DFRA: Demodulation-free Random Access for UAV Ad Hoc Networks

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***Abstract*—Due to the agility, low-cost and robustness, UAV (Unmanned Aerial Vehicle) Ad Hoc Networks formed by small UAVs have popular application in the battlefield. Considering the high mobility of UAV which may exit and join in the networks frequently, random access is critical for UAV Ad Hoc Networks. Due to the complex and serious electromagnetic environment in the battlefield, how to identify the MAC protocol when demodulation is unrealistic and switch to this MAC protocol adaptively is challenging. In this paper, we propose Demodulation-free Random Access (DFRA) scheme which can help UAVs join in the UAV ad hoc networks without demodulating the property field of MAC protocol header. First, we propose an adaptive feature extraction algorithm and use it for machine learning based MAC protocol identification. Then, DFRA adopts an adaptive MAC switching framework to access the networks. We implement DFRA with USRP N210 and evaluate the performance by experiments. The results show that DFRA can guarantee access accuracy rate over 95% when demodulation is unrealistic.**

I. Introduction

In recent years, due to low-cost and agility, small Unmanned Aerial Vehicle (UAV) has attracted great attention of academia and industry [1-4] especially for military application [5]. And the related researches have also studied a lot [6]. Compared with single UAV, UAV ad hoc networks which can be viewed as a special form of MANETs and VANETs [7] has more powerful capability. Up to now, more and more military applications about UAV ad hoc networks have been reported. In 2012, GRASP laboratory from University of Pennsylvania implement a UAVs swarm consisted of dozens of UAVs and predict the application of UAVs swarm in battlefield [8]. In 2016, America's defence secretary Carter presented "Swarm" UAVs will be used in battlefield for future wars at the Economic Club of Washington [9], etc. Therefore, study on UAV Ad hoc networks in the battlefield is very important and urgent for future wars.

Compared to the node in MANETs and VANETs, due to the higher mobility and more vulnerable in battlefield, UAV may exit and join in the networks frequently. Thus random access is critical for UAV ad hoc networks in the battlefield. MAC protocol is responsible for how UAV access the wireless channel and there exist a few MAC protocols for different military applications. Therefore, how to identify the MAC protocol of current UAV ad hoc networks and switch to corresponding MAC protocol adaptively are critical two steps for random access technique of UAV ad hoc networks..

Currently, most MAC protocol identification schemes are demodulation-based. By extracting the property field from received packets [10-12], the used MAC protocols can be identified. However, due to the serious and complex electromagnetic environment in the battlefield, UAV may not be able to demodulate the received packets and identify the MAC protocol. For example, in the battlefield, a UAV wants to access the UAV ad hoc network in the current region. But, due to the strong electromagnetic interference, signal noise ratio (SNR) of received signals can not satisfy demodulation requirement to extract the property field of MAC protocol header. Consequently, MAC identification with demodulation-based schemes can not respond to this situation. For another example in complex electromagnetic environment, a UAV is executing interference task. However, blindly jamming enemy's network without any prior knowledge is very inefficient. If the UAV can identify the MAC protocol of enemy networks through demodulation-free method, it can interfere the enemy communication more accurately [13].

In the past several years, there are some works about identifying MAC protocol without demodulation [14][15], which can distinguish MAC protocols only with physical layer (PHY) information. However, these methods are most for relatively static networks, i.e. cognitive radio (CR) networks [16][18], whose channel attributes, such as SNR, are not changing dynamically. But in the battlefield, due to the strong electromagnetic interference, channel attributes can change dramatically. If MAC identification cannot dynamically adjust its distinguish method according to current channel attribute, MAC protocol cannot be identified accurately. Therefore, demodulation-free random access for UAV ad hoc networks in the battlefield is challenging.

In this paper, we proposed a demodulation-free random access scheme called DFRA which can help the UAV access the networks when demodulation is unrealistic in the battlefield. First, we propose a demodulation-free MAC identification scheme which includes an adaptive feature extraction algorithm and a machine learning classifier. Adaptive feature extraction algorithm can adaptively extract features based on the current channel attribute and the machine learning classifier is able to identify MAC protocols according to these features. Then, DFRA utilizes the adaptive MAC framework [16] to switch MAC protocol. The main contributions of this paper can be summarized as follows:

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1. We propose DFRA which can help UAV join in the UAV ad hoc networks without demodulating the property field of MAC protocol header in dynamic battlefield. The demodulation-free MAC protocol identification scheme can also be used to other applications, i.e., interfering MAC protocol of the enemy.

2. In order to guarantee MAC identification accuracy in dynamic electromagnetic environment, we propose an adaptive feature extraction algorithm which can extract features according to current channel condition and reduce even eliminate the affects of dynamic change channel attributes.

3. We implement DFRA with USRP N210 [17] and build a testbed network to evaluate the performance. The experiment results show that DFRA can guarantee access accuracy over 95% when demodulation is unrealistic.

The remaining sections of this paper are constructed as follows. Section II presents a review of related works. Section III introduces the design of demodulation-free random access technology. The implementation and experiment are given in section IV. Finally, section V concludes the paper.

II. Related Works

In the past research, most of random access methods are demodulation-based, such as [10][11][12]. Through decoding and extracting the information carried in the MAC header of packets, access nodes can obtain the knowledge of MAC protocol used in the network and complete random access. However, in the recent years, studies on MAC identification only with PHY information have flourished. But these studies mostly serve for static cognitive networks to take full advantage of spectrum resource. In [14], Li, etc. present a novel approach which only use PHY signals to distinguish Bluetooth, Zigbee, 802.11b and 802.11g/n. In [15], Sanqing Hu, et al., proposed a new scheme which utilizes support vector machine (SVM) and PHY signals to identify MAC protocol in CR networks. Then spectrum hole found by this scheme can be used to transmit packets without interference to primary user. In [18], Samer A. Rajab, et al., also aim to make full use of spectrum resource. They extract energy and time features and utilize machine-learning algorithm to recognize 802.11 b/g/n.

In sum, the current demodulation-free MAC identification schemes mainly aim for static wireless networks, and cannot satisfy the requirement of random access in dynamic battlefield. Due to the dramatic change channel attributes,such as SNR, will make the feature extraction in [14-16] cannot extract required time features and frequency features and the MAC identification accuracy cannot be guaranteed. However, in this paper, we analyze the impact of dramatic channel change from several aspects for MAC identification and design adaptive feature extraction algorithm in DFRA to address this issue.

III. Design of demodulation-free random access

The flow graph of DFRA is illustrated by Fig. 1. The first step is demodulation-free MAC identification and the second is switching to identified MAC protocol adaptively based on adaptive MAC framework. Due to the complex

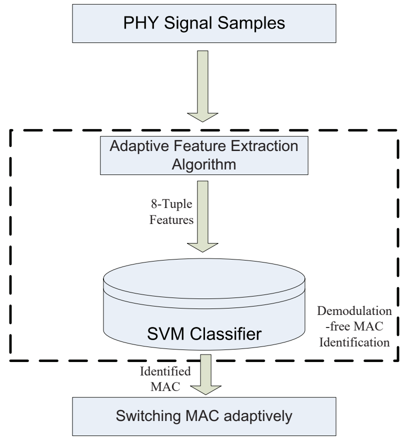


Fig. 1. Demodulation-free random access

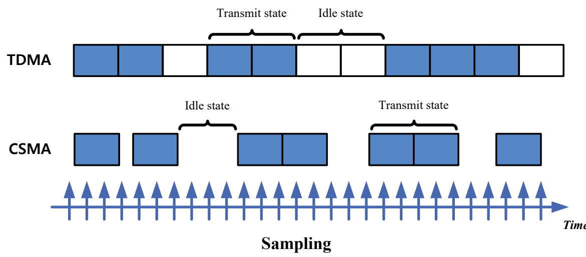
UAV ad hoc network environment in battlefield, channel condition is dynamic change. In order to address this issue, an adaptive feature extraction algorithm is proposed as one part of demodulation-free MAC identification. This algorithm can extract the features adaptively based on the current channel condition and its output, extracted features, will be sent to a SVM classifier, the other part of demodulation-free MAC identification, to separate MAC protocols.

In this paper, TDMA and CSMA/CA protocols, two typical protocol of controlled access protocols and competed access protocols respectively, as examples are used to verify the feasibility of DFRA.

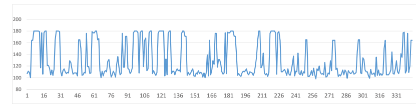
A. Feature selection

Physical layer information can be used by demodulation-free MAC identification is various. They can characterize from frequency domain, such as carrier frequency and signal bandwidth etc., and time domain, i.e., time division and power distribution etc. Based on previous research experience [13][14], temporal activity and inactivity distributions from measured received signal strength (RSS) can reflect the protocol level behavior.

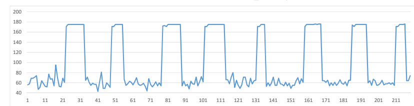
Fig. 2 shows the difference of CSMA/CA and TDMA in time domain from both theoretical analysis in MAC layer, in Fig .2(a), and experiment in PHY layer, in Fig. 2(b)(c). In Fig. 2(a), each rectangle represents one packet and the time length that is used for transmitting one packet, that is, one packet transmission duration (OPTD), is equal to the length of a time slot. As illustrated in Fig. 2(a), in TDMA networks, the durations of channel idle state and busy state are modeled as integral times of the OPTD. However, in CSMA/CA network, packet transmission collisions among nodes are avoided through carrier sensing. Thus, the duration of the channel busy states is also integral times of the OPTD. However, the duration time of the channel idle state is not necessarily integral times of the OPTD because a CSMA/CA node starts its transmission or retransmission process randomly in time. Fig. 2(b)(c) illustrates the RSS gathered by USRP N210 in TDMA and CSMA/CA networks respectively. From



(a) MAC protocol

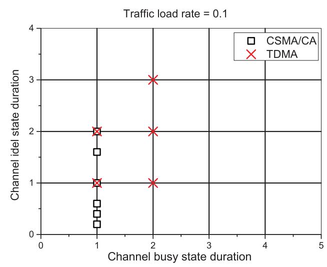


(b) CSMA sampling

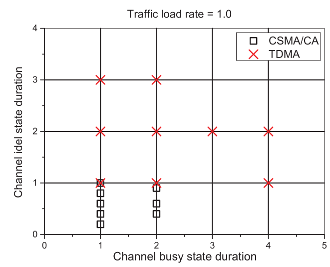


(c) TDMA sampling

Fig. 2. TDMA & CSMA/CA in MAC & PHY layer



(a) Time distribution under 10% traffic load



(b) Time distribution under 100% traffic load

Fig. 3. Time feature space

the figure, we observe that the distribution of PHY signals is obviously different between TDMA and CSMA/CA. The signal distribution of TDMA shows periodicity clearly and the CSMA/CA shows randomness just like its characteristic in MAC layer.

According to the analysis of Fig. 2, Fig. 3 is drawn to illustrate the time feature spaces of TDMA and CSMA/CA. In the figure, OPTD of each network is normalized to 1. The channel busy state duration and channel idle state duration are plotted in the figure. The abscissa indicates the channel busy state duration and the ordinate is channel idle state duration. Thus the coordinate of plot means the distribution of channel busy and idle state duration, i.e. Plot(2,1) indicates the continues three slots are consisted of two busy slots and one idle slot. From the figure, it can be clearly observed that CSMA/CA and TDMA have their unique channel access and collision avoidance characteristic, the channel busy state duration and channel idle state duration can be used to identify MAC protocols.

B. Adaptive feature extraction

According to the above analysis, we list the channel state features to distinguish CSMA/CA and TDMA in Table 1. However, in battlefield environment, strong electromagnetic interference causes dramatic changes in channel state. The signal sampling and feature extraction will be influenced by these changes, thus some fixed channel state features cannot guarantee the accuracy of MAC identification. Consequently, according to the current channel condition, adjusting the channel state feature extraction dynamically and extracting features adaptively are necessary and critical. In this section, we first analyze the influence of dynamic change SNR and traffic load, then propose an adaptive feature extraction algorithm according to the results of analysis in the end of this section.

TABLE I
PHY FEATURES

Channel state features	
T_{imin}	Minimum channel idle state duration
T_{imid}	Medium channel idle state duration
T_{imax}	Maximum channel idle state duration
T_{bmin}	Minimum channel busy state duration
T_{bmid}	Medium channel busy state duration
T_{bmax}	Maximum channel busy state duration
Adaptive extracted features	
R_f	Rate of short frames and long frames
P	Period

1) SNR vs feature extraction: SNR is an important indicator of PHY signals, it is directly related to RSS of signals. In demodulation-free MAC identification scheme, distinguishing the signal and noise is very important. For example, when the RSS of signal is about -100 dBm which can't satisfy the demodulation requirement of -80 dBm. Meanwhile, the noise is -130 dBm, thus -120 dBm can be the rational threshold to distinguish noise and signals. However, due to the electromagnetic interference, noise enhancing and SNR decreasing, RSS of signal may be below -110 dBm. In this situation, still using -120 dBm as threshold is not appropriate, thus access UAV should choose another threshold. Therefore, dynamically adjusting the channel busy/idle state threshold according to the current channel SNR is critical for access UAV to extract channel state features.

2) Traffic load vs feature extraction: Traffic load directly influences the distribution of PHY signals, since demodulation-free MAC identification only utilizes the PHY information, thus traffic load is a key factor to the results of MAC identification. From Fig. 3, we observe that the change of traffic load affects the distribution of two protocols. If one application pours traffic into network periodically, the distribution of CSMA/CA may be extremely similar to TDMA. In this situation, the feature, whether there are always short frames around long frames or not, which can be extracted from signal samples is able to separate the CSMA/CA protocol. This feature describes the relationship of short function frames, such as request to send (RTS), clear to send (CTS), ACK, and the data frames in CSMA/CA from physical layer. With this unique feature about CSMA/CA, machine learning classifier is able to identify CSMA/CA under various traffic load.

3) Periodicity feature extraction: Compared to the signals of long frames, when the SNR is much low, signals of short frames will be mixed into noise. In this situation, short function frames, CTS, RTS and ACK will disappear, so the feature about distribution of short and long frames can not help MAC identification. Thankfully, from another aspect, we can distinguish these two MAC protocols by identifying whether it is TDMA. Periodicity is the most unique characteristic of TDMA and utilizing this characteristic can help us complete MAC identification. However, due to the period is unknown in advance, access UAV needs to search all the possibilities, which can be costly. In order to find the period efficiently, we choose the Fast Folding Algorithm (PSFA) algorithm proposed in [18]. The main idea of PSFA can be explained in Fig. 4.

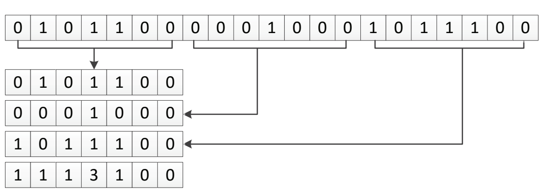


Fig. 4. Operation of Precision-Stable Folding Algorithm. In this time series, there is a periodic symbol with period 7 at position 4. After PSFA, there is a peak with magnitude 3 at position 4.

Finally, according to the above analysis we propose an adaptive feature extraction algorithm. This algorithm can not only dynamically adjust the channel state features extraction, but also adaptively extracts features according to current channel attributes. Thus the accuracy rate of MAC identification can be greatly improved in battlefield environment. The pseudo code of the adaptive feature extraction algorithm is shown in Algorithm 1.

In the feature extraction algorithm, access UAV first senses the channel and records RSS samples and then adjust the discretization threshold according to the samples. After that, it utilize the threshold to discrete the samples array with 0 as channel idle state, 1 as channel busy idle and build an array of discretization samples. Afterwards access UAV checks the discretization array. If the sensed channel is switched from 0 to 1, the algorithm records the channel idle duration and inserts it into the channel idle state duration array. If the sensed channel is switched from 1 to 0, the algorithm records the channel busy duration and inserts it into the channel busy state duration array. Finally, algorithm extract features with these three arrays.

Algorithm 1 Feature Extraction Algorithm

Input: Samples
Output: Feature output T_{imin}, T_{imid}, T_{imax}, T_{bmin}, T_{bmid}, T_{bmax}, R_f, P
1: Adjust the discretization threshold adaptively according to samples
2: Build array of samples $S[N]$ with 0 and 1, 0 is channel idle, 1 is channel busy
  Annotation: Line 3-9 build array of idle duration $T_i[N]$, array of busy duration $T_b[N]$
3: **while** i $< Length(S[N])$ **do**
4:   **if** channel switched from idle to busy **then**
5:     record the channel idle duration T_i
6:   **else if** channel switched from busy to idle **then**
7:     record the channel busy duration T_b
8:   **end if**
9: **end while**
10: Find the minimum, median and maximum of channel idle duration and busy duration with $T_i[N]$ and $T_b[N]$, T_{imin}, T_{imid}, T_{imax}, T_{bmin}, T_{bmid}, T_{bmax}, respectively;
11: Calculate the traffic load based on $T_i[N]$ and $T_b[N]$
12: **if** traffic load is lower than 0.7 **then**
13:   Calculate the rate of short frames and long frames R_f with $T_b[N]$
14: **end if**
15: **if** R_f is lower than 0.5 **then**
16:   Calculate the period P with $S[N]$ by PSFA
17: **end if**

C. SVM based MAC identification

The SVM as a state-of-the-art machine learning technique, has been widely used as the pattern classification technique for spectrum sensing, modulation classification, user identification, and power allocation in cognitive radio. In demodulation-free MAC identification, using SVM to identify MAC protocols is very fitting.

Support vector machine is a machine learning method that can be used to separate two classes of data [19,20] by finding an optimal hyperplane. SVM usually conducts an N-dimensional hyperplane, which optimally separates the data into two categories in the feature space, for the input data and patterns. In SVM, if the data points in its original data space are linearly separable, the SVM can find an optimal hyperplane to separate them. However, when the data points are not linearly separable, the SVM should handle this by using a kernel function.

D. Adaptive MAC framework for random access

In order to satisfy the self control of UAVs, a mechanism which can automatically switch to the identified MAC protocol to transmit packets is necessary.

Adaptive MAC framework proposed by [15] is the appropriate approach to address this issue, as shown in Fig. 5. It respectively adds MAC adaptation layer above and below the existing MAC layer. MAC adaption layer can select the appropriate MAC protocol and allow multiple MAC protocols to switch mutually based on some kind of information. In order to distinguish different MAC protocols, adaptive MAC framework adds 1-byte Global MAC Identifier (GMI) to the header of each frame.

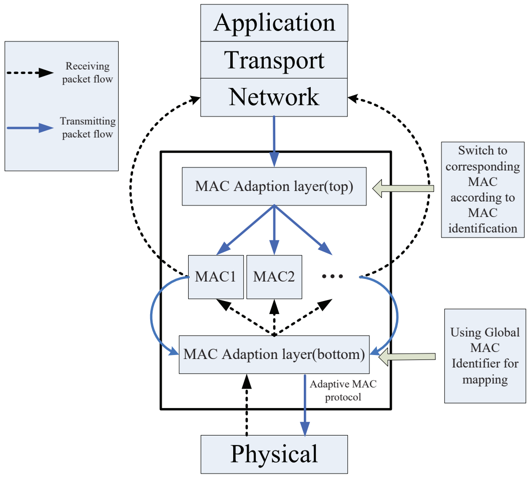


Fig. 5. Adaptive MAC framework

Based on this framework, we implement the adaptive MAC protocol which allow access UAV to switch to the MAC protocol identified by SVM.

IV. Implementation and Performance Evaluation

A. Implementation

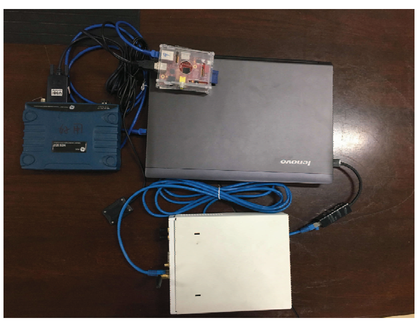


Fig. 6. access UAV prototype

In order to verify the feasibility and effect of DFRA, we implement the system on a prototype, as shown in Fig. 6, with one USRP N210, one laptop and one communication node. The communication node which is consisted of Raspberry Pi, MDS Radio and GPS device can be seen in Fig. 7. We implement the adaptive MAC protocol based on adaptive MAC framework on Raspberry Pi, but the demodulation-free MAC identification is implemented on the laptop because of the computing limitation of Raspberry Pi. The laptop respectively connects with Raspberry Pi and USRP N210 with a network cable, and Raspberry Pi is connected to a MDS radio and a GPS device with a RS232 to USB cable and a USB cable respectively. USRP N210 aims to gather RSS samples and transmit them to the laptop by User Datagram Protocol (UDP). According to these samples, laptop will extract features by adaptive feature extraction algorithm and identify the MAC protocol by SVM. Then it will transmit identification result to Raspberry Pi by UDP either. After that, the adaptive MAC protocol will switch to the corresponding MAC protocol and transmit packets through MDS radio for network access.

Fig. 7. Communication node in UAV

B. Experiment Setup

Fig. 9. UAV loading communication node

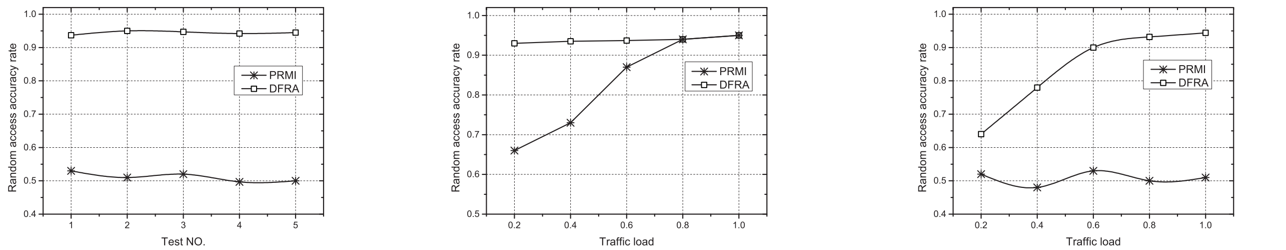
In the experiment, four UAVs which are loading communication node forming a network, one of them in shown in Fig. 9. The access UAV prototype is put in an barrow and moved close to the transmitting nodes. During this procedure, USRP N210 continue gathering signals and convey to the laptop.

In order to compare our method with the past demodulation-free MAC identification which do not consider the serious electromagnetic environment, the feature extraction algorithm of [14] has been implemented by us according to its pseud code and we name it past research MAC identification (PRMI). The traffic load of the network is set as 0.2 to 1.0 step by 0.2. Before experiment, we have divided the way of barrow moving to the network into three adjacent areas which are as follows:

- Area I: In this area, SNR is so low that short frames can not be identified from RSS samples.
- Area II: In this area, SNR is higher than in area I, so that the short frames can be distinguish, but it is also not high enough to demodulation.
- Area III: In this area, SNR can satisfy the demodulation requirement.

To model the dynamic change SNR of real situation in battlefield, the difference of SNR is controlled by moving the barrow from one area to another.

- Scenario I: Move the barrow between Area I and Area II to model the situation of SNR is up and down leading to short frames appear and disappear under full traffic load.



(a)Accuracy rate curve under dynamic SNR (b)Accuracy rate curve under different traffic load (c)Accuracy rate curve under dynamic SNR and traffic load

Fig. 8. Random access accuracy rate

- Scenario II: Move the barrow in Area II and change the traffic load.
- Scenario III: Move the barrow between Area I and Area II and change the traffic load, thus the traffic load and SNR are both dynamic change.

We first extract 500 feature sets under each traffic load and SNR, which means a total of 7500 sets are used to train SVM, then extract 1000 feature sets in each scenario to test the trained SVMs.

C. Experiment Result

Fig. 8 illustrates the random access accuracy rate under 3 different scenarios. The three figures in Fig. 8 respectively illustrate the accuracy rate curve of DFRA and PRMI. From the figure, we can observe that DFRA always shows greater performance than PRMI except under the traffic load over 0.8 in Scenario II. In this situation, due to the SNR is static and the traffic load is enough to identify MAC protocols, PRMI already has good performance and the features do not need to be extracted adaptively. However when the traffic load is under 0.8, PRMI is influenced by the change of traffic load, thus adaptive feature extraction, such as DFRA, is necessary to guarantee the accuracy rate. In Scenario I and III, due to PRMI can not dynamically adjust the channel state feature extracted, the accuracy rate is around 50% but the accuracy rate of DFRA is 95% and 90%. Thus the SVM cannot find efficient support vectors to form an optimal line for PRMI but can conduct an optimal line for DFRA.

