Hardware Prototype Demonstration of A Cognitive Sub-Nyquist Automotive Radar

Gilad Feinberg, Satish Mulleti, Eli Shoshan, and Yonina C. Eldar

Automotive radar (AR) plays a key role in autonomous vehicles. A modern-day AR requires cognition to adapt to its dynamically changing environment. In an automotive environment, the number of ARs that need to operate simultaneously varies rapidly and these ARs should transceive without mutual interference. Most widely used AR systems use frequency-modulated continuous-wave (FMCW) radar due to their smaller bandwidth and cost compared with pulse Doppler radar (PDR). By using sub-Nyquist based techniques, such as Xampling, we show here that the targets could be estimated from low rate samples even with a PDR. In this paper, we demonstrate a hardware prototype demonstrating the applicability of sub-Nyquist PDR as a cognitive AR. We consider a scenario where a number of ARs are mounted on a vehicle and need to look simultaneously into different directions without interfering with each other. The available bandwidth is divided into several non-overlapping subbands which depend on the number of ARs required. Each AR is assigned a set of randomly spaced subbands for its transceiver to operate. Through simulations, we show that the ARs could detect targets simultaneously without interference. Furthermore, the noise robustness of our sub-Nyquist reconstruction method is better than the standard matched-filtering approach.

Introduction: Automotive radar (AR) plays an indispensable role in the development of autonomous vehicles and driver assistance systems [1]. A few attributes an AR should have are adaptability to the environment or cognition, noise robustness, cost-effectiveness, low-computational cost, and the capability of detecting multiple targets. Most commercially available ARs employ FMCW radars due to their lower sampling rate compared with pulse Doppler radars (PDR). However, a classical FMCW radar has two major drawbacks. First, to simultaneously detect multiple moving targets, the transmit waveform has to be modified considerably and it requires a computationally expensive reconstruction algorithm. Second, when multiple FMCW-based ARs have to operate simultaneously, designing waveforms with mutual interference cancellation is a complex task [2].

An alternative is to use the classical pulse-Doppler radar (PDR) for automotive applications. With PDRs, multiple targets could be efficiently detected without altering the transmit waveform. However, high range-resolution requires a large bandwidth and hence, higher sampling rate. This is a major limitation of the applicability of classical PDR to AR. With recent developments in sub-Nyquist sampling and reconstruction techniques, such as Xampling [3, 4] and compressive sensing (CS) [5, 6], it has been shown that classical PDRs could operate at much lower sampling rate even if the transmit pulse has a large bandwidth. In particular, the ranges and velocities of the targets can be efficiently estimated from a few spectral samples of the received signal which are computed from sub-Nyquist samples [7, 8].

Another necessary attribute an AR should have is its adaptability to the surrounding environment. An AR has to operate in a highly dynamic environment where the number of targets, noise levels, and clutter change over time. Furthermore, the number of ARs that operate simultaneously changes when the number of vehicles within a region of interest varies. The works of [9, 10] have demonstrated that a sub-Nyquist PDR can have such cognitive capability.

In this paper, we demonstrate the applicability of cognitive sub-Nyquist PDR for automotive applications by adapting the hardware prototype as developed in [10, 11] to this setting. In particular, we consider the scenario where the number of ARs required to share the available bandwidth changes dynamically. We show that by intelligently sharing the available bandwidth among ARs one can achieve simultaneous transmission and robust target estimation without interference. Using hardware simulations, we demonstrate accurate range and velocity estimation using our sub-Nyquist algorithm, and improved performance over standard matched filtering (MF).

Next, we describe the cognitive AR system proposed, followed by an overview of the sub-Nyquist radar and hardware description.

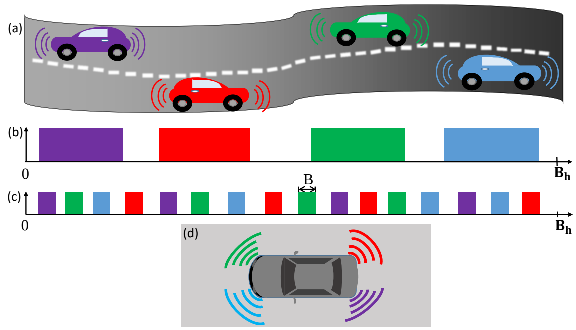

Fig. 1 *A demonstration of cognitive automotive radar: The four cars adaptively share the common spectrum either as shown in (b) or (c); the spectrum sharing policy in (c) leads to improved recovery performance; (d) multiple AR's operating simultaneously on a single vehicle.*

Cognitive AR: A typical cognitive radar has the following sequence of operations: (1) Scan the environment; (b) estimate the environmental parameters and perceive it; (3) adapt transceiver accordingly. In an AR application scenario, the environment consists of multiple moving vehicles, moving pedestrians, and stationary objects such as roads and surrounding buildings. The environment parameters include range and velocities of the moving targets, clutter due to stationary objects, and interference levels due to transmission of other ARs mounted either on the same or a different vehicle. When multiple ARs are operating simultaneously and their numbers are changing dynamically, it is necessary to adjust the transmit pulse to avoid interference. In this note, we focus on this aspect. We assume that the number of ARs at any given time is already estimated and each AR system is a sub-Nyquist PDR. The task is to adaptively share the spectrum among the ARs to avoid interference and simultaneously achieve robust reconstruction, by relying on the methods of [10, 11].

