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# High-Resolution SAR Based on the IEEE 802.11 Protocol

Jun Shi, Yang Liu, Wei Liu and Xiaoling Zhang

This is a feasibility study for developing low-cost SAR systems based on the IEEE 802.11ac protocol. We find that the baseband module of IEEE 802.11ac is similar to SAR, and its frequency coverage is wide enough to meet the requirement of high-resolution SAR imaging. By using the subbands merging technique, the spatial resolution can reach  $0.3\text{m} \times 0.3\text{m}$  in theory.

**Introduction:** Synthetic aperture radar (SAR) is a microwave imaging technology with an all-day and all-weather surveillance capacity, and has been used widely in the fields of resource exploration, military reconnaissance, disaster monitoring, and topographic mapping, etc. Its spatial resolving ability has two aspects: the range resolution via the pulse-compression technique, and the azimuth resolution via the synthetic aperture technique. To achieve a high range resolution, a set of broadband electronic devices (typically, several hundred megahertz, even gigahertz) [1, 2] is necessary. As a result, its cost is always high and limits its application in some low-cost fields.

IEEE 802.11 protocol is a mature and widely-used local area wireless communication standard working at 2.4 GHz (UHF) and 5 GHz (SHF) [3, 4]. Due to huge demand by the wireless communications sector, Wi-Fi chips are volume-produced with a rather low cost. Initially, the Wi-Fi's bandwidth is relatively narrow (typically, tens of megahertz) and cannot meet the requirement of high resolution SAR. The IEEE\_802.11ac protocol was released in January 2014, with a bandwidth up to 500MHz corresponding to a 0.3m range resolution. This makes it possible to develop a high-resolution SAR with very low cost based on this protocol. This letter will discuss its feasibility and possible problems.

**Baseband Structure:** The IEEE 802.11ac protocol operates at the 5GHz band including three frequency ranges: 5.15-5.33GHz, 5.49-5.73GHz and 5.735-5.835GHz (for US) [4]. The orthogonal frequency division multiplexing (OFDM) technique divides the frequency band into a group of subbands with 20, 40, 80 and 160MHz (optional) bandwidth. For each subband, quadrature amplitude modulation (QAM) is used for data transmission [3].

According to [5], the baseband diagram of a QAM system is illustrated in Fig. 1.

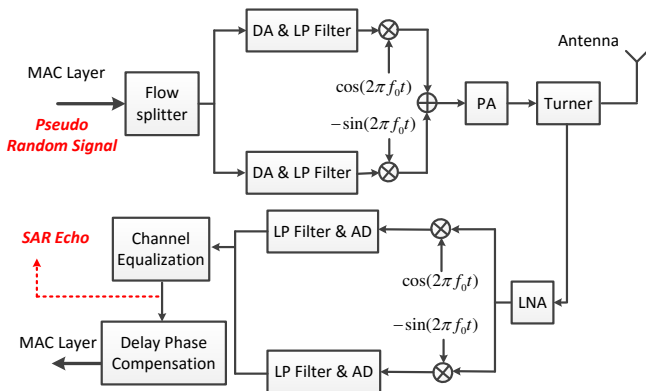


Fig. 1 Baseband diagram of QAM.

At first, the bit stream from the MAC layer is split into two equal parts (I-Q signals) and encoded according to the constellation diagram of IEEE 802.11ac. Then, they are transformed into analog signals via digital to analog (DA) converters and low-pass(LP) filters, and are emitted after quadrature carrier frequency modulation and power amplification (PA). The receiver amplifies the radio frequency signal via the low noise amplifier (LNA), splits it into I-Q parts via quadrature demodulation and transforms them into a digital form via the analog to digital (AD) converters, which is then followed by channel equalization

and delay phase compensation, before merging the I-Q signals into bit stream.

Comparing the diagram with SAR, we find that they are extremely similar except that: 1. for SAR, the pseudo random signal should be transmitted with a fixed pulse repetition frequency (PRF); 2. the delay phase (Doppler phase) is useful for SAR azimuth processing and thus, phase compensation should be bypassed (by Wi-Fi chip design) or neutralized (multiplying the phase back before SAR processing); 3. timing sequence should be modified to acquire and store the echoes; 4. the three frequency bands should be fully utilized, and all of the subbands should be merged together for higher range resolution.