From the experiment results, the accuracy rate of DFRA is much better than PRMI especially in serious electromagnetic environment. In other words, with DFRA which can complete random access based on the adaptively extracted features, access UAVs is able to join in the UAV ad hoc networks in battlefield.

V. Conclusion and Future work

In this paper, we propose a novel random access mechanism DFRA which can help UAVs join in the UAV ad hoc networks without demodulating the property field of MAC protocol header. DFRA utilizes SVM to identify MAC protocols and adaptive MAC framework to implement an adaptive MAC protocol to switch to the identified MAC. In addition, in order to guarantee the access accuracy rate, we analyze the relationship between various features and MAC protocols and present an adaptive feature extraction algorithm to extract features adaptively according to current channel condition in serious electromagnetic environment. At last, we implement this system and experiment. From the experiment results, we can find the access accuracy rate is over 95% in most situation.

References

[1] E. Semsch, M. Jakob, D. Pavlłcek, M. Pechoucek, *Autonomous UAV Surveillance in Complex Urban Environments*, Web Intelligence, 2009, pp. 82 - 85.
[2] E.P. de Freitas, T. Heimfarth, I.F. Netto, C.E. Lino, C.E. Pereira, A.M. Ferreira, F.R. Wagner, T. Larsson, *UAV relay network to support WSN connectivity*, IEEE ICUMT, 2010, pp. 309 - 314.
[3] F. Jiang, A.L. Swindlehurst, *Dynamic UAV relay positioning for the ground-to-air uplink*, IEEE Globecom Workshops, 2010.
[4] H. Xiang, L. Tian, *Development of a low-cost agricultural remote sensing system based on an autonomous unmanned aerial vehicle*, Biosystems Engineering, 2011, pp. 174 - 190.
[5] Stuart D. Milner, et al., *Autonomous Reconfiguration and Control in Directional Mobile Ad Hoc Networks*, IEEE Circuits and Systems Magzine, 2009.
[6] Shibo He, et al., *Full-View Area Coverage in Camera Sensor Networks: Dimension Reduction andNear-Optimal Solutions*, IEEE Transactions on Vehicular Technology, Vol. 65, No. 9, September 2016
[7] I. Bekmezci, et al., *Flying Ad-Hoc Networks (FANETs): A survey*, Ad Hoc Netw, 2013.
[8] http://dronecenter.bard.edu/tech-update-upenns-grasp-lab/
[9] http://foreignpolicy.com/
[10] Wireshark, 2014 ¡http://www.wireshark.org/¿.
[11] *Wireless LAN medium access control (MAC) and physical layer (PHY) specifications*, Tech. rep., IEEE Std. 802.11, 2012.
[12] *Wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (WPANs)*, Tech. rep., IEEE Std. 802.15.4, 2006.
[13] Acharya M, Thuente D, *Intelligent Jamming Attacks, Counterattacks and (Counter) 2 Attacks in 802.11b Wireless Networks*, OPNETWORK Conference 2005
[14] A. Li et al., *Demodulation-free protocol identification in heterogeneous wireless networks*, Comput. Commun, 2014.
[15] Sanqing Hu et al., *MAC protocol identification using Support Vector Machines for cognitive radio networks*, IEEE Wireless Communications, 2014, pp. 52 - 60.
[16] Weijun Wang et al, *Design and Implementation of Adaptive MAC Framework for UAV Ad Hoc Networks*, MSN, 2016.
[17] Ettus Research, 2014 /¡http://www.ettus.com/¿.
[18] Samer A. Rajab et al., *Energy detection and machine learning for the identification of wireless MAC technologies*, IWCMC, 2015.
[19] D. Staelin, *Fast folding algorithm for detection of periodic pulse trains*, Proceedings of the IEEE, vol. 57, IEEE, 1969, pp. 724 - 725.
[20] C. Burges, A Tutorial on Support Vector Machines for Pattern Recognition, Kluwer, 1998.
[21] C. Cortes and V. Vapnik, *Support-Vector Networks*, Machine Learning, vol. 20, no. 3, 1995.