Adaptive Communication Protocols in Flying Ad Hoc Network

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The authors propose adaptive hybrid communication protocols, including a novel position-prediction-based directional MAC protocol and a self-learning routing protocol based on reinforcement learning. The performance results show that the proposed PPMAC overcomes the directional deafness problem with directional antennas, and RLSRP provides an automatically evolving and more effective routing scheme.

Abstract

The flying ad hoc network (FANET) is a new paradigm of wireless communication that governs the autonomous movement of UAVs and supports UAV-to-UAV communication. A FANET can provide an effective real-time communication solution for the multiple UAV systems considering each flying UAV as a router. However, existing mobile ad hoc protocols cannot meet the needs of FANETs due to high-speed mobility and frequent topology change. In addition, the complicated flight environment and varied flight tasks lead to the traditional built-in-rules protocols no longer meeting the demands of autonomy. Hence, we have proposed adaptive hybrid communication protocols including a novel position-prediction-based directional MAC protocol (PPMAC) and a self-learning routing protocol based on reinforcement learning (RLSRP). The performance results show that the proposed PPMAC overcomes the directional deafness problem with directional antennas, and RLSRP provides an automatically evolving and more effective routing scheme. Our proposed hybrid adaptive communication protocols have the potential to provide an intelligent and highly autonomous communication solution for FANETs, and indicate the main research orientation of FANET protocols.

Introduction

Unmanned aerial vehicles (UAVs) have already been applied to solve problems in a variety of application areas including real-time surveillance, electric power lines inspection, search and rescue, forest fire monitoring [1], and so forth. As the UAV application range constantly expands, its working condition is getting more complex, and is always unknown and dynamic. Accordingly, multiple UAV systems have increasingly been addressed, and their cooperation can complete some tasks that cannot be completed by a single UAV system. Meanwhile, a higher requirement for autonomy is put forward in multiple UAV systems, which leads to ever increasing demands for portable and flexible communications.

Ad hoc networks, which allow communication between devices without the need for any central infrastructure, are preferred in the UAV area. In this area, the flying ad hoc network (FANET), a new paradigm of wireless communication, is emerging [2]. It can govern the autonomous movement of UAVs and support UAV-to-UAV communication, considering each flying UAV as a router and without complex hardware deployment. Moreover, a FANET provides an effective real-time communication solution for multiple UAV systems.

However, there are some challenging issues regarding communications and networking [3] to overcome. First, the UAVs (FANET nodes) are highly mobile with speeds ranging from 30 to 460 km/h in three-dimensional space. Hence, the communication links between UAVs fiercely fluctuate and are extremely unstable. Second, frequent topology changes increase the packet loss, routing overhead, and communication delays. High moving speed, long distance between flying nodes, environmental uncertainties, failures of flying nodes, and so on result in link interruption, and a new routing path needs to be established. Other factors like mission updates may also cause topology changes. Moreover, low latency, high reliability, and robustness must be considered in some military and emergency rescue applications. Conclusively, a FANET is characterized by rapid changes and activities, and designing efficient communication protocols is fairly challenging.

Currently, the existing communication protocols of FANETs are heuristic built-in rules, which heuristically specify which UAV node, and when and how to connect in what conditions. They are easy to realize, and can optimize and fit the network communications temporally. However, the complicated flight environment and varied flight tasks lead to the status of FANETs being in unpredictable stochastic fluctuation. Accordingly, such heuristic communication protocols are hard to use in such an environment and cannot adapt to changes in real time, which may deteriorate the network communication performance in the long term. Hence, an adaptive and highly autonomous protocol solution that can develop and establish communication links adaptively and autonomously is desired.

According to the above motivations, we propose adaptive communication protocols, including the medium access control (MAC) protocol and the routing protocol. The main contributions of this article can be summarized as follows:

- We propose a novel position-predic-

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tion-based directional MAC protocol for FANETs (PPMAC). It combines the directional antennas and position prediction in the MAC layer, and overcomes the directional deafness problem.
- We propose a self-learning routing protocol based on reinforcement learning for FANETs (RLSRP). It allows updating the local routing policies with the position information of UAVs and a reward function defined based on the global network utility, while avoiding the necessity for other global knowledge of the networks. The proposed routing protocol can evolve automatically.
- The proposed communication protocols are more robust and reliable, and can guarantee fast link establishment and successful data delivery with low latency.

