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ORIGINAL ARTICLES

Security Estimation Model for Military Aircrafts Using Directional Antennas

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ABSTRACT

In the real military scenarios and particularly using Unmanned Aerial Vehicles (UAVs) that perform aspecific communication task; it is not desirable to have an antenna that covers a wide angle. Omni directional antenna transmits power into all directions and thus it gives transmitter benefits of increasing the probability of being detected by hostile receivers. This paper addresses the problem by exploring the security advantagesof using directional antennas in the battlefield. In this respect, we considered a collection of military UAVs that communicates through a wireless link and forms a Mobile Ad- Hoc Network (MANET) using directionalantenna. We develop a security estimation model for each UAV that is capable for calculating the probability of detecting any transmitter in its range. With this model, each UAV can determine the total area in which the probability of detecting hostile transmitter is bigger than zero. Transmission between UAVs will be established using directional antenna that is able to form a directional beam pointing to anyreceiver locatedoutside the previous area. The results of the Optimized Network Engineering Tool (OPNET) simulator indicatesan overall improvement in security level of directional transmission over Omni directional transmission.

Key words: Unmanned Aerial Vehicle, Mobile Ad-Hoc Networks, Medium Access Control, Directional Antenna, Omni Directional Antenna.

Introduction

A mobile ad-hoc network is one of the popular types of wireless networks that are formed by a collection of mobile nodes. Each node in MANET has the capability to communicate with its neighbors over a shared wireless medium without any support from the base station. Moreover, nodes in MANET are designed to act as an end system and a router. The common assumption for MANET is that nodes are equipped with Omni directional antenna in which the power is transmitted to all directions. This assumption provides the desired receiver with a small portion of the transmitted power while wasting the large one. From military viewpoint, some hostile receivers around the transmitter may detect that signal and have the chance to benefit from it. On the other hand, directional antenna concentrates the power into a certain direction and provides the transmitter with less opportunity to be detected by the undesired receivers.

Directional antenna allows the signal to be transmitted in one direction more efficiently. It reduces the interference by ignoring signals coming from places other than the desired direction. Moreover, directional antenna is being recognized as a powerful method for increasing the connectivity of ad-hoc networks. The transmission range of directional antennas is usually larger than that of Omni directional antennas, and thus it results in reducing hops between the transmitter and the receiver.

In some applications, the key point to solve weak reception and increase range is to use a high gain directional antenna that will send a strong signal in a specific direction. In military scenario and particularly in aircrafts (UAVs) that perform a specific task;itisnotdesirabletohaveawideangle of coverage. The best solution is using an antenna that produces constant field strength in both azimuth and elevation in which we think it is difficult to be mounted on the UAVs. Adding a directional capability to the UAVs will provides a long range and high-rate data link. In addition, it will further raise the security concerns.

UAV is defined as an aerial vehicle that does not require a human operator. Historically, UAV has been mainly used for military applications Srinivasan and H. Latchman, (2004) such as:real-time surveillance and

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reconnaissance operations.In general, Military UAVs are classified into three main categories:tactical, medium altitude and high altitude UAVs. Tactical UAV is small and inexpensive, its range is 160 km and it has the capability to reach altitude of 5000 ft. A medium altitude UAV costs around 1,000,000 dollar, its range is 200 km and it reaches altitude of 20,000 ft. On the other hand, high altitude UAV costs around 10,000,000 dollar and it has the capability to reach distances higher than the medium UAV (30,000 ft and above) Tozer, *et al.,* (2000).

For this purpose, to integrate the directional antenna successfully into UAV ad-hoc networks; an estimation model is introduced in this paper so that the use of directional antenna will assist in enhancing the security issues in the battlefield. The remainder of this paper is organized as follows. In the next section we start with a survey of current research regarding the directional protocols and the concept of using UAV as a communication node in MANET. In section 3, we describe our security estimation model. In section 4, we explain how doweimplementUAVinOPNETandin section 5, we present our simulation results and we provide a comparison betweenthedirectionaltransmissionandOmni directional transmission. Finally, we summarize the main results in section 6.

