Adaptive MAC Protocol for UAV Communication Networks Using Directional Antennas

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***Abstract*— Unmanned aerial vehicle (UAV) has been used recently a lot in military applications as well as in civilian. It shows great advantages and importance in the search and rescue, real-time surveillance, reconnaissance operations, traffic monitoring, hazardous site inspection and range extension. Moreover, UAVs are suited for situations that are too dangerous for direct human monitoring. In general, UAVs have the potential to create an ad-hoc network and greatly reduce the hops from source to destination. However, the type of the mission and the capability of the UAV which are determined by its shape and construction causes a lot of networking issues. Most UAVs used in communication networks assumed the use of omni-directional antenna. In this paper, we considered a collection of UAVs that communicate through a wireless link as a mobile ad-hoc network (MANET) using directional antenna. This technique offers tremendous advantages over that of using omni-directional antenna, although it requires an adaptive medium access control (MAC) to adapt the new antenna system as well as the constraint imposed by the UAV. To be more specific, we introduced a new mechanism that is called target information table to work with our new scheme during the switch from omni-directional to directional antenna. We made a comparison between the two techniques using optimized network engineering tool (OPNET). Our results show good improvement for end-to-end delay as well as throughput.**

I. Introduction

OVER the past ten years, the high flexibility and the easy deployment that the fixed-wing UAVs possess have endowed them to serve as a mobile node in an ad-hoc networks [1]. Fixed-wing UAV has the capabilities to be stable during high speed as well as its ability to maneuver during bad conditions. In addition, takeoff and landing are not so complicated due to the light weight of such UAVs. All missions done today using UAVs assumed that each UAV is equipped with omni-directional antenna where signal is transmitted to all directions [2], [3], [4], [5]. As a result, capacity limitation and jamming are common problems for mobile ad-hoc UAVs. These problems can be largely eliminated by using directional antenna [6], [7]. Meanwhile, directional antenna offers lots of benefits such as longer transmission, less delay and spatial reuse. These benefits are gained by focusing the energy in the desired direction. Moreover, directional antenna is suitable for military environments that are characterized by jamming phenomena.

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Recently, there is a significant commercial and military interest in developing a communication system that enables the UAV to communicate directly with other UAVs without any connection to the ground station. The possible solution to this problem would be the use of directional antenna. This solution should be suited for different applications while using fixed-wing UAVs. The high mobility as well as the physical constraints which are imposed by UAVs may cause some degradation to the performance of the wireless link. In addition, The three critical flight dynamics parameters known as pitch, roll and yaw may also do the same degradation and have large implications on the network. Thus, an effective MAC protocol should be designed to control the channel access and at the same time has the capability to sense the changes in the aircraft attitude and automatically adjusting the antenna reference point to maintain high signal strength.

The current MAC protocol that implements the omni-directional antenna may not be suitable for some missions done by the UAV. This is due to different factors such as long distance between nodes . Directional antenna has the ability to address such factors but under the full control of the MAC layer so that pointing the antenna to the right direction should not be affected by the constraint imposed by the UAV. This paper provides an adaptive MAC protocol that has the capability to address all challenges, deals with directional antenna and endures aircrafts attitude.

The primary challenge to use directional antenna is the errors in UAV position, this leads to the reduction of the directivity in the desired direction. Wind and other disturbances may prevent our scheme to switch to the directional antenna and may cause a reduction in antenna directivity. Therefore, a combination of more than one navigation systems are the central requirements for a practical solution to the UAV communication system. As known, GPS provides position information at (1) second interval, this interval will not benefit our scheme since our scheme needs high update rate for the position of the UAV. As a result, each UAV should be equipped with a GPS and an inertial measurement unit (IMU) to offer the position to the other UAVs at any time. The benefit of using an IMU with a GPS is that the IMU may be calibrated by the GPS signal, and thus, it can provide position and angle at a quicker rate than GPS [8], [9].

The remainder of this paper is organized as follows. In the next section we summarize the previous work that is done regarding the directionality of the antenna. In section III, we describe our scheme that is called adaptive medium access control protocol for unmanned aerial vehicle (AMUAV) and

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discuss how it is capable of adapting the external parameters imposed by the UAV. In Section IV, we present our OPNET simulation results and we provide a comparison with the omni-directional antenna (IEEE 802.11). Finally, we summarize the main results in section V.