The rest of this article is organized as follows. Related works are discussed. We present the proposed adaptive communication protocols and their features in detail. Then the performance evaluation of the proposed communication protocols is detailed. Conclusions and future works are drawn.

Related Works

Many existing studies have been investigated at different layers, such as the MAC layer and network layer, to improve the communication performance of FANETs. Due to the big challenges, the designs of MAC protocol and routing protocol must be careful and thoughtful. Cai *et al.* [4] proposed a token-based MAC protocol to improve the link interruption due to high mobility. Alshbatat *et al.* [5] proposed an adaptive MAC protocol that incorporates an omnidirectional antenna and a directional antenna. Unfortunately, the omnidirectional antenna would lead to the collisions and limited communication range. Then Temel *et al.* [6] proposed the LODMAC protocol using a directional antenna that has a longer transmission range and higher spatial reuse of the network in the MAC layer to overcome the problems under an omnidirectional antenna as well as the well-known deafness problem of directional MAC (DMAC).

Meanwhile, many routing protocols have been proposed. Liu *et al.* [7] proposed a clustering algorithm for the UAV near-space communication system to overcome the problems of poor networking capability and over-horizon communication among UAVs. However, the working principle of its routing protocol was not presented. Alshbatat *et al.* [8] proposed a routing protocol that uses optimized link state routing (OLSR) and directional antenna to reduce the number of multi-point relays (MPRs) and the transferring delay and to improve the throughput. Lin *et al.* [9] proposed a geography-based routing protocol GPMOR to address the issue of the link interruption due to the high mobility by selecting the optimal next hop. Gankhuyag *et al.* [10] proposed the RARP routing protocol to increase the robustness and reliability of the established routing path and improve the communication performance.

With more complex communication environments and UAV applications, more comprehensive solutions that use a hybrid approach which work at the MAC and network layers are urgently needed. Alshbatat *et al.* [11] used intelligent MAC and OLSR as the MAC layer protocol and network layer protocol, respectively, which can provide better end-to-end delay and control the overhead. However, the scheme would stop working when the topology of a FANET changes fast. Qingwen *et al.* [12] proposed a forwarding mechanism for FANETs to reduce redundant broadcasts and collisions, thus improving the end-to-end delay and the packet delivery ratio. However, there are several drawbacks in the studies mentioned above that need to be overcome:
- The existing protocols are heuristic policy-based, which have a low degree of autonomy and cannot satisfy the performance demands of high mobility, the complicated flight environment, and varied flight tasks.
- The communication protocols of FANETs covering MAC protocol and network protocol have just started and been unable to meet the actual needs.
- The existing hybrid approaches that works at MAC layer and network layer simplify some assumed conditions, lacking of robustness and reliability.

Consequently, it is imperative that the communication protocols can develop and implement communication operations according to the UAVs' states and evolution of the flying environment. In other words, the communication protocols should be intelligent and adaptive, with the capacities of decision making and self-optimizing. Besides, the protocols should be robust and reliable, as well as have high overall performance. In this article, we focus on investigating such adaptive communication protocols in FANETs.

Adaptive Communication Protocols

In the FANET scenario of this article, there are several flying UAVs as the nodes whose number ranging 5 to 20. Each flying node is equipped with a GPS and an identical switched beam antenna array whose switching time between the antenna beams can be or ignored, and has its own node ID and can publish its own position $\{x_i, y_i, z_i\}$ and velocity $\{v^x_i, v^y_i, v^z_i\}$.

Our proposed communication protocols include two protocols, the PPMAC protocol with the MAC layer and the RLSRP protocol within the network layer, to provide a comprehensive and high-performance protocol scheme for FANETs. The proposed protocols use two cooperative transceivers to operate concurrently, where one of them takes charge of position release and interchange of control packets, and the other one takes charge of data transmission; they are denoted as TS 1 and TS 2, respectively. Accordingly, the control and data channels are separated, and the overall network capacity is enhanced. In the following subsections, the PPMAC protocol and RLSRP protocol are represented.