Related work:

A tremendous number of directional MAC schemes have been proposed nowadays for MANETs that are equipped with directional antenna.Most papers that discussed the directional antenna concentrate on the modification of the MAC protocols (Singh *et al.,* 2005; Mundarath *et al.,* 2005; Choudhury *et al.,* 2006; Takata; 2005; Nasipuri *et al.,* 2000), the authors proposed a directional protocol that utilizes switched beam antenna. In their mechanism; as soon as the transmitter receives the control packet, it estimates the angle of arrival and transmits its data using directional antenna.

Using the switched beam antenna as the author did in Nasipuri *et al.,* (2000), the authors in Ko *et al.,* (2000) assumed that the directional gain equals theOmni directionalgainandproposedthatRequest-To-Send(RTS),acknowledgment (ACK)anddata packetsare sent directionally while Clear-To-Send (CTS) packet is sent Omni directionally. Nodes that hear the CTS packet should block the antenna on which it was received. On the other hand, the authors in (Nader *et al.,* 2004; Harkirat and Suresh, 2004) and (Bao *et al*., 2002) studied the performance of MAC protocols with adaptive array antennas. Bao, *et al.* (2002) developed a distributed Receiver-Oriented Multiple Access (ROMA) protocol for ad-hoc networks in which all nodes are equipped with a multi-beam adaptive array antenna. This protocol is capable for forming multiple beams and creating several simultaneous communication sessions.

The authors in Takai *et al.,* (2002) proposed a new carrier sensing mechanism that is called DVCS (Directional Virtual Carrier Sensing). This mechanism required information regarding the angle of arrival for each signal received from the physical layer.They have proposed the use of caching mechanism to store information about angular location of neighboring nodes.As soon as the MAC layer receives packet from the upper layer, it will look in the cache to determine whether it has the information about the angular position of the destination node or not. If the angular position of the destination node is known, the packet is transmitted using the directional antenna; otherwise it will be sent using Omni directional antenna.

Another MAC protocol was designed in Choudhury *et al.,* (2002). This protocol uses multi hop RTSs to establish links between distant nodes. In this protocol, when any node receives RTS, it transmits CTS, DATA and ACK over a single hop. Choudhury *et al.,* (2002) and Takai *et al.,* (2002) have suggested the use of Directional Network Allocation Vector (DNAV). DNAV is similar to the NAV that is used in standard IEEE 802.11 except that the DNAV stores the angle of arrival of the RTS packets in any given direction. For each packet to be transmitted, the DNAV is consulted to see whether the angle of the packet to be transmitted is overlapped with any ongoing transmissions. If there are overlaps, the packet transmission is deferred; otherwise, the packet is transmitted.

In spite of the previous efforts, directional antenna has been presented new problems for ad- hoc networks. In Wang *et al.,* (2006), the author proposed a new mechanism to solve the hidden terminal problem and exposed terminal problem. This mechanism is based on a MAC timing structure. In Jakllari, (2007), the authors proposed a polling based MAC protocol that addresses the problem of neighbor discovery. The proposed MAC protocol is based on the polling strategy wherein a node polls its neighbors periodically. Time is segmented into consecutive frames and nodes are synchronized with each other. By this technique each node is able to adjust its antenna weight in order to track its neighbors.

Applications with UAV have specific requirements to reduce the overhead under heavy transmission load (Brown *et al.,* 2004; 2004; Cheng *et al.,* 2006; C.I. and K.S., 2004). the authors presented a new contention-based medium access control protocol for wireless ad-hoc networks of unmanned aerial vehicles. They called their protocol a Receiver-initiated Access Control with Sender Scheduling (RACSS). The RACSS MAC protocol uses the concept of contention-based protocol where the receivers have the power to decide which node to transmit. In mobile ad-hoc network, data transmissioncanbeperformedbyoneofthreemethods: direct transmission, multi-hop relaying through intermediate nodes, and data ferrying through a node that physically moves between sources and destinations D. C *et al.,* (2006). Implementation of these methods is restricted by the nature of the UAV and the application.

