Collecting and Processing WiMAX Ground Returns for SAR Imaging

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Abstract—Employing signals of opportunity for synthetic aperture radar (SAR) imaging is the subject of recent research. This paper presents concepts on the collection and processing of WiMAX OFDM waveforms to produce SAR ground images. A radar collection model is presented followed by the signal processing approach based on previously derived OFDM phase history models. Two multi-symbol match filter designs are described. Experimental SAR images using WiMAX waveforms are shown to validate the overarching signal processing approach.

I. INTRODUCTION

In this paper, we present collection and signal processing approaches which allow the use of the IEEE 802.16 communication standard [1] known as Worldwide Interoperability for Microwave Access (WiMAX) in a passive synthetic aperture radar (SAR) ground imaging construct. WiMAX uses orthogonal frequency division multiplexing (OFDM) as its modulation scheme—shown to be a viable source for imaging in [2].

OFDM is used extensively in modern communication systems and has been considered recently for radar applications. In [3] and under the name multi-carrier phase-coded waveforms, Levanon introduced OFDM as a potential radar waveform source. There is on-going research on the use of the waveform for dual purpose in integrated radar-communication systems [4], [5]. Passive radar research using OFDM has emerged in recent publications. For example, Berger describes the signal processing of a passive OFDM radar using digital audio and digital video broadcast (DAB/DVB) for target detection in range and Doppler [6]. In [7] WiMAX signals are considered for maritime detection. In [8], [9], the problem of passive SAR ground imaging using WiMAX signals is evaluated and signal processing strategies are developed. This paper summarizes the signal processing approaches developed in [8], [9] and shows experimental images that validate the proposed methods.

The discussion begins with an introduction to the WiMAX standard and the network parameters relevant to the radar designer. Next, the collection geometric model is defined and the signal processing using multi-symbol OFDM match filter designs is presented. The paper concludes with the evaluation of experimental SAR images using generic OFDM and WiMAX waveforms.

II. 802.16-2009, WiMAX

WiMAX is defined by the IEEE 802.16-2009 standard [1]. WiMAX provides wireless networking connectivity for broadband access directly competing against widely-used cable, DSL, and T1 systems. Operating in the frequency band between 2 and 11 GHz, WiMAX systems can provide 5 to 10 km of service area with a maximum data rate of 70 Mbps in a scalable 20 MHz channel [1]. Given its current and expected future worldwide deployment, WiMAX is selected as the OFDM signal of opportunity for this research.

The 802.16-2009 standard defines three physical layer (PHY) configurations: single carrier, 256-point OFDM for fixed stations, and OFDMA with up to 2048 subcarriers for mobile subscribers. This research only considers the 256-point fixed OFDM PHY layer. Each communication symbol in the OFDM PHY is comprised of \( N = 256 \) subcarriers and each subcarrier is modulated by some complex data \( d_n \). The separation between subcarriers is \( \Delta f = B/N \) where \( B \) is the passband bandwidth of the symbol.

