An Experimental Study on Secondary Radar Transponder UMOP Characteristics

Xiaohu Ru, Haohuan Ye, Zheng Liu, Zhitao Huang, Fenghua Wang, Wenli Jiang
College of Electronic Science and Engineering, National University of Defense Technology
Changsha, Hunan, 410073, P.R. China
ruxiaohu88@163.com

***Abstract*—Under the ever more complex and dense electromagnetic environment, specific emitter identification (SEI) technique opens up prospects for discriminating and identifying different emitters of the same class. SEI is implemented by employing the unintentional modulation on pulse (UMOP), which is unavoidable and unique to individual emitters. However, the characteristics of UMOP have not been sufficiently investigated via real-world data experiments. To this end, this paper focuses on an experimental study of UMOP characteristics based on measured data of secondary radar transponders. Pulses from 411 transponders of the same class are first collected during a data collection experiment. Time domain features are then extracted and used to validate the consistency and uniqueness of UMOP. Lastly, several UMOP features are defined and applied to SEI tests, showing that 104 emitters can be identified with a recognition accuracy exceeding 92%. This work sufficiently substantiates the feasibility of the SEI technique and offers practical guidance on how to put it into practice. The conclusions derived in this paper are applicable to the identification friend or foe (IFF) systems, and can also be easily expanded to general radar emitters.**

Keywords—Mode S; secondary radar; specific emitter identification (SEI); unintentional modulation on pulse (UMOP)

I. Introduction

Emitter identification is an important and frontal issue in electronic intelligence (ELINT) and electronic support measure (ESM) systems. At the beginning, conventional parameters such as radio frequency (RF), pulse width (PW), and pulse repetition interval (PRI) are usually utilized for the purpose of emitter identification. However, the ever-increasing emitters, especially those of the same classes, are widely equipped and used, making it difficult to identify different emitters. Then specific emitter identification (SEI) technique is proposed and developed [1]–[3]. The implementation of SEI relies on the so-called unintentional modulation on pulse (UMOP). UMOP is mainly generated by the nonideal and nonlinear devices in the emitter, which will bring unwanted modulation to the transmitted signals [4]–[6]. Since UMOP is unavoidable and unique to individual emitters, the developing SEI technique offers attractive prospects for emitter identification.

A great many UMOP features have been proposed for SEI. The fine frequency structure at the pulse leading edge is used in a flight test program [1], and approximately achieves 90%-95% confidence levels. However, the number of radar emitters used in the test and other details are not given. The feature discrimination and stability under different operating modes are considered in [4] using signals from two radar emitters. A total of 18 features are extracted from the instantaneous amplitude, phase and frequency in [5] and the recognition ratio exceeds 92% when recognizing three radar emitters of the same class. A feature vector extracted from the amplitude and frequency is defined in [6] and the correct identification coefficient (CIC) is found to achieve 98% for three emitters of the same class. Fractal features is used in [2] to recognize three copies of radar and the CIC achieves approximately 97%. UMOP features based on the slices of ambiguity function (AF) are used in [7] and [3], and the recognition ratios can achieve 81% and 94% for 8 and 30 radar emitters, respectively. Compressed features and a two-stage classifier are proposed in [8] and a probability of correct classification of 87% is obtained in a test containing 22 radar classes. It is reported in [9] that a real data set of 46 navigation radars from the same manufactory has been collected and the overall classification accuracy of greater than 95% is achieved by using intrapulse parameters. In addition, higher-order statistics such as cumulants [10] and bispectrum [11] are also considered to implement SEI.

Two main problems still exist in previous works. Firstly, most researches utilize only a small amount of emitters to verify the effectiveness of proposed UMOP features. Although satisfactory results are derived, the features may fail to distinguish more emitters. In other words, the uniqueness of UMOP is not validated sufficiently. Secondly, the stability or consistency of UMOP has not been examined designedly. Realizing this, we first meticulously chose the experimental emitters and field, and then carried out a data collection experiment lasting for about a month, during which signals from 411 secondary radar transponders of the same class were collected. Based on the plentiful measured data, UMOP characteristics, including the consistency and uniqueness, are studied in detail in this paper.

The rest of this paper is organized as follows. Section II presents the emitters used for our experimental study. Section III shows our data collection experiment. The consistency and uniqueness of UMOP are then examined in Section IV. Lastly, we conclude this work.

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II. CHOOSING THE EXPERIMENTAL EMITTERS

The ideal experimental emitters for UMOP analysis and SEI tests are expected to have the following characteristics:

(1) A large number of individuals with similar conventional parameters are available. In this way, the unique contributions of UMOP can be evaluated.

(2) The signals of one specific emitter can be repeatedly collected in different days so as to assess the stability and consistency of UMOP.

(3) Class labels of the collected data are convenient to be obtained because "ground truth" data are needed in the tests.