II. Related work

Most papers that discuss the directional antenna are focused on the modification of the medium access control. Some used switched beam antenna while others used adaptive antenna. Hetal Jasani, Kang Yen [10] proposed a novel preventive link maintenance scheme based on directional antennas. They aimed to extend the life of the link that is about to break. A warning is generated within a node when the received power is reduced below a certain threshold. A node then creates a directional antenna pattern to raise the received power up.

Ram Ramanathan, Jason Redi, Cesar Santivanez, David Wiggins, and Stephen Polit [11] presented a scheme called utilizing directional antennas for ad hoc (UDAAN). UDAAN consists of several new mechanisms such as neighbor discovery with beam forming, link characterization for directional antennas and proactive routing and forwarding. All the mechanisms are designed to provide a complete system solution.

Jianfeng Wang, Yuguang Fang, Dapeng Wu [12] proposed a new mechanism to solve different problems using directional antenna. For instance, deafness problem, hidden terminal problem, exposed terminal problem and head-of-line(HOL) blocking problem. All these problems are solved by building a MAC timing structure.

In [13], the author proposed two schemes 1) request-to-send (RTS), acknowledgment (ACK) and data packets are sent directionally while clear-to-send (CTS) Packet is sent omni-directionally. Other nodes that hear the CTS should block the antenna on which it was received. 2) Two types of RTS are proposed, directional request-to-send (DRTS) and omni-directional request-to-send (ORTS) based on the following rule:

A. If none of the directional antennas of the node are blocked the node will send an ORTS.

B. Otherwise the node will send a DRTS provided that the desired directional antenna is not blocked. The CTS, Data and ACK are the same as before.

Mineo Takai, Jay Martin, Aifeng Ren, Rajive Bagrodia [14] have proposed the use of the caching mechanism. This mechanism has been made to find the angular location of neighboring nodes. If the angular location of the node is not available, the packet will be sent using omni-directional antenna , otherwise it will be sent using directional antenna. Each node should update the angle-of-arrival (AOA) every time it receives a new signal. In spite of these previous efforts, there are still significant problems that arise with the deployment of directional antennas in the UAVs.

III. Adaptive MAC protocol (AMUAV) scheme

The UAVs are desired nowadays to extend the range of the communication networks. We propose the use of directional antenna that can be steered in all necessary directions. In contrast to a traditional omni-directional antenna, our approach provides robustness to the link (better end-to-end delay, lower interference and better throughput). In general, directional antennas can be classified into two kinds: adaptive array and switched beam. The adaptive array can be implemented with an array of antenna while in switched beam antenna the technique is different where the system follows the basic switching between predefined beams. Adaptive array can be more beneficial than switched beam but with high complexity in reality. Our antenna system involves the two types with a slight modification that suited the UAVs.

The performance of the unmanned aerial vehicle ad-hoc network depends on several factors such as mobility and aircraft attitude. We assumed that all UAVs are placed over the ground and flew at different altitudes. The distance between any two UAVs will not go beyond the range of the directional antenna. Two external hardware are needed in our scheme for UAV location: GPS and IMU. When a packet comes from the upper layer, the node requires the position of the destination in order to steer the main lobe in the right direction. Control packet of type RTS will be sent using omni-directional antenna; it should include the position of the aircraft and duration of transmission. On the other hand, the destination node will respond with a CTS packet that has the same information regarding itself. Each node that hears the CTS or RTS should cache these information and update its table for future use. The data packet will be sent using directional antenna. To make things easy, we present a simple scheme in Fig. 1 based on the following facts.

Case A: Every UAV has four antennas. Two of them are directional. One is located above the UAV and marked primary. The second one is located beneath the UAV and marked secondary. Others are omni-directional. If the UAV has no packet to send, it will listen to other UAVs using one of the omni-directional antenna. On the other hand, if the UAV has a packet to send, it has two choices to send this packet either using directional or omni-directional antenna.

Case B: The locations of the UAVs are significant factors in our scheme. The new MAC should frequently monitor the positions of other UAVs and compute the effect of Euler angles on the directional antenna.

Case C: The new MAC should frequently monitor the distance, bit error rate and retry counter so that it switches to omni-directional antenna if the values exceed the limits.

Case D: In case that there is no activity during a period of one second, UAV should send a heartbeat message using omni-directional antenna. This message contains the location of the UAV . When it is received by another UAV, the UAV should update its table and respond with a similar heartbeat message.

Case E: In our scheme each UAV is capable of electronically steering the beam towards a specific direction. Our modeling to the antenna is based on a single beam that can target the boresight to any direction.

Case F: In the case that the aircraft changes its attitude, the pattern of the antenna will rotate with respect to its axis, resulting in fluctuations in antenna gain, these fluctuations affect the range of the UAV. Thus, the MAC protocol should compensate for any changes by applying the same value to the target location.

Case G: Switching time between primary and secondary antenna is assumed to be zero.

Case H: The mobility model in such a network is not completely random. In military scenarios, each UAV should move to a predefined location. Thus, our model is based on a rounded rectangle [15] mobility model.

According to the IEEE 802.11 standard, a packet is discarded after the retransmit counter exceeds (7). Meanwhile, as the number of retransmission attempts increase, the number of possibilities for delay increases. Based on the distribution coordination function (DCF), a node should sense the channel to determine whether it is idle or not. Sensing is done through physical and virtual mechanisms. If the medium is sensed idle for a DCF inter-frame-space (DIFS) interval, the node has the right to use the medium and start sending data. On the other hand, if the medium is busy or it becomes busy during the DIFS time interval, the transmission will be deferred for a certain time until no other node occupied the medium, like this situation backoff timer is enabled. Our scheme follows the IEEE 802.11 standard with some modification to the retry counter.

There are two methods for carrier sensing in IEEE 802.11 standard, physical carrier sensing and virtual sensing. Virtual sensing is done through the use of network allocation vector (NAV). Two messages should precede the data transmission which are RTS and CTS, these messages contain the duration for which the UAV should reserve the channel to complete the data transmission. On the other hand, any UAV that overhears those messages should defer data transmission for this duration to avoid interfering with other UAV transmission. In our scheme, RTS and CTS should contain the location and orientation of the UAV. We used the directional network allocation vector (DNAV) mechanism [16] with some modification to adapt our scheme while using UAVs. Our DNAV is synchronized with the target information table that is created through the handling of the control messages. In addition, the original NAV is also used in our scheme.

The behavior of our scheme works as follows:

1) To resolve the hidden terminal problem a CTS/RTS is exchanged between the UAVs. Consider the case when a UAV number one is attempting to send a packet to a UAV number two, if the packet is of type control, UAV number one will perform physical carrier sensing as in IEEE 802.11 standard. If the channel is idle, another sensing will be done for NAV to see if the channel is still reserved by another UAV. Once the medium as well as the NAV are all idle, the UAV will enter the backoff for a certain time then RTS packet will be sent through the omni-directional antenna along with the parameters of UAV number one (location, orientation).

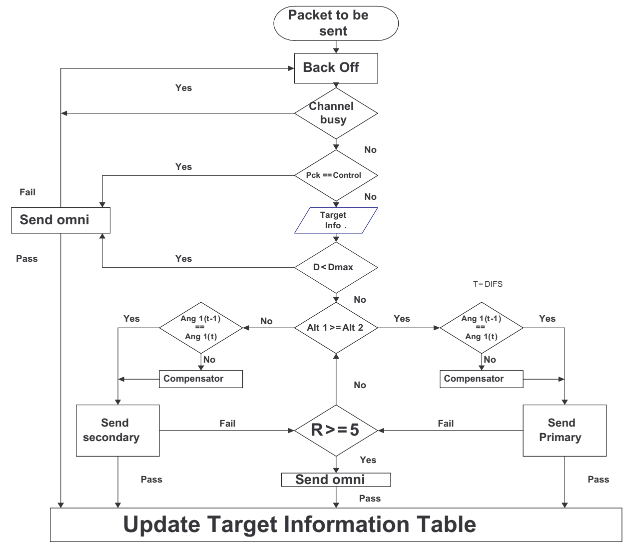

Fig. 1. MAC scheme flow chart for UAV.

TABLE I
TARGET INFORMATION TABLE

Target ID	LATITUDE (Deg Min Sec)	LONGITUDE (Deg Min Sec)	ALTITUDE (Feet)	DIRECTION
1	43 16 32 N	85 38 46 W	500	90
2	43 16 32 N	85 38 36 W	450	90

2) UAV number one as well as number two are equipped with a GPS and IMU to offer the position at high rates. Once the UAV number two receives RTS from UAV number one, it will sense the channel for short-inter-frame-space (SIFS) interval. If the channel is free, it will send the CTS along with the previous parameters in response using omni-directional antenna and update the target information table as shown in table I. UAVs other than number two that also receive either RTS or CTS should update their target information table as well as DNAV and NAV.

3) Once UAV number one receives the CTS message, it will update its target information table. Before initiating the transmission of data packet, the MAC will check the distance between the UAVs. If the distance is less than the range of the omni-directional antenna (Dmax), the data will be sent using omni-directional antenna, otherwise the MAC will check UAVs altitude. If the altitude of UAV number one is equal or less than UAV number two, data will be sent through the primary antenna (directional antenna) along with UAV parameters then the MAC steers the beam to the direction of UAV number two, otherwise secondary antenna will be steered to the same direction.

4) As soon as UAV number two receives the data suc-

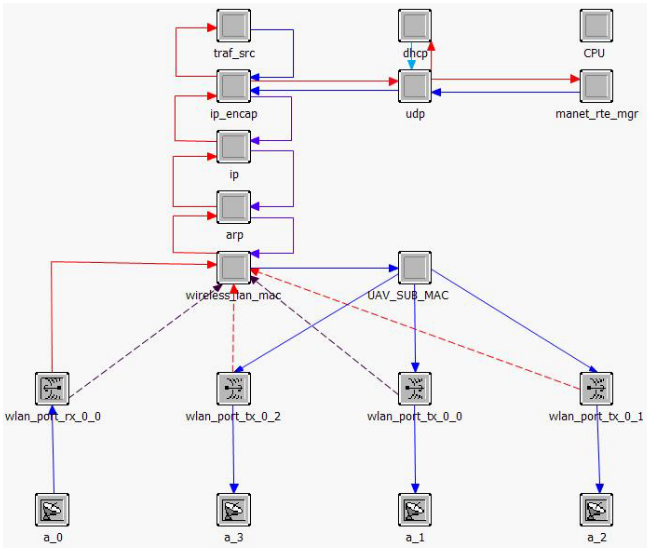

Fig. 2. Modeling UAV in OPNET.

cessfully and updates its target information table, ACK will be sent using omni-directional antenna along with UAV parameters.

5) For each data packet, antenna is steered based on the destination location as well as the source Euler angles. To be more specific, consider UAV number one's attempt to send the second data packet, location of the UAV number two is obtained from the ACK packet, the MAC of the first UAV sensed some changes in the angles after receiving the target location. At this point the MAC should compensate for this by applying the same value to the target location.

6) As mentioned above, a packet is discarded after the retransmit counter exceeds (7), since our goal is to minimize the end-to-end delay, our scheme will switch the transmission from directional to omni-directional if the retransmit counter reaches five.

IV. OPNET SIMULATION RESULTS AND DISCUSSIONS

We have implemented AMUAV in OPNET Modeler 14.5. UAV model is shown in Fig. 2. The process model for the UAV_SUB_MAC is given in Fig. 3, we will next briefly explain the functioning of each state. UAV_SUB_MAC module will work jointly with wirless_lan_mac. The process is constructed by seven states. Below is the function of each state.

Init state: This state initializes state variables and target information table.

Idle state: This is the default state. The node enters an idle state and waits for an incoming event. The event can be either self interrupt or an incoming packet from the wirless_lan_mac module. An incoming packet from the wirless_lan_mac will be checked based on its type, control packets will be sent to the omni state while data packets will be sent to target table state. In addition, this state will read in the initial

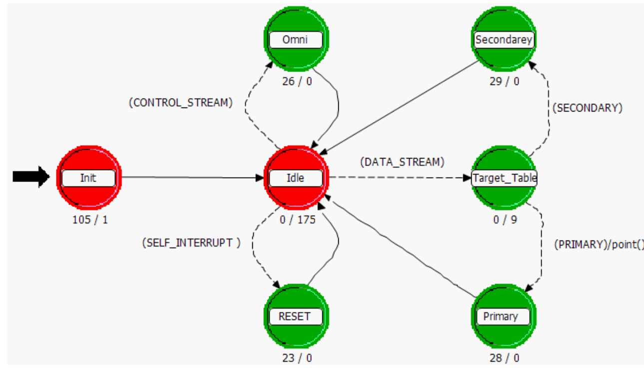

Fig. 3. OPNET process model of UAV_SUB_MAC.

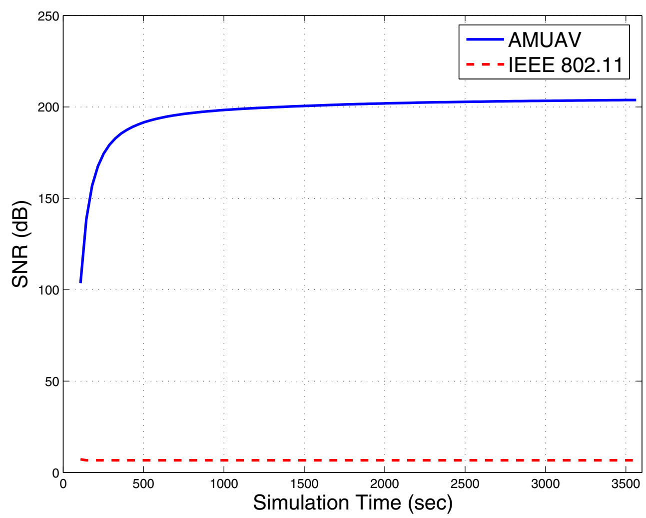

Fig. 4. SNR versus simulation time.

parameters that affect the selection of antenna as well as the MAC attribute values.

Omni state: In this state, the incoming packet will forward to omni-directional antenna.

Reset state: This state adds some delay to permit other modules to register their selves.

Target Table state: This state determines whether the packet belongs to the primary state or secondary state based on the UAVs altitude.

Primary state: In this state, the target location is obtained in order to point the directional antenna to that location . The UAV attitude is recorded for each packet so that any change will trigger the compensator.

Secondary state: This state performs the same functionality as primary state.

We conducted several scenarios comparing the effects of using directional antenna as well as the effects of changing UAV parameters during the use of this type of antenna. Fig. 4 compares the signal to noise ratio measured by two UAVs. It is clear that the average SNR gained while using directional antenna is much higher than that gained by using omni-directional antenna. Also, as shown in the figure, the

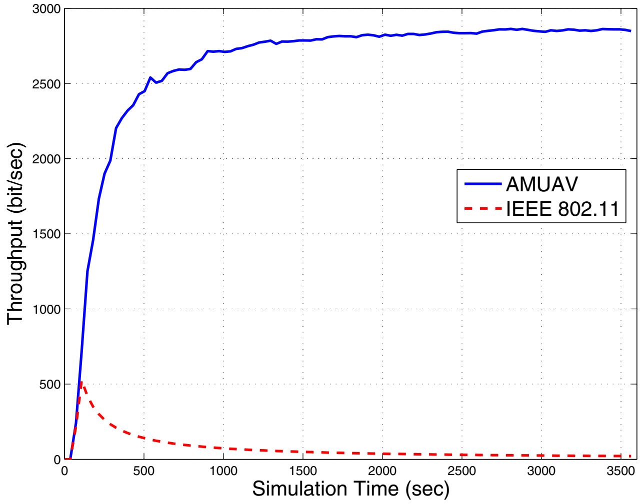

Fig. 5. Throughput versus simulation time.

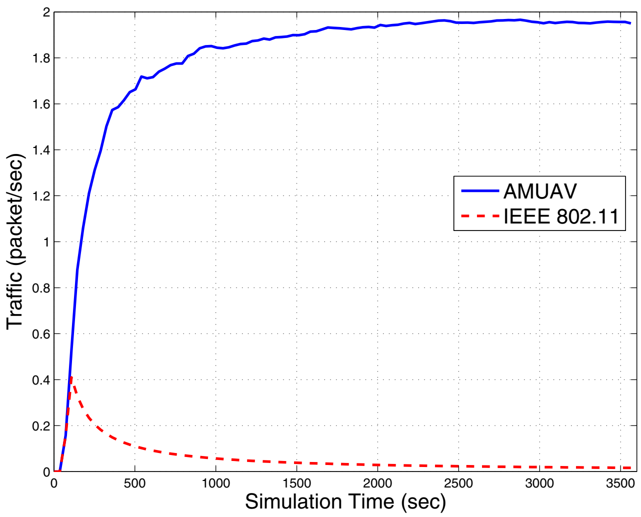

Fig. 6. Traffic received versus simulation time.

SNR converges over the time for both cases. Fig. 5 compares the throughput (bits/sec) using both types of antenna. It was noticed that when the UAV moves away while using omni-directional antenna, the performance degraded to (150 bits/s). On the other hand, the performance improved as the UAV moved away while using directional antenna and converge over the time. The conclusion is clear and it is the same regarding the average of traffic received in Fig. 6.

The total delay of the network is shown in Fig. 7. Due to the high mobility of the UAV, the total delay using omni-directional antenna is much higher than that of using directional antenna.

Fig. 8 compares the bit error rate that is attained by using the two types of antenna. The figure shows that the longer the distance to the second UAV that implements the omni-directional antenna the bigger is the bit error rate. this figure shows the benefit of the directional antenna as the distance

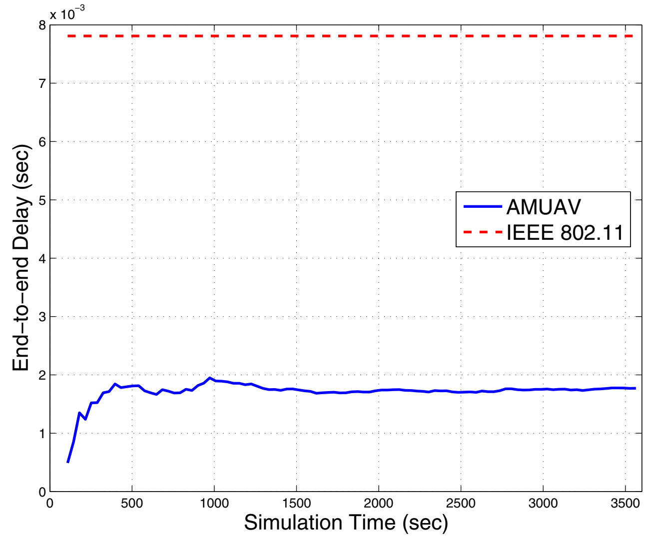

Fig. 7. End-to-end delay versus simulation time.

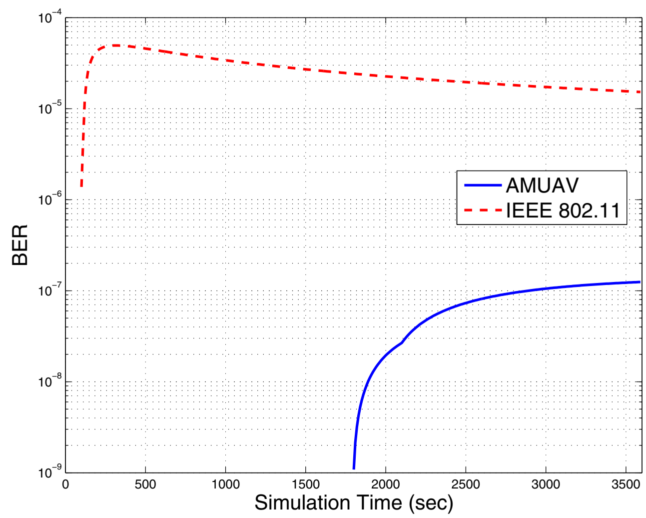

Fig. 8. Bit error rate (BER) versus simulation time.

gets large between UAVs.

V. Conclusion

Due to the high flexibility and easy deployment of a UAV and yet the availability of low-cost communications equipment, it is now possible to use them all as a mobile node in any ad hoc network. In addition, to enhance and improve the performance of the communication network that involves the UAVs, a directional antenna has the capability to extend the communication range and increase the network throughput. In this paper, we have introduced a new scheme that has the capability to adapt the directional antenna and other parameters imposed by the UAV. By OPNET simulator, we compare our new scheme to the IEEE802.11 protocol. We found that our new scheme can improve the network performance since it combines the directionality of the antenna system with the external parameters.

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