In B.P. *et al.,* (2004), the authors studied the problem of UAV placement over ground nodes with the end goal of improving network connectivity by applying flocking algorithm. Flocking algorithm for UAV placement can provide good coverage, connectivity and load-balance to the underlying mobile nodes by using local information in making decisions about where to move and thus keeping the overhead packets very low. The authors assumed that there is no direct connectivity between ground nodes and only UAVs are responsible for connecting the ground nodes. Simply, by applying flocking algorithm, UAVs should maintain safe distance from each other, maintain connectivity among themselves and track the motion of ground nodes so that overall network connectivity is maintained.

To improve the reliability of ad-hoc ground based networks. The concept of using UAV as a communication relay was presented in Palat *et al.,* (2005). The authors studied the performance of the ad-hoc ground network using UAV as a relay node and the effects of UAVs' positions and velocities on Bit-Error-Rate (BER). In Cheng *et al.,* (2007), the authors presented the load-carry-and-deliver (LCAD) networking paradigm to relay messages between two distant ground nodes. This paradigm, LCAD, is designed for maximizing the throughput of UAV relaying networks by having a UAV load from a source ground node, carry the data while flying to the destination, and finally deliver the data to a destination ground node. They compared their paradigm against the conventional multi-hop and they claimed that the proposed LCAD paradigm can be used to provide high throughput between ground nodes.

In Henkel and T. X. Brown, (2007), the authors investigate the properties of relay-enabled networks as a function of the number of relays in the network. Three basic communication modes were taken into consideration: 1) direct communication, 2) relay communication with one transmission at a time (single transmitter case), and 3) relay communication with multiple simultaneous transmissions at different relays (parallel transmitter case). They summarized their finding as follows:When multiple packets are sent at a time (the second packet is generated while the first packet is still in its path to the destination), the performance depends on the separation in hops between simultaneous transmissions in the relay chain and doesn't depend on the distance and noise. On the other hand, when packets are sent one at a time (packet is forwarded completely from source to destination before the next packet is forwarded), the performance depends on the number of relays.

Movement pattern of UAVs has significant impact on networking performance. In Erik and S. Nadjm-Tehrani, (2006), the authors presented algorithms for determining a desirable mobility model for UAVs in reconnaissance operations. Two mobility models were provided: in the first one, the UAVs move independently and randomly while in the second one, the pheromone model guides their movement. Based on their conclusion, the random model is simple and it achieves good results. The pheromone model achieves good result, but it has problems with respect to network connectivity. In addition, their study shows that coverage and connectivity of communication are two conflicting objectives.

Security Estimation Model Using Directional Antenna:

Generally speaking, Antenna system is classified into two types: directional antenna and Omni directional antenna. In directional antenna, the signal propagates in a certain direction while in Omni directional antenna; the signal propagates in all directions. With directional antenna, higher gain allows UAV to communicate with other UAVs located at higher distance in fewer hops. In addition, it narrows the coverage area. The primary challenge to use directional antenna in such network is the errors in UAV position; this leads to the reduction of the directivity in the desired direction. Therefore, a combination of more than one navigation system is the central requirements for a practical solution to the UAV communication system.

In this paper, we proposed the use of directional antenna that can be steered in all necessary directions. In contrast to the Omni directional antenna, our approach will enhance the security level that is needed by any military group. 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 switched beam antenna follows the basic switching technique between predefined beams.

Inoursecurityestimationmodel,weassumedthatthe hostileUAVdoesnotknow thetransmitter / receiverlocation; its antenna is Omni directional antenna and non of the UAVs are able to modify the received signal, the decision that is taken by a UAV is based on the signal to noise ratio (SNR) where low SNR indicates the presence of the hostile UAV. Any UAV involves in transmission is forced to switch from Omni directional mode to directional mode.

To determine how much power is required to send the data successfully from transmitter to the receiver; Effective Isotropic Radiated Power (EIRP) relation is used to find the total power radiated in a certain direction and it is given in following equation.

$$EIRP = Pt + Gt \quad (1)$$

Where Pt is the power radiated out from the transmitter and Gt is the antenna gain of the transmitting node. To compare the EIRP using the Omni directional antenna and directional antenna, we can say the EI RPfor directional antenna is much larger than that the Omni directional antenna.