Based on the above considerations, we choose the secondary surveillance radar (SSR) transponders [12] used in civil airplanes as our experimental emitters. In the SSR systems, each airplane carries an individual transponder to respond to interrogation signals from the airport or other airplanes. This ensures safety of civil aviation by identifying the airplanes and knowing their dynamic altitudes.

Every day, many airplanes carrying SSR transponders enter or leave the airport, continuously transmitting reply signals with the same nominal parameters. Moreover, the same airplane carrying the same transponder usually appears repeatedly. Thus, it is possible to keep collecting signals from the same emitter over a long period of time. Lastly, the collected data can be easily labeled, since Mode S has been widely used in the SSR systems. According to the Mode S standard, each aircraft is assigned a specific 24-bit address code (AC) which will be contained in the encoded signals and shall not be changed in general cases [13]. Therefore, the reply signals from one Mode S transponder can be reliably labeled with the AC of the corresponding aircraft.

In addition, Mode S transponders transmit groups of closely spaced pulses with two PW modes, namely 0.5 μs and 1 μs [12]. This is beneficial for investigating the feature consistency versus pulse width variation. Furthermore, Standard Mode S transponders normally use amplifier-based and solid-state transmitters [14], which have now been increasingly applied to modern radar systems. All things considered, SSR transponders with Mode S are ideal emitters for the experimental study on UMOP.

III. DATA COLLECTION EXPERIMENT

In this section, we show the details of our data collection experiment, which was carried out near the civil airport of Changsha, China.

A. Experimental System

Many concrete guidelines for a typical SEI system design have been proposed in [15]. Following these guidelines, and considering the parameters and formats of Mode S reply signals, the block diagram of our experimental system is designed and shown in Fig. 1.

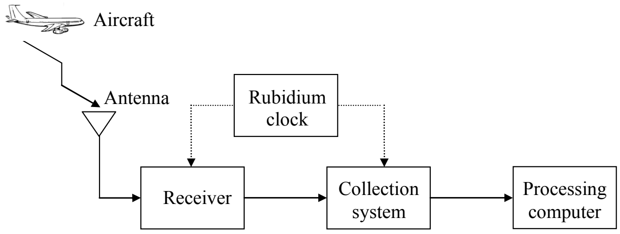


Fig. 1. The block diagram of the experimental system.

Our system comprises an antenna for receiving reply signals with a RF of 1090MHz, a superheterodyne receiver acting as the downconverter to obtain intermediate frequency (IF) signals, a collection system for receiving and sampling the analog IF signals, and a computer for storing and processing the collected data. A toolbox is also developed and installed in the computer to automatically store, decode, and de-interleave the signal data. The analog IF signals are centered at the frequency of 60MHz, and the sampling rate is set at 250MHz.

The experiment was carried out in a house no further than 1 kilometer away from the runway. The experimental field and deployment are shown in Fig. 2. The antenna is located on the top of the house, and a cable which drills through the window connects the antenna to the receiver system. Other parts of the experimental system are placed in a bedroom on the second floor.

B. Experimental Data

In order to label the collected data, Mode S reply signals are first recognized, and then the 24-bit address code contained in the reply data is decoded. Finally, using the address information, the data from the same transponder are associated together and labeled with the corresponding address. The reply signals of a landing airplane are kept collecting for several minutes before it eventually touches the ground. For a given airplane, the reply pulses recorded during the whole landing course are grouped and stored together. Each pulse group obtained in this way is called a *collection*.

The collection experiment lasted about one month. At last, data from 411 emitters were collected, 104 of which possess no less than three collections. The total number of collections is 1118, each containing more than 2000 pulses.

IV. EVALUATION OF UMOP CHARACTERISTICS

Based on the measured transponder data, we now evaluate the consistency and uniqueness of UMOP. Instantaneous

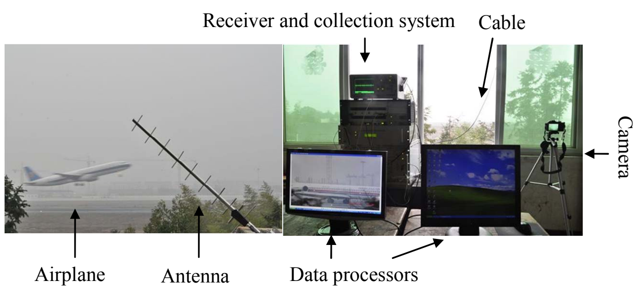


Fig. 2. The field and deployment of the data collection experiment.

amplitude and frequency, which are basic UMOP features, are employed to characterize the unintentional modulation on amplitude and frequency of the signal [5], [6]. These two kinds of features will be called AM and FM, respectively.