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PPMAC Protocol

The PPMAC protocol includes three phases: position prediction, communication control, and data transmission. The exact position of each flying node is predicted and estimated at the position prediction phases. Some key control packets

In our self-learning routing protocol based on reinforcement learning (RLSRP), each flying node exchanges their status information occasionally or regularly with the FANET to update its stored data, and implement the decision-making of routing path that has the shortest delivery delay.

are interchanged at the communication control phase. The data is transferred from a flying node to a neighboring flying node at the data transmission phase.

Position Prediction: The directional antennas have a requirement that the specific position of each flying node must be known. In PPMAC, each flying node directionally transmits its GPS-coordinate vector. In FANETs, each flying node can be a position sender without any contention. As illustrated, the position packet includes the node ID, the GPS-coordinate indicating the current position of a node, the current status of data transmission, the current antenna bearing of TS 2, and the route information. Hence, each position packet brings only an extra 17 bytes of overhead for the MAC layer.

When a flying node is a data sender, it first directionally transmits its GPS-coordinate vector through TS 1 and publishes the position packet clockwise. Notably, the position packet is sent to the nodes in the directional antenna transmission range. At that point, the neighboring nodes are switched to listeners and postpone their information transmission to avoid collision. Accordingly, the range of position transmission is confined to one hop between neighboring nodes; thus, the network overhead is reduced significantly. Meanwhile, the position packet shares the information of the node status and current antenna bearing among the nodes in a FANET, which can get rid of the problem of head-of-line blocking [13]. Similarly, if the sender node is aware of the current position and movement velocity of its listener, it can estimate accurately the position at subsequent time t as

$$\begin{cases} x_i' = x_i + v_i^x(t-t_0) \\ y_i' = y_i + v_i^y(t-t_0) \\ z_i' = z_i + v_i^z(t-t_0) \end{cases} \tag{1}$$

where t_0 is the position update time. Consequently, each node in a FANET can learn the accurate position information of its neighbors in real time.

Communication Control: PPMAC protocol employs TS 1 to conduct three control packet interchanges, request to send (RTS), clear to send (CTS), and wait to send (WTS), to guarantee reliable communication. When a flying node as a sender attempts to establish communication with another flying node as a receiver, the sender will transmit an RTS packet and get a response if the receiver is idle. Otherwise, the sender will get a WTS packet, which means that the receiver is busy and it needs to wait until the receiver finishes the last interchange operation. The key to solve the deafness problem lies in the fact that the operation of answering an RTS packet with a WTS packet is parallel with the operation of data transmission.

Data Transmission: PPMAC uses TS 2 to transfer some data from a source flying node to a neighboring receiver flying node. During the setup of data transmission, the source flying node first gets the position information of the receiver flying node and points its directional antenna toward the receiver flying node. Subsequently, the receiver flying node points its directional antenna toward the source flying node after finishing the RTS and CTS control packet sequence.

RLSRP Protocol

To improve the capacity of autonomy of the FANET is the research emphasis of the investigators. Q-routing [5] is the first routing algorithm based on reinforcement learning (RL), which can realize the intelligent decision-making and self-optimizing without unfaithful human interventions and is appropriate for the FANET with the features of rapid changes and activities. It has gradually been applied in the domains of traffic control and mobile ad hoc networks (MANETs), which enables a node to determine how to transmit a packet to any destination via its neighboring node. Similar to other routing protocols, RL-based routing protocols mainly focus on searching for the shortest route in the shortest time. However, the traffic load is neglected, which has a significant influence on the data delivery delay. Hence, in our self-learning routing protocol based on reinforcement learning (RLSRP), all flying nodes exchange their status information occasionally or regularly with the FANET to update its stored data and implement the decision making on the routing path that has the shortest delivery delay.