Among them, the first problem can be solved in the MAC layer by packaging some pseudo random signals into the MAC frames; the second and third can be solved by some considerations during the Wi-Fi chip design. The fourth problem is fundamental and crucial for SAR image quality and it is the focus of our feasibility study, which will be discussed in the next section.

**Subbands Merging:** Subbands merging can be conducted either in the signal domain or the image domain. If the subbands work simultaneously, it is valid to merge them in the signal domain; if they work in turn in different pulses, and different delay phases are imposed on them, then it is more reasonable to merge the subbands in the image domain. This section will discuss the signal-domain merging technique only, and the image-domain merging is the same in principle.

Generally, the echo of an electronic radio system can be written as:

$$\tilde{s}_k(t) \square C_k \int \sigma(\tau) B_k(t - \tau - \alpha_k) e^{j2\pi f_k(t - \tau)} d\tau \quad (1.1)$$

$$\sigma(\tau) \square \int_{\|\mathbf{p} - \mathbf{p}_A\|/c = \tau} \sigma(\mathbf{p}) d\mathbf{p} \quad (1.2)$$

where  $t$  is the time variable,  $\tau$  is the delay,  $\tilde{s}_k(t)$  is the echo of the  $k$ th channel (subband),  $\sigma(\mathbf{p})$  the scattering coefficient at position  $\mathbf{p}$ ,  $B_k$  the baseband signal of the  $k$ th channel,  $f_k$  the carrier frequency of the  $k$ th channel,  $c$  the speed of light,  $\mathbf{p}_A$  the antenna's position,  $\|\cdot\|$  the 2-norm,  $C_k$  the complex-valued channel factor, and  $\alpha_k$  represents the channel's delay error.

After demodulation and range-compression (RC), the resultant echo signal can be expressed as:

$$s_k(t) = C_k \int \sigma(\tau) \chi_k(t - \tau - \alpha_k) e^{-j2\pi f_c \tau} d\tau \quad (2)$$

or 
$$s_k(t) = C_k (\sigma(t) e^{-j2\pi f_c t}) * \chi_k(t - \alpha_k) \quad (3)$$

where  $\chi_k$  denotes the point spread function (PSF) of the  $k$ th channel,  $*$  is the convolution operator.

Equation (3) can be expressed in the frequency domain as:

$$S_k(f) = C_k X_k(f) e^{-j2\pi f \alpha_k} [\sigma(f) * \delta(f + f_k)] \quad (5)$$

where  $S_k(f)$ ,  $X_k(f)$  and  $\sigma(f)$  are the Fourier transforms of  $s_k(t)$ ,  $\chi_k(t)$  and  $\sigma(t)$ , respectively, with  $\delta(\cdot)$  being the impulse function.

Similarly, the Fourier transform  $S_M(f)$  of the merged signal  $s_M(t)$  can be expressed as:

$$S_M(f) = X_M(f) [\sigma(f) * \delta(f + f_M)] \quad (6)$$

Where the subscript  $M$  means "merged".

Comparing (5) and (6), we further have:

$$S_M(f) = \sum_{k=1}^M [C_k^{-1} S_k(f) e^{j2\pi f \alpha_k} * \delta(f - (f_k - f_M))] \quad (7)$$

According to (7), the steps for subbands merging can be described as:

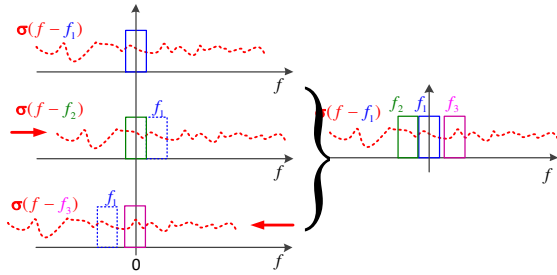
- Step 1.** Transform the RC echoes into the frequency domain;
- Step 2.** Multiply the frequency domain echoes by  $e^{j2\pi f \alpha_k}$ ;

**Step 3.** Shift the frequency domain echoes by  $f_k - f_M$ ;

**Step 4.** Add the echoes of different subbands together;

**Step 5.** Inverse Fourier transform.

The implementation of (7) is illustrated in Fig. 2

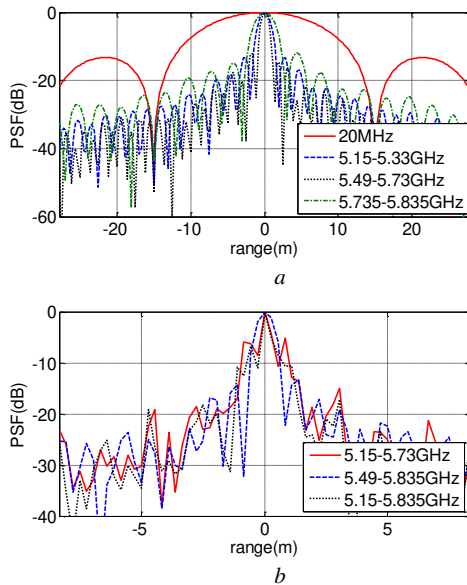


**Fig. 2** Frequency domain illustration of subbands merging.

When the system's resolution is infinite, the scattering coefficient will occupy the whole spectrum. In practice, only a part of the spectrum can be observed because of limit of system's bandwidth. It contains different spectrum information for different subbands. The core of subbands merging is to combine the spectrum segments together to obtain a better observation on the scattering coefficient distribution, i.e., higher resolution.

According to the above analysis, when the spectrum is continuous, the merging result is equivalent to the single channel system with broader bandwidth. However, for the IEEE 802.11ac protocol, its spectrum is discontinuous. Those spectrum gaps might degrade the SAR image quality, and will be discussed in the next section via simulation results.

**Performance Analysis:** This section discusses the imaging performance of IEEE 802.11ac-based SAR system through some representative simulation results. Assume that the three frequency bands are divided into a group of subbands with 20MHz bandwidth (broader bandwidths (such as 40MHz) mean fewer number of merging channels; 20MHz bandwidth is the most difficult case in the viewpoint of SAR imaging), a random channel factor and a random channel delay (known during the course of merging) are added for different channels.

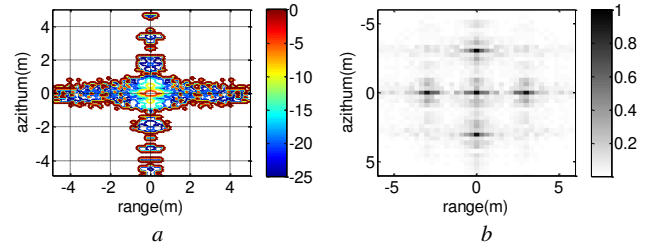


**Fig. 3** Range PSFs after subbands merging: a, merging results within each of the three individual frequency bands; b, merging results using multiple frequency bands.

The PSFs in the range direction after subbands merging are plotted in Fig. 3, where we can see that the proposed merging method works very well. For a single frequency band, the PSFs are all sinc functions. The range resolution of the lower band (5.15~5.33GHz) is superior to the upper one (5.735~5.835 GHz), but not as good as the middle range

(5.49~5.73GHz). For multiple frequency bandmerging, the PSLRs become worse (-6dB) due to existence of spectrum gaps, but the range resolution can reach about 0.3m by merging all of the three bands.

Fig. 4 shows the simulated SAR images after subbands merging.



**Fig. 4** SAR images after subbands merging: a, PSF of SAR image by merging the three frequency bands; b, 5-points imaging result by merging the three frequency bands.

Overall, we can say that the IEEE 802.11ac-based SAR system works effectively with a 2D spatial resolution better than  $0.5m \times 0.5m$ . However, its sidelobes are higher than traditional SAR systems and this problem could be solved by some sidelobe suppression techniques after imaging.

**Conclusions:** The frequency coverage of IEEE 802.11ac protocol is wide enough to obtain high range resolution, and its baseband module is compatible to SAR to a great extent. Thus, IEEE 802.11ac has the potential to be used to develop some low-cost SAR systems. One problem is that the spectrum gaps of IEEE 802.11ac protocol lead to higher sidelobe levels, and it is necessary to improve the resultant image quality by some sidelobe suppression techniques.

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