A. Consistency Evaluation

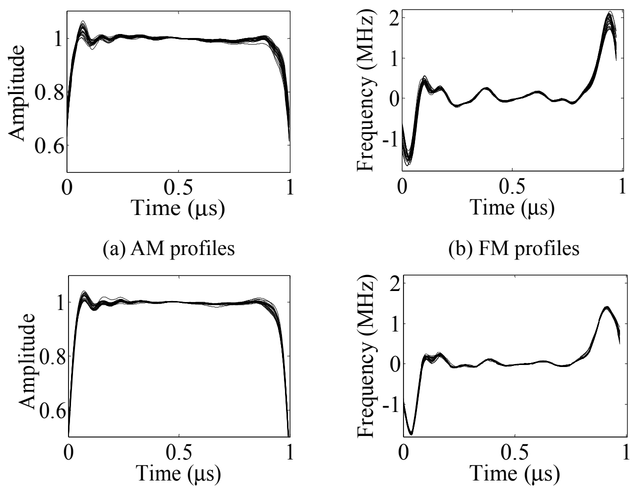
Two emitters which possess more than 20 collections are chosen for the consistency evaluation. For both of them, the data were collected in different days and under different environmental conditions.

The superimposed intrapulse AM and FM profiles of all the collections regarding the first emitter (Emitter 1) are shown in Fig. 3(a) and Fig. 3(b), respectively, while those of the second emitter (Emitter 2) are shown in Fig. 3(c) and Fig. 3(d). It can be seen that both AM and FM profiles exhibit nonideal shapes, indicating the existence of UMOP; and features extracted from all the collections of one specific emitter congregate quite well, proving the stability and consistency of UMOP.

As mentioned in Section II, Mode S transponder transmits reply signals with two kinds of nominal PWs (0.5 μs and 1 μs). Fig. 4 shows the UMOP features extracted from signals with these two PWs. Clearly, both the AM and FM profiles at the leading and trailing edges remain consistent, showing the invariability of UMOP under different operating modes. This is quite different from many magnetron-based navigation radar emitters, whose UMOP features are substantially different under different PW modes [1], [9].

B. Uniqueness Evaluation

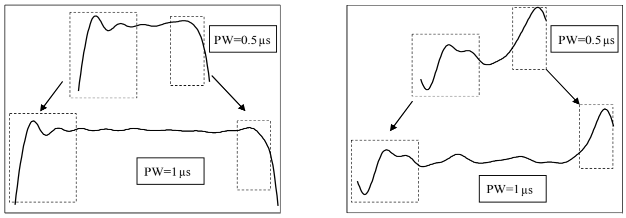
After examining the UMOP features of 104 emitters with three or more collections, we find that most of them could be roughly grouped into three types, denoted by Types I, II, and III, respectively. For each type, three emitters are picked out to visually assess the uniqueness of UMOP.



(a) AM profiles (b) FM profiles

(c) AM profiles (d) FM profiles

Fig. 3. Superimposed intrapulse AM and FM profiles of two emitters. (a) and (b) show the AM and FM profiles of 24 collections from Emitter 1, respectively; while (c) and (d) illustrate the results of 22 collections from Emitter 2. Features extracted from pulses within one collection are averaged.



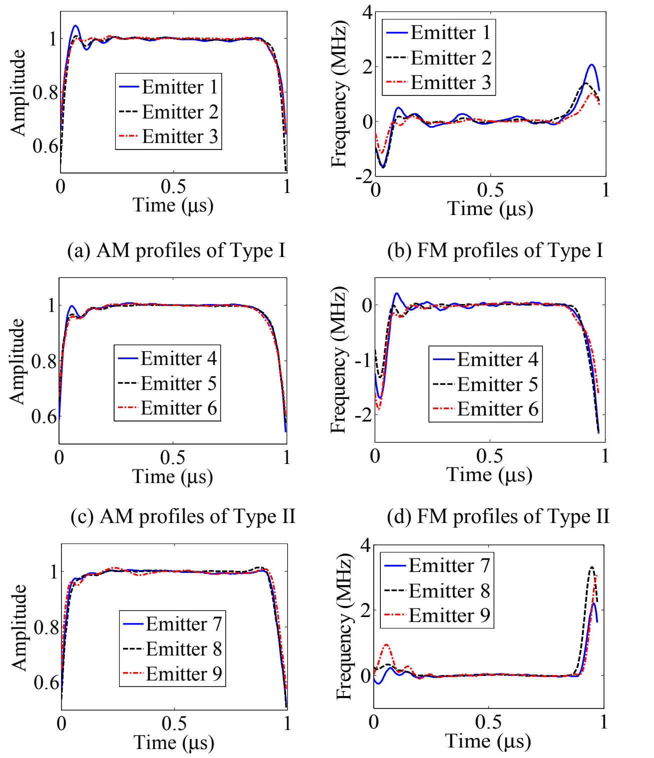
(a) AM profiles (b) FM profiles

Fig. 4. Comparison of UMOP features of Emitter 1 operating under two PW modes.