We regard the routing process as a partially observable Markov decision process (POMDP) because it is hard to acquire all relevant information for describing the network states and constructing reward functions. Given a set of states S and a set of actions A, an agent node takes an action $a_m \in A$ in the state $s_m \in S$ at time t_m, and then transfers into the state $s_{m+1} \in S$ at time t_{m+1} with the state transition probability $P(s_{m+1} | s_m, a_m)$. The expected reward of a node under a policy π at state s is

$$V(s,\pi) = E\left[\sum_{m=0}^{\infty} \int_{tm}^{t_{m+1}} e^{-\alpha t} r(s_m, s_{m+1}) dt \mid s_0 = s, \pi\right] \tag{2}$$

where α is the discounted coefficient. It is known that RL is usually applied to solve the problem of delayed reward; however, each route setup and data transmission action would influence the states of the involved flying nodes immediately. Then we use the value function to present the reward function as follows:

$$V(s, \pi) = V(s, \pi) + \rho_m \Delta_m z_m(s) \tag{3}$$

where $z_m(s)$ is the eligibility trace function, Δ_m is the difference value at time t_m [15], and ρ_m is the learning coefficient at time t_m. $z_m(s)$, recording the recent occurrence frequency of each state in a circular manner, and when a state occurs, its value will increase; otherwise, its value will decrease exponentially. $z_m(s)$ determines how relevant the states are to what has just happened. When a state transition occurs, the value function iteration is executed simultaneously for all $s \in S$.

Then the values of $V(s, \pi)$ can be calculated iteratively based on the conditional probability of success or failure of transmitting a packet to the next hop, and the optimal policy π' can be obtained by the following iterative rule:

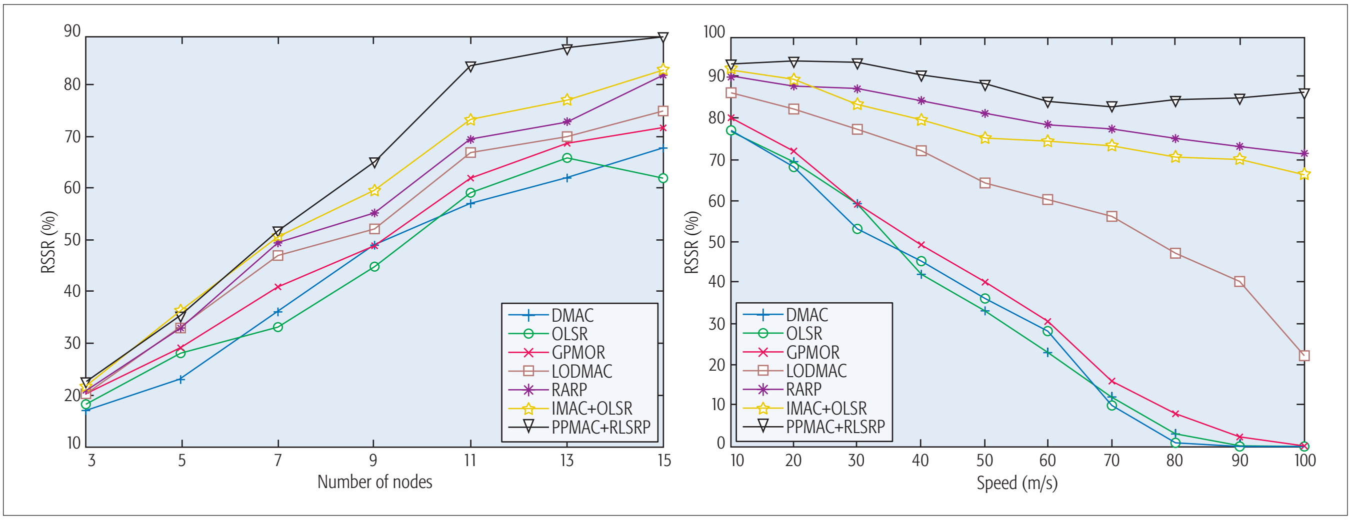

Figure 1. RSSR vs. number of nodes and speed.

$$\pi'(s_m) = \arg\max_{a \in A} E\{V(s_m)\} \tag{3}$$

Additionally, we also use the policy iteration (PI), which can find a good policy after several iterations and never adopts a bad policy, and is suitable for the real-time online learning. By PI, FANETs can realize fast routing decision and protocol self-optimizing in the manner of multi-agent quasi-real time.

