFIT)*, Sep. 2020, pp. 220–222.

[6] J. Liu *et al.*, “Sidelobe reduction in stepped-frequency-continuous-wave MIMO TWRI of moving targets,” in *2016 CIE International Conference on Radar (RADAR)*, Oct. 2016, pp. 1–5.

[7] S. Dill *et al.*, “A drone carried multichannel Synthetic Aperture Radar for advanced buried object detection,” in *2019 IEEE Radar Conference (RadarConf)*, Apr. 2019, pp. 1–6.

[8] Y. Zhang *et al.*, “Compressive Sensing based Software Defined GPR for Subsurface Imaging,” in *2021 IEEE Radar Conference (RadarConf21)*, May 2021, pp. 1–6.

[9] N. F. A. Hakim *et al.*, “Accuracy analysis of range detection for SFCW portable through-wall radar,” in *2017 3rd International Conference on Wireless and Telematics (ICWT)*, Jul. 2017, pp. 35–38.

[10] M. Mercuri, D. Schreurs, and P. Leroux, “SFCW microwave radar for in-door fall detection,” in *2012 IEEE Topical Conference on Biomedical Wireless Technologies, Networks, and Sensing Systems (BioWireleSS)*, Jan. 2012, pp. 53–56.

[11] D. Cohen, Y. C. Eldar and A. M. Haimovich, "SUMMeR: Sub-Nyquist MIMO Radar," in IEEE Transactions on Signal Processing, vol. 66, no. 16, pp. 4315-4330, 15 Aug.15, 2018

[12] H. Griffiths, "Where has all the spectrum gone?" 2013 International Conference on Radar, Adelaide, SA, Australia, 2013, pp. 1-5