Fig.5 illustrates the intrapulse AM and FM profiles of nine emitters belonging to three types. We can see that (1) emitters of the same type have similar UMOP features, but distinct differences can be found among emitters of different types; (2) UMOP mainly occurs at the leading and trailing edges, and behaves relatively unobvious in the central part of the signal; and (3) comparing with AM, FM can better distinguish different emitters. Some emitters can hardly be distinguished via AM profiles, i.e. Emitters 5 and 6 (see Fig. 5(c)). However, by adopting FM profiles all the nine emitters can be easily differentiated.

C. SEI Experiments

This part implements SEI experiments to further evaluate the uniqueness and effectiveness of UMOP features. Only the



(a) AM profiles of Type I (b) FM profiles of Type I

(c) AM profiles of Type II (d) FM profiles of Type II

(e) AM profiles of Type III (f) FM profiles of Type III

Fig. 5. Superimposed intrapulse AM and FM profiles of nine emitters belonging to three types. (a) and (b) show the AM and FM profiles of three emitters of Type I, respectively; (c) and (d) show the results from Type II; and (e) and (f) show the results from Type III. Features extracted from pulses within one collection are averaged.

pulses with a nominal PW of 1 μs are used, and the test emitters are chosen from the 104 ones which have three or more collections (656 collections in total). Randomly select one collection of each emitter to form the training set, and the remaining ones for testing. Features extracted from the pulses in one collection are averaged. The classical and commonly used nearest-neighbor algorithm [10], [16] is adopted as the classifier; and the percentage of collections which are correctly identified gives an accuracy score in a single trial. The average of scores derived from 10 trials will give the final recognition ratio.

We first test the recognition capability of UMOP in different parts of the signal. Use letters "L", "R", and "M" to denote the left 0.2 μs, right 0.2 μs, and middle 0.6 μs of the signal, respectively, and then six AM and FM features can be defined. Test results are shown in Table I. It can be seen that FM profiles at the leading and trailing edges (L_FM and R_FM) are the most effective, followed by the FM profile at the middle part (M_FM). However, features obtained from the AM profiles perform relatively poorly. The results are consistent with those derived in the above subsection.

Based on the six features defined in the above experiment, five combined feature sets and their recognition capabilities are shown in Table II, where CFS1-CFS5 denote {L_FM, R_FM}, the whole FM profile, {L_AM, R_AM}, the whole AM profile, and {CFS2, CFS4}, respectively. When testing on CFS5, AM and FM features will be normalized to make both of them have equal standard deviation. We can see that under any circumstance, the intrapulse FM profile (CFS2) can achieve the best recognition performance. As can be seen, the discriminability of CFS2 is so powerful that it can distinguish 104 emitters with an accuracy of 92.2%. These experimental results sufficiently validate the uniqueness of UMOP, as well as the feasibility of employing UMOP features to realize SEI.

TABLE I. RECOGNITION CAPABILITIES OF SIX UMOP FEATURES IN DIFFERENT PARTS OF THE SIGNAL. BEST RESULTS ARE REPORTED BOLDFACED.

Number of Emitters	Recognition ratio (%)					
	L_AM	R_AM	M_AM	L_FM	R_FM	M_FM
30	80.0	81.1	44.4	**97.2**	94.4	83.3
50	62.4	64.0	32.9	**92.5**	91.1	74.7
75	57.8	59.7	29.7	89.1	**91.8**	75.5
104	53.6	58.8	27.2	80.1	**87.3**	72.1

TABLE II. RECOGNITION CAPABILITIES OF FIVE COMBINED FEATURE SETS. BEST RESULTS ARE REPORTED BOLDFACED.

Number of Emitters	Recognition ratio (%)				
	CFS1	CFS2	CFS3	CFS4	CFS5
30	**99.4**	**99.4**	88.3	87.8	99.3
50	94.7	**95.0**	75.2	75.2	93.2
75	94.8	**95.0**	71.7	71.5	93.8
104	91.6	**92.2**	68.4	68.1	91.5

V. CONCLUSION

In this paper, we investigated the UMOP characteristics based on measured SSR transponder data. We first designed a low-cost and long-term collection experiment to obtain abundant labeled data. Subsequently, we examined the UMOP characteristics of more than one hundred emitters, and found that: (1) UMOP mainly appears at the leading and trailing edges, and remains stable and consistent in different days; (2) the unintentional modulation on frequency is relatively more obvious than that on amplitude; and (3) by solely employing UMOP, 104 emitters can be correctly recognized with an accuracy exceeding 92%. The experimental results validate the consistency and uniqueness of UMOP, indicating that the SEI technique can be reliably applied to SSR emitters and potentially general radar emitters.

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