Noted that the network size of a FANET may be scaled up in some special applications, which would lead to a very large and continuous state space. Hence, it is infeasible to assign a reward function to each state. A greedy methodology or a nonlinear approximation algorithm could be a possible solution for this issue. However, its specific details are no longer discussed in this article.

Hence, each action taken by a flying node would make an impact on the current state of the FANET, and accordingly the value of *V*(*s*). If a packet is sent to the receiver node, *V*(*s*) will only decline a little; while if a packet fails to be sent to the receiver node, *V*(*s*) will decline badly. Besides, the value of *V*(*s*) is stored and shared among the neighboring flying nodes via the position packet. The next hop is the neighboring flying node with a greater *V*(*s*) than that on the current flying node.

Simulation Results

In this section, the comprehensive performance evaluation of our proposed adaptive communication protocols is presented. MATLAB and NS2 operating environments and a directional antenna with range of 1 km and main beam angle of 60° are used for implementing the adaptive communication protocols. To simplify the simulation and eliminate unexpected interference, we limit the simulation space to 5 × 5 × 2 km^3 and set each flying node with a random waypoint mobility model and flying speed ranging from 10 m/s to100 m/s, always staying in the communication range of each other to avoid the packet loss caused by long-distance data transmission.

Different MAC protocols, routing protocols, and hybrid protocols are investigated and run on the same simulation environment with our proposed protocols. Seven protocol schemes, DMAC, LODMAC, OLSR, GPMOR, RARP, IMAC+OLSR, and the proposed PPMAC+RLSRP have been considered. In the following experimental simulations, the indicators of route setup success rate (RSSR), average path lifetime (APL), hop count (HC), successful data delivery ratio (SDDR), successful throughout without retransmissions (STWR), and average network delay (AND) are used to evaluate the performance of the protocols in a FANET. Additionally, the random waypoint mobility model is adopted as the mobility model to mimic the movement of a flying UAV. In this model, a flying node moves in one direction at a certain speed for a period of time that is referred to as the holding time. Subsequently, the flying node keeps moving in another direction at a different speed for a different holding time. All of the experiments have been repeated 100 times, and the reported results are averages.

Figures 1a and 1b show the RSSRs under different numbers of nodes where the speed of flying UAVs is around 40 m/s and under different speeds of flying UAVs where the number of nodes is 10, respectively. The RSSR implies that an RTS packet is sent successfully to a receiver node, and the receiver node feeds back a CTS packet. Obviously, with the increase in the number of nodes, the RSST of every protocol increases due to more alternative intermediate nodes. The proposed adaptive protocols always have the highest RSSR compared to other protocol schemes. Because PPMAC can estimate the position of each node and has the WTS control packet to lower the failure rate, the RLSRP protocol scheme has considered the status of each node and reward. In addition, the increase in the speed has nearly no effect on the RSSR due to using the directional antenna and considering the mobility model. At the same time, it can easily be seen that the RSSR degrades with the increase of the speed of flying UAVs, especially in protocols such as DMAC and GPMOR, which leave the mobility model out of consideration or adopt omnidirectional antennas. LODMAC utilizes directional antennas and location estimation within the MAC layer to enhance the communication range. RARP uses unicasting and geocasting routing using location and trajec-