Figure 1(a) depicts a typical traffic scenario which consists of four cars at a given instant. Assume that each car has an AR and the total available bandwidth is B_h Hz. To enable multiple radars share the bandwidth resource simultaneously without interference, in Fig. 1(b) and (c), two different bandwidth sharing policies are shown. In the first policy, a single chunk of bandwidth is made available for each radar, whereas, in the second allocation policy, each radar simultaneously transmits a set of N (four in this example) different randomly spaced sub-bands of individual bandwidths B Hz. The total available bandwidth ($= NB$ Hz) in both the policies is the same for each radar. It has been shown in [7, 9, 11] that with widely spread frequency bands (as in Fig. 1(c)) the sub-Nyquist reconstruction algorithms are more robust in the presence of noise.

Another scenario where adaptability is required is shown in Fig. 1(d). In this case, a single vehicle has multiple ARs and each AR operates in a different direction to detect targets and help in driving assistance. At any instant, if the vehicles require target information from more or fewer directions than the current instant, the available spectrum for the vehicle has to reassign to more or fewer ARs adaptively. In this paper, we consider this scenario and build a hardware prototype to address this setting.

Mathematical Modeling: Consider a PDR system with transmit pulse $x(t) = \sum_{p=1}^{P} h(t - p\tau)$ consisting of P equally spaced known pulses $h(t)$. The time interval τ denotes the pulse repetition interval (PRI). By following standard assumptions on the target scene model [7], the received signal assuming L targets is modeled as $f(t) = \sum_{p=1}^{P} f_p(t)$, where $f_p(t) = \sum_{\ell=1}^{L} a_\ell h(t - \tau_\ell - p\tau) e^{-\mathrm{j}\nu_\ell p\tau}$ denotes the received signal due to the p-th transmit pulse. Here $a_\ell \in \mathbb{C}$, $\tau_\ell \in [0, \tau)$, and $\nu_\ell \in [-\pi/\tau, \pi/\tau)$ denotes the amplitude (or target's radar cross section), time-delay (proportional to range of the target), and Doppler frequency (proportional redial velocity) of the ℓ-th target, respectively. By applying the Xampling technique [3], the spectral samples of $f_p(t)$ are computed as $c_p[k] = \frac{1}{\tau} H(k\omega_0) \sum_{\ell=1}^{L} a_\ell e^{-\mathrm{j}\nu_\ell p\tau} e^{-\mathrm{j}k\omega_0\tau_\ell}$, where $\omega_0 = \frac{2\pi}{\tau}$ and $k \in \mathcal{K} \subset \mathbb{Z}$ indicates the set of frequency locations at which the spectrum is measured. It has been shown that the parameters $\{a_\ell, \tau_\ell, \nu_\ell\}_{\ell=1}^{L}$ can be perfectly recovered from the spectral samples provided that $|\mathcal{K}| \geq 2L$ and $P \geq 2L$ [7], which dictates the sampling rate.

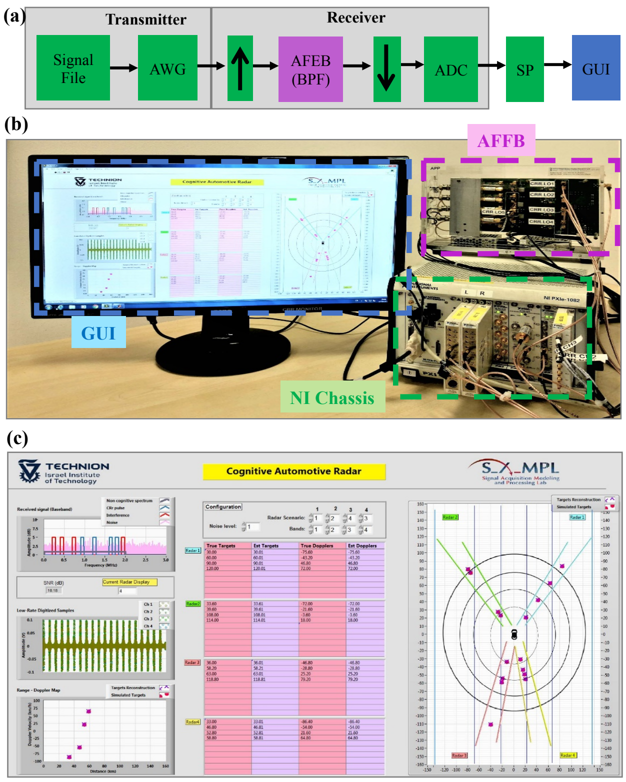

Fig. 2 *A hardware prototype of a cognitive sub-Nyquist automotive radar: (a) Flowchart of the demo system: in green NI chassis components, in magenta the AFEB unit and, in blue the GUI ; (b) full prototype with indications corresponding to the flowchart; (c) a screen shot of GUI.*