Data between users and base stations are transmitted using OFDM symbols in downlink (DL) and uplink (UL) subframes in a time division duplexing (TDD) structure. For this research, only the DL subframe is considered. Figure 1 shows the DL general structure. The DL preamble consists of either one or two symbols and is used for initial ranging and synchronization. The preamble data is subcarrier dependent, always employs the same standard-defined bit sequence, and is 3dB higher in amplitude relative to the rest of the data symbols. The frame control header (FCH) symbol contains subcarrier mapping information for the entire subframe. A detailed evaluation of the WiMAX OFDM waveform for SAR can be found in [2], [8]–[11]. For a thorough description of
tower will usually have three or more
model is developed under the aforementioned conditions.
the illuminated scene will always be constant. The collection
fixed (in ground networks) and the angle of incidence upon
airborne bistatic systems is that the transmitter is always
configuration. One of the most salient differences from other
of the airborne radar operator, forcing a necessary bistatic
concept where
A
degree sector is assumed to be the illuminated area of interest
coverage over the entire cell. For this study, a single 120-
illuminate areas
Fig. 2: General collection model. The transmitter and receiver
the standard, the reader is referred to [1].
III. THE WiMAX COLLECTION MODEL
As a signal of opportunity, WiMAX is outside the control of
of the airborne bistatic systems is that the transmitter is always
and the angle of incidence upon the illuminated scene will always be constant. The collection
WiMAX ground networks are designed using the concepts used for cellular ground network designs. Each transmission
tower will usually have three or more sectors providing coverage over the entire cell. For this study, a single 120-
single bistatic azimuth. Knowledge of the returns starting time leads to knowledge of their relative
During a collection, the receiver is turned “ON” at a time \(t_a\)
and turned “OFF” at time \(t_b\). During this period, \(P\) complete
are collected (based on the transmitter’s frame rate) from a single WiMAX sector and stored for
Interference from neighboring sectors is assumed negligible through WiMAX network design. The transmitter
is either known a-priori (in the case of the preambles) or perfectly obtained using a communications receiver.
The center \(m_0\) of the scene \(A_T\) is commonly known as the
motion compensation point (MOCOMP) and is used in
in the spotlight mode SAR process as a common reference to
align all the pulses in phase. For this analysis, \(m_0\) is defined by coordinates \((0,0)\) in terms of downrange and
crossrange respectively. The bistatic downrange is defined along the bistatic line-of-sight (LOS) vector at the center of
As shown in Figure 2, downrange is along
the line between the WiMAX transmitter and \(m_0\), where \(t_c\)
is the time at the collection center (\(\beta_p = 0\)). However, the following signal processing approach applies to any general bistatic configuration.

IV. SAR DIGITAL SIGNAL PROCESSING
Before obtaining phase history data, the signal processor must prepare the received data to allow proper range compression. When using TDD, the WiMAX base station transmits a series of DL subframes. Network users transmit UL subframes between the DL transmissions. The UL subframes are assumed to have just enough power to propagate within the service sector and should not reach the airborne receiver. This transmission scheme parallels that of a pulse SAR radar system and is the underlying assumption of the collection and signal processing approach.

Figure 3 shows a notional data collection between times \(t_a\)
and \(t_b\). Each block represents the combined DL returns from all the scatterers in the scene shifted in time by their associated path delays. Note that the spacing between returns will depend on the frame rate and the bistatic range \(R_{TO} + R_{R0}\), where \(R_{TO}\) is constant. This behavior is exaggerated in Figure 3 which represents an airborne platform that is getting closer to the \(\beta_p = 0\) point. The return timing can be exploited using a transmission reference time corrected for range. Let \(t_r\) be the reference time at any point before the first complete DL return (any point between returns DL1 and DL2 in Figure 3). Then the same relative point for the \((p+1)\)th DL return can be determined by

\[
t_{p+1} = t_r + p T_p - \frac{\Delta R_{R0}}{c}
\]

where \(\Delta R_{R0}\) is the change in receiver range between times \(t_a\) and \(t_r + p T_p\). The utility of this timing approach is that the entire collection can now be partitioned into \(P\) returns, each collected from a particular bistatic azimuth. Knowledge of the returns starting time leads to knowledge of their relative starting phase. Note that the absolute starting phase does not need to be estimated; a constant phase bias error across all returns will have no effect on the quality of the final SAR image.

Having partitioned the collection into slow-time bins, one can define segments of arbitrary length for processing, each encompassing a complete or partial portion of a single DL return. The length of each segment is user-defined and can
be adjusted to include one or more symbols. The relative starting phase of each segment can be estimated and used to achieve phase coherence. Each segment is used to create one-dimensional phase histories along the resulting bistatic LOS.

It is important to note that in a return segment, there are an infinite number of copies of the time-domain symbols based on the scattering properties of the scene. One can only approximate the timing of the particular symbol(s) to be processed and define a segment wide enough to encompass most of its (their) return energy. The timing of the symbols can be approximated by detecting the beginning of the DL return (using an envelope detector for example) and using the symbol duration $T_s$.