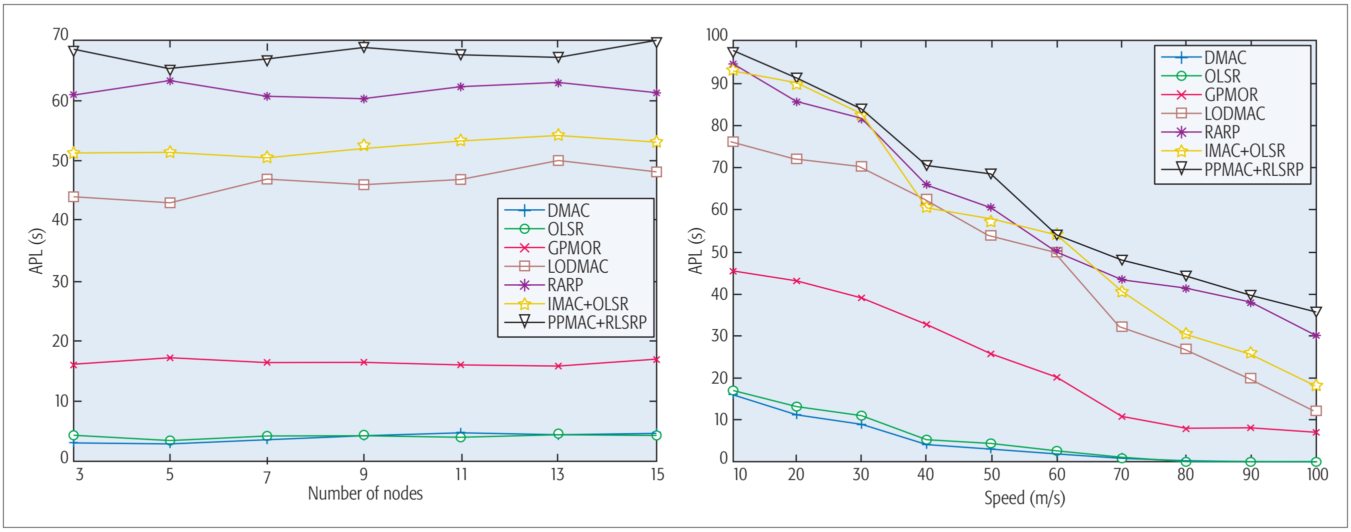

Figure 2. APL vs. number of nodes and speed.

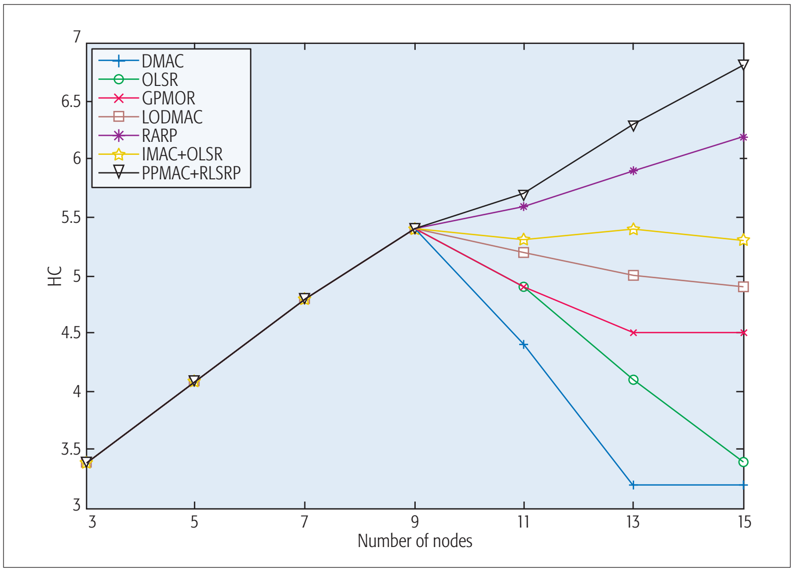

Figure 3. HC vs. number of nodes.

tory information so as to keep track of high-speed flying UAVs whose topology changes. Our proposed protocols consider high mobility and utilize directional antennas and the dual channel mode within the MAC layer to enhance the communication range and an intelligent and evolving routing scheme based on network rewards to find a reliable destination node. Moreover, the RSSR is on the upswing after a slight decline. Hence, in general, there is almost downside with the increase of the speed.

Figures 2a and 2b illustrate the APL under the different number of nodes where the speed of flying UAVs is at around 40 m/s and under a different speed of flying UAVs where the number of nodes is 10, respectively. The APL of PPMAC+RLSRP is the longest compared to the other protocols because of the directional transmission with directional antenna beams and the three-dimensional position estimation and prediction. RARP uses directional transmission with an update mechanism and a dynamic angle adjustment algorithm within the network layer to ensure its robustness, and consequently it also has an acceptable APL. Additionally, the APL is almost unconcerned with the number of nodes, even though more nodes lead to higher RSSR. Meanwhile, we can see that the APLs of all protocol schemes degrade significantly with increase in speed, while our proposed protocols still outperform the other protocols. The protocols utilizing directional antennas have better APL since they can cope with the extra distance transmission. Moreover, the consideration of the mobility model can extend the actual APL.

Figure 3 shows the HC under different numbers of nodes where the speed of flying UAVs is around 40 m/s. It is clear that HC increases until the number of nodes reaches nine and remains the same for all of the protocols, and decreases badly except RARP and PPMAC+RLSRP as the number of nodes exceeds nine. This is because not all nodes have established communication connection, and the shortest routing path rule is used in the other protocols. However, risk and connection time are considered in RARP, and the rewards and costs of hops are considered in our proposed protocols. Thus, the HC of RARP and PPMAC+RLSRP present the trend of continual increase.

Figure 4 shows the SDDR under different data transmission intervals where the number of nodes is 10 and the speed of flying UAVs is around 40 m/s. We can see that the SDDR declines sharply, while our proposed protocols have the lowest decline rate compared to the other protocols.

Figure 5 demonstrates the STWR under different numbers of nodes where the speed of flying UAVs is around 40 m/s. Obviously, our proposed protocols are more effective than the other protocols. Even under heavy network load, PPMAC+RLSRP still outperforms the other protocols because the network load is considered in the PPMAC protocol, and the cost and reward of retransmission are considered in the RLSRP protocol.

Figure 6 illustrates AND under different numbers of nodes where the speed of flying UAVs is around 40 m/s. It can be seen that our proposed communication protocols have the least AND compared to the other protocols. This is mostly because the WTS control packet significantly shortens the waiting time of data transmission, and the routing protocol is evolving continually for self-optimization.

By the above results in the simulations, we have proved that our proposed adaptive communication protocols outperform the other protocols considerably. The proposed protocols have the capabilities of self-optimization and autonomy, and can establish the network connections and select the best routing solution. Hence, our proposed protocols can reduce the average network delay and average path lifetime. Additionally, our proposed protocols are independent of the a priori assumptions that may be unreasonable and unpractical, and achieve self-learning with an RL framework. We only give an initial reward function, and the protocols iteratively learn and modify the communication strategies based on the environment and state parameters without any other manual interventions. Thus, our proposed protocols are more robust and reliable to improve the route setup success rate and successful data delivery ratio. Conclusively, our proposed protocols significantly optimize the network performance and upgrade the utility of FANETs.

Conclusion

A FANET can provide an effective real-time communication solution for multiple UAV systems, but at the same time it also faces some challenging issues in communications and networking. We propose adaptive hybrid communication protocols including PPMAC and RLSRP. Simulation results show that the proposed communication protocols outperform the existing protocol schemes and can guarantee fast link establishment and successful data delivery with low latency. The first contribution of this article is that the proposed protocols can overcome the directional deafness problem. The second is that our proposed intelligent and adaptive protocol solution can develop communication operations according to the states and the environmental evolution of the flying UAVs. The third is that the proposed protocols are robust and reliable. Finally, our proposed hybrid adaptive communication protocols have the potential to provide an intelligent and highly autonomous communication solution for FANETs, and point out the main research orientation of FANET protocols.

In this work, we only consider the simplest mobility model, and in the future, we will consider more mobility models of flying UAVs. In addition, we plan to optimize the calculating speed of the RL-based routing protocol to improve the flexibility and practicality. We will scale up the FANET size where more nodes are in place to examine the performance of the proposed protocols further.

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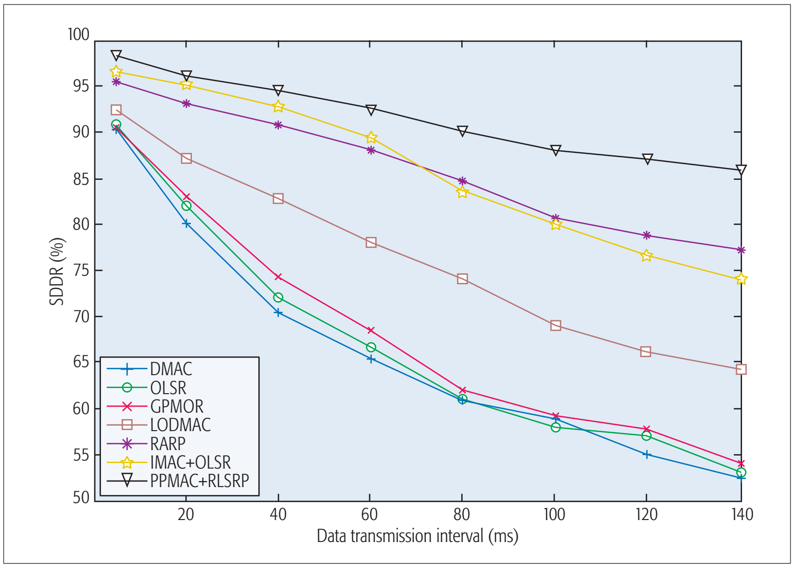

Figure 4. SDDR vs. data transmission interval.

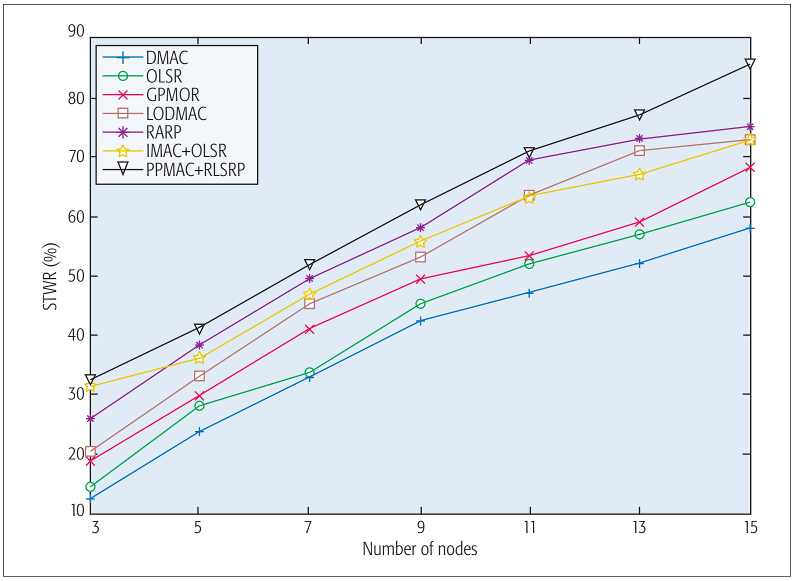

Figure 5. STWR vs. number of nodes.

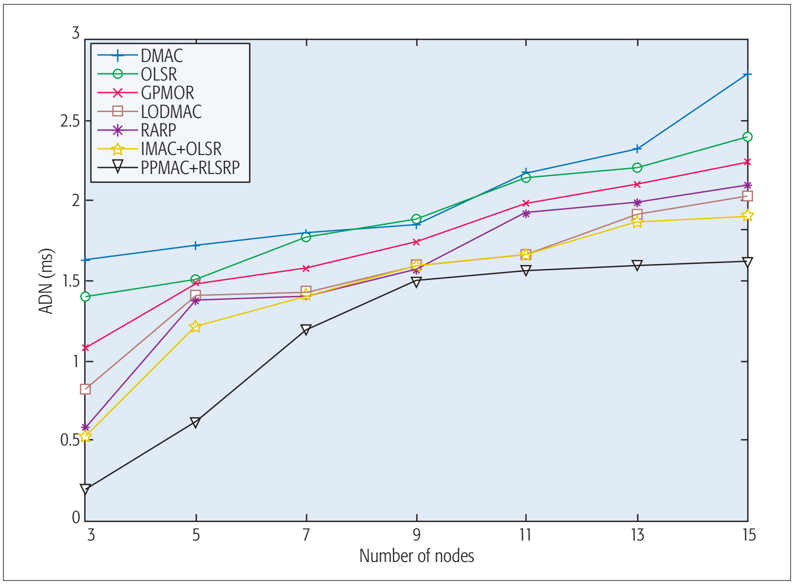

Figure 6. AND vs. number of nodes.

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