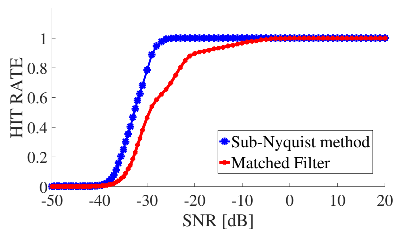

Fig. 3 *A comparison of sub-Nyquist vs. MF radars: The sub-Nyquist radar performs better than the MF radar in terms of hit-rate for SNRs in the range* $[-45, -10]$ *dB.*

Hardware Prototype: The underlying hardware to realize the proposed demo is similar to that used for the sub-Nyquist radar in [11]. The novelty lies in its application to cognitive AR. In Fig. 2(a), a high-level schematic of the proposed prototype for a single AR is shown. The transmitter consists of an arbitrary waveform generator (AWG) module which generates the analog received signal based on adaptive bands. The transmit signal parameters are set by a predefined MATLAB signal file. The receiver consists of a set of up and down converters (depicted by up and down arrows); an analog front end board (AFEB) or bandpass filter (BPF) and an analog to digital converter (ADC). The AEFB acts as a band selector. Post filtering, the signal is sampled by the ADC. The target parameters are estimated by the signal processing (SP) block. For more details, the reader is referred to [11, 10].

The graphical user interface or GUI is shown in Fig. 2(c). It shows a single vehicle with four ARs illuminating four different directions at a given time. Each AR is adaptively allocating four subbands for its transceiver. The estimated targets are simultaneously shown in the range-Doppler plane for all four ARs. As we have a single transceiver, we demonstrate the cognition aspect in a sequential manner. The transmit bands allocated for each radar change in different realizations based on the number of directions to look into and near-by ARs. Since an automotive environment is highly dynamic various options were implemented in the demonstration. For example, a user can choose a combination of the following configurations: eight different target scenarios, three decreasing noise levels, and four different sets of none-overlapping bands.

Next, we compare the performance of a cognitive sub-Nyquist radar and standard MF-based radar in terms of hit-rate [7] in estimating the Doppler and range. By using the frequency allocation policy shown in Fig. 1(c), in both radars, we assumed that the transmit pulses consist of a set of four random subbands with $B = 80$ kHz. The transmit signals parameters are chosen as $P = 100$ and $\tau = 1$ msec. In the receiver, these subbands are separately sampled by using a bank of filter banks with the passbands of each filter coinciding with the subbands. In the MF-based reconstruction, MF is applied to all the four subbands put together. Thus, MF does not allow for adaptability. In the target scenario, we consider $L = 5$ targets and assume that the targets are on a grid of resolution $\Delta_\tau = \frac{\tau}{N}$, that is, $\tau_\ell = n_\ell \Delta_\tau$, $n_\ell \in [0, N] \subset \mathbb{Z}$. In the simulations, we set $N = 500$ and chose n_ℓs uniformly at random over the set $[0, N-1]$. Similarly, the Doppler frequencies are also assumed to be on a grid of resolution $\frac{2\pi}{P\tau}$ and the grid locations are chosen uniformly at random from the integer set $[-P/2, P/2)$. The amplitudes a_ℓs are chosen uniformly at random between 0.5 and 1. For each signal-to-noise ratio (SNR), hit-rate is computed over 5000 independent noise realizations and shown in Fig. 3. For SNRs between -45 dB to 10 dB, the hit-rate for the sub-Nyquist based method is higher compared with the MF technique, which does not allow to adapt the bandwidth.

Conclusion: In this paper, a prototype of a cognitive sub-Nyquist pulse Doppler radar is shown for automotive applications. Contrary to standard FMCW automotive radars, the proposed prototype is a pulse-Doppler one and uses sub-Nyquist or the Xampling framework for parameter estimation. The proposed cognitive AR can simultaneously detect multiple targets, and multiple ARs may operate simultaneously by sharing the available spectrum without interference. In the hardware prototype, we demonstrate a scenario where the multiple ARs simultaneously look into different directions to asses traffic and aid the driver assistance systems. Based on the requirements the number of ARs can adaptively change by altering the spectrum allocation in real time.

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