From [8], [9], the phase history solution for the $p$th multi-symbol OFDM DL signal is

$$
G_p = D_p^{-1} \Psi_p^{-1} S_p = \left[ G_p[k_{-\frac{N}{2}}] \ldots G_p[k_{-1}] \right]^T
$$

(2)

$$
D_p^{-1} = \begin{bmatrix}
 d_{-\frac{N}{2}}^T & 0 & \cdots & 0 \\
 0 & \ddots & \cdots & 0 \\
 \vdots & \ddots & \ddots & \ddots \\
 0 & 0 & 0 & d_{-1}^T
\end{bmatrix}
$$

(3)

$$
\Psi_p = \begin{bmatrix}
 e^{-j\frac{N}{2} \Delta \omega \tau_{0p}} & 0 & \cdots & 0 \\
 0 & \ddots & \cdots & 0 \\
 \vdots & \ddots & \ddots & \ddots \\
 0 & 0 & 0 & e^{j\left(\frac{N}{2} - 1\right) \Delta \omega \tau_{0p}}
\end{bmatrix}
$$

(4)

$$
S_p = \left[ S_p[k_{-\frac{N}{2}}] \ldots S_p[k_{\frac{N}{2} - 1}] \right]^T
$$

(5)

where $k_n$ is the wavenumber of the $n$th subcarrier, $\tau_{0p}$ is the delay associated with the scene center for DL frame $p$, and $S_p$ is the discrete Fourier transform (DFT) of the received signal. In (3), the reference signal is built from a delayed sum of the $L$ transmitted symbols such that $d_l^T = \left( \sum_{n=0}^{L-1} d_l e^{-jn\Delta\omega(T_s+PT_p)} \right)$, when the denominator is non-zero and $d_l^T = 0$ otherwise [2], [9], [10]. $T_s$ is the symbol duration, $T_p$ is the frame interval, and $\Delta\omega$ is the OFDM subcarrier separation in radians. Phase terms associated with discrete times $T_s$ and $PT_p$ account for the phase shift due to frame and symbol transmission time. The pseudo-inverse form of $d_l^T$ accounts for cases when subcarriers are intentionally set to zero (i.e. guardbands or the DC subcarrier), producing a non-invertible matrix $D$.

The phase history solution involves the correlation of return signal $S_p$ with a phase-corrected version of the reference signal $(D_p^* \Psi_p^{-1})$. Fourier inversion of $G_p$ yields the one-dimensional range profile for the $p$th DL pulse. Range profile results for a single symbol ($L = 1$) are shown in [2], [12]. Individually processed returns are arranged in matrix form to complete the two-dimensional $N$-by-$P$ phase history array. The accumulation of phase history

$$
G = \left[ G_1 \ldots G_P \right]
$$

(6)

for $P > 1$ pulses yields a two-dimensional image of the scene via standard SAR processing, e.g. backprojection [13] or polar format algorithm (PFA) [14]. In Section V we show example OFDM SAR images, including WiMAX examples.

The phase history solution in (2) considers a single OFDM symbol with no cyclic prefix (CP) as the reference signal in the match filter process. Compensation for the CP is shown in [8], [9]; an example is shown in Section V. Other WiMAX features are also explored in [8], [9] to create processing opportunities not available with other waveforms. For example, the symbol sequence nature of the transmission gives way to multi-symbol processing schemes discussed next.

Many creative algorithms can be designed to take advantage of the information diversity present in a WiMAX signal. In this preliminary work, we assume that the modulation data $d_n$ for every OFDM symbol is either known or attainable. Then, the multi-symbol matched filter in (2) may be implemented. However, for large scenes and short symbol durations, scene echoes from adjacent symbols will be mixed at the receiver. Thus, one may wish to apply coherent averaging techniques within a single radar pulse (a single DL frame) to reduce this inter-symbol interference and other noise effects. For this reason, a multi-symbol segment averaging matched filter

$$
\tilde{G}_p = \frac{1}{M} \sum_{m=0}^{M-1} \tilde{D}_p \Psi_p^{-1} S_{p,m}
$$

(7)

is proposed in [9], where $S_{p,m}$ is the spectral vector corresponding to the Fourier coefficients of the received signal over the $m$th time segment of length $T_{seg}$ and $\tilde{D}_p$ is as in (3) but with the $d_n^T$ terms including a user-selected subset of reference symbols $l$.