A hostile UAV can detect any transmission if and only if the signal to noise ratio is larger than a certain threshold X.

$$P\ (Detection)=P\ (SNR>X) \quad (2)$$

Where P denotes the probability of any transmitter being detected by a hostile UAV, SNR denotes the signal to noise ratio and is given by the following equation:

$$SNR=S-N \quad (3)$$

The signal to noise ratio is the difference in power between the intended signal and the noise in the communication channel, equation number (3) can be rewritten as:

$$SNR=Pr-N \quad (4)$$

$$P\ (Detection) = (Pt+ Gt) + Gr - Ploss \quad (5)$$

$$P\ (Detection) = EIRP + Gr - Ploss \quad (6)$$

Pr in equation (4) represents the received power and it is equal to (Pt + Gt) + Gr).PLoss represents the total free space loss and is given by the following equation:

$$PLoss\ (D,F) = -27.55 + 20\ log10\ (FMHz) + 20\ log10\ (Dkm) \quad (7)$$

Equation (7) is applicable for UAVs since there is a line of sight between them during the communication session.

$$SNR = \{Pt + Gt + Gr\ (\varphi,\theta) + 27.55 - 20\ log10\ (FMHz) -20\ log10\ (Dkm)\}$$

In equation (8),Gt = 0dBandsomeparametersare constant, theseparameters can be represented by K where K= P t – 27.55 – 20log(f) – N, equation number (8) can be rewritten as:

SNR= Gr (φ,θ) -20log10(Dkm) + K

Substitute equation (9) into equation (2).

$$P\ (Detection) = P\ (SN\ R > X) \quad (10)$$

$$P\ (Detection) = P(Gr\ (\varphi,\theta) - 20\ log10\ (Dkm) + K > X) \quad (11)$$

$$P\ (SN\ R > X) = F\ (D,(\varphi,\theta))$$

Uav Implementation in Opnet:

We have constructed our directional antenna pattern in Optimized Network Engineering Tool (OPNET). In our modeling of the antenna system, the maximum gain in the pointed direction is set to 200dB and -10dB in other directions. The beam width is set to 5 degrees and two modes of operations are used: directional and Omni directional. In directional mode, antenna consists of only a steerable single beam which is dedicated for transmission in one direction, while in Omni directional mode; antenna is dedicated for transmission in all direction. Each UAV is equipped with a transmitter, receiver, directional antennas and Omni directional antennas.The link between the UAVs is modeled with fourteen pipeline stages.These stages are provided by the OPNET modeler and divided between transmitter and receiver as shown in Fig.1.Six stages are associated with radio transmitter and eight stages are associated with radio receiver. All stages are used to compute the antenna gain, bit error rate and SNR.

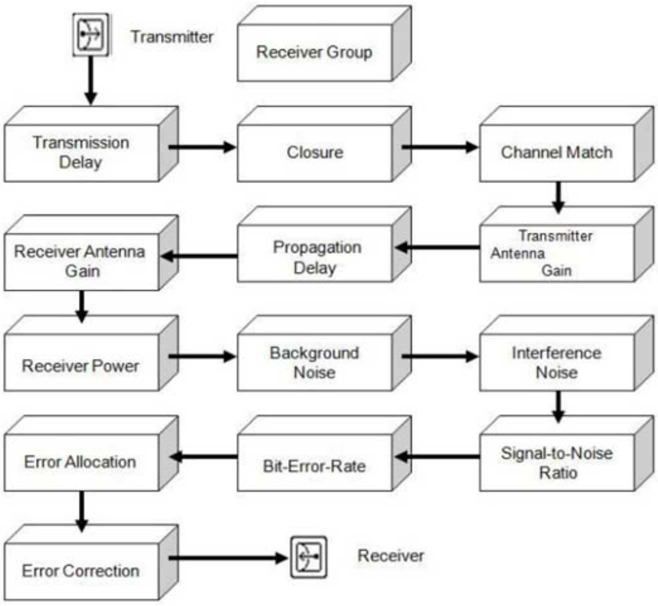

Fig.1:OPNET Radio Transceiver Pipeline Stages.