In this paper we consider the two extreme cases of (7): the full segment match filter (FSMF), and the averaging match filter (AMF). The FSMF corresponds to typical SAR processing in that it uses the complete $T_{seg} = MT_s$ length of the received pulse segment in the matched filter. In the extreme $M = L$, the full pulse length. The AMF is the other extreme; it chooses $T_{seg} = T_s$, i.e. $M = 1$. The AMF forms one matched filter result for each transmitted symbol and coherently averages to form the phase history for the $p$th pulse. In this way, the AMF results in a processing gain similar to that produced through the increase of a coherent processing interval (CPI) in detection radar, reducing noise in the averaged solution. The AMF is consistent with the MTI.
A SAR experiment is set up to produce SAR imagery using both generic OFDM and WiMAX pulses. An experimental OFDM radar system designed for this research is used to collect returns from individual transmissions at varying receiver azimuths [2]. The receiver antenna is mounted on a controllable linear moving track. Four receiver azimuths [2]. The receiver antenna is mounted on to collect returns from individual transmissions at varying

Depictions of the FSMF and AMF implementations are shown in Figure 5. In both cases, the processed receive signal segment $S_p$ must contain the spectrum of at least one symbol in the reference matrix. Ideally, the segment will contain return energy from the symbols in the reference matrix exclusively. Note that a segment in the AMF can be extracted through the implementation of a sliding window over the collected return.

V. EXPERIMENTAL SAR RESULTS

A SAR experiment is set up to produce SAR imagery using both generic OFDM and WiMAX pulses. An experimental OFDM radar system designed for this research is used to collect returns from individual transmissions at varying receiver azimuths [2]. The receiver antenna is mounted on a controllable linear moving track. Four 0.4 m$^2$ flat plate targets are arranged to exploit the crossrange dimension and oriented to maximize the return energy to the receiving antenna. Configuration I produces a bistatic angle of $\beta = 0$ (measured at the center of the collection) and is used to demonstrate general filter performance and the impact of particular WiMAX features. Configuration II is used to show performance under a larger bistatic angle ($\beta = 100$ degrees) and to validate the OFDM bistatic SAR model. It is of interest to explore the experimental SAR results using the following research concepts: 1) the performance of the AMF and FSMF filters, 2) the impact of the WiMAX features on SAR, and 3) large bistatic angles.

A. Filter Performance

Configuration I is shown in Figure 6, where target $A$ defines the center of the scene. A 344 MHz bandwidth is employed$^1$, producing a resolution of $\rho_y = 0.5$ meters. The geometry and transmitting frequency of 2.3 GHz are chosen to produce a similar resolution in cross range ($\rho_x = 0.43$ meters). A total of 33 pulses are transmitted and their returns collected uniformly over a 2-meter linear span.

A 10-symbol, 256-point generic OFDM waveform (no preambles, CP, guard bands, or other WiMAX features) is created using random $d_n$ sequences. The SAR geometry employed resembles Figure 2 although the receiver and transmitter are at the same height. The center pulse is transmitted

$^1$We have scaled the WiMAX signal bandwidth beyond the maximum standard definition of 20MHz to achieve reasonable range resolution for our limited experimental scene extent and low signal power. Results are a size-scaled version of attainable images with real-world WiMAX.

at approximately $\beta_p = 0$ and the maximum bistatic angle is $\approx \pm 4.4^\circ$.

The target array is radiated with the generic OFDM pulse. The OFDM symbols use all 256 subcarriers forming the complete 344 MHz bandwidth. The received signal is processed using either the FSMF or AMF, and PFA is applied to the phase history to form an image. Figure 7a shows the image results from using a segment length of $M = 1$ symbol. (In this case FSMF and AMF are equivalent.) The identification of the targets is clear for this small scene, but only a fraction of available receive data is utilized. Employing $M = 5$ sequential symbols$^2$ in the FSMF utilizes more echo data but results in an increased noise and clutter level, partially due to inter-symbol interference, as can be seen in Figure 7b. Instead, employing the AMF to average results of the five individual symbols provides a coherent integration gain, as shown in Figure 7c. The improvement is most noticeable along downrange, where the averaging nature of the filter acts. The crossrange noise is not a function of the waveform; hence, it is not improved.

B. WiMAX Features

Next, a 10-symbol WiMAX waveform consisting of two preambles and eight data symbols is used over the same target array. The preambles are generated per [1] while the data symbols are created using random data sequences $d_n$. All the symbols are modified with the appropriate OFDM physical layer (PHY) features according to the WiMAX standard: null DC carrier, guardbands, pilot subcarriers, and cyclic prefix (CP). The 200 subcarriers used in the WiMAX DL produce a reduced bandwidth of 200(1.345 kHz) = 269 MHz.

Applying the AMF for $M = 10$ symbols$^2$ and subsequently applying PFA yields the image in Figure 8a. The targets are not clearly discerned because the WiMAX CP alters the length and content of the transmitted symbols. When processing with a reference signal built without the CP, the matched filter is no longer matched! The CP must be accounted for by 1) taking the inverse DFT of the original coefficients $d_{l,n}$ for the $l$th symbol, 2) appending a copy of the last $\gamma T_s$ seconds

$^2$All available received symbols due to capture memory of oscilloscope.
and clutter in the target region compared to the OFDM case is attributed to averaging over more symbols and differing ground conditions at the times of the two experiments.

![Fig. 7: FSMF and AMF SAR image for processing $M$-symbol segments of each OFDM pulse.](image)

3) taking the DFT of the modified waveform to generate the required, modified coefficients $d_{l,n}$ for use in (3). The appropriate CP length $\gamma$ may be known or estimated from a handful of allowable values set by the WiMAX standard [1]. The CP-corrected WiMAX image is shown in Figure 8b where coherence and spatial accuracy are restored. The reduced downrange resolution is visually apparent (0.5 meters for the 269 MHz WiMAX signal versus 0.4 meters for the 344 MHz generic OFDM signal). The reduction of noise

![Fig. 8: SAR image for AMF using $M = 10$ symbols of WiMAX pulse without and with CP correction.](image)

**C. Bistatic Scenes**

We repeat the experiments above for Configuration II, depicted in Figure 9, with bistatic angle $\beta = 100$. Again, target $A$ is located at the scene center reference point. A 10-symbol WiMAX waveform is transmitted for 33 pulses and returns are again collected uniformly over a 2-meter linear span. The bistatic azimuth aperture is approximately 4.2 degrees with the center pulse transmitted at a virtual look angle of -39 degrees from the horizontal axis.

Figure 10 shows the simulated bistatic SAR image for the large bistatic angle using four point targets. Note the parallel orientation of the four targets with respect to the bistatic LOS in accordance with the model. The SAR from the actual collected data is shown in Figure 11. In the image, the two large and two small targets appear at each downrange location with some blurring between them in cross range. This effect is the result of placing the targets in pairs side-by-side to form two effective targets (for maximum return energy), rather than the result of the signal processing. Thus, even for large bistatic angles, the proposed signal processing method is validated.
VI. CONCLUSION

A bistatic collection model and its signal processing are presented for multi-symbol OFDM waveforms. Two matched filters, the FSMF and the AMF, were introduced as practical multi-symbol processing solutions. Experimental SAR imagery results verified that the AMF outperforms the FSMF by reducing image noise and clutter in the downrange domain. Furthermore, it was demonstrated that WiMAX waveforms may be used with minor modification to the matched filter to account for the WiMAX cyclic prefix. Results confirm the viability of the approach and validate the signal processing concept for passive WiMAX SAR ground imaging.

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