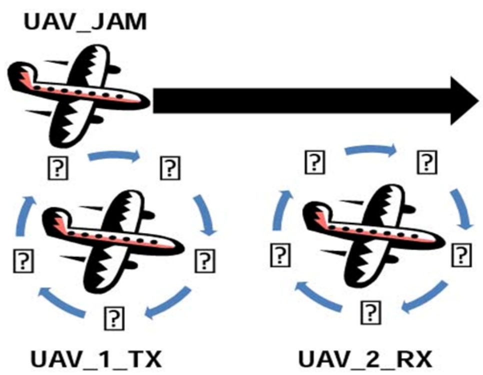

Fig. 2: UAV Simulation Scenario.

As shown in Fig.2, our system consists of three UAVs. The first UAV is modeled as a mobile transmitter and the second one is modeled as a mobile receiver. The third UAV is modeled as a mobile jammer that is moving in a trajectory route. UAVs number one and two are moving in a circular route.

As shown in Fig.3, UAV number one transmits at uniform strength in all directions. It is modeled with three modules: packet generator module (tx_gen), radio transmitter module (radio_tx) and antenna module (ant_tx).Packet generator module generates packets in which the radio transmitter module transmits those packets to the isotropic antenna at 1024 bits/second.

Fig.4 shows UAV number two. It composed of four modules: Antenna module (ant_rx), radio receiver module (radio rx), sink processor module (rx_sink) and an additional pointing processor module that works with the directionalantenna (rx_point), it calculates the information that the directional antenna needs to point towards the transmitter: latitude, longitude, and altitude coordinates.

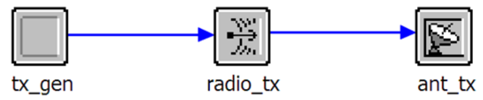

Fig. 3: Transmitter Node Model.

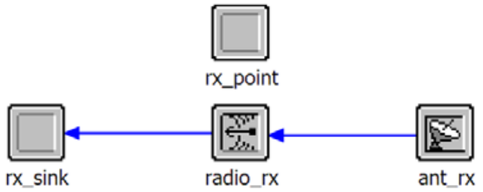

Fig. 4: Receiver Node Model.

The third UAV is modeled as a mobile jammer. It looks like the transmitter node and consists of a packet generator module, a radio transmitter module, and an antenna module. Since the channel power and signal modulation are different from those used in the transmitter node, the packets transmitted by the jammer sound like noise to the receiver.

Opnet Simulation Results and Discussions:

For the analysis of this phenomenon presented in this paper, we study different parameters for two types of antenna. Isotropic and directional antenna; isotropic antenna is mounted over the first UAV and the directional antennas as well as the isotropic antenna are mounted over the second UAV. Both UAVs are moving in a circular path while the jammer is moving in a trajectory as shown in Fig. 2. The intended transmitter sends sequences of frames with a fixed payload while the jammer transmits continuously.

Fig. 5 shows the average SNR as a function of the distance between the UAV_JAM node and UAV_2_RX node, in this figure and also in all the figures that follow, the X axis is labeled as a simulation time, this axis is corresponding to the distance between the UAV_JAM and UAV_ 2_ RX nodes. As we concluded in section 3, the probability that a packet isreceived isbasedontheperceived SNRlevelandthus itisafunction of thedistance between thenodes. Fig. 5 part (a) shows the average SNR using the Omni directional antenna. Clearly it can be seen from this figure that during the time interval 0 to 10 second the SNR at the UAV_2_RX node gradually increases. After that and during the entire simulation, the average SNR declined as the distance between the UAV_JAM and UAV_2_ RX nodes decreases. On the other Fig. 5 part (b) shows that during the time interval 20 to 420 second, there is no change on the average SNR since the direction vector connecting the UAV_JAM and UAV_2_RX antennas is not inline. During the time interval 10 to 20 second, the direction vector connecting both UAVs is in line with the direction of greatest gain for the receiver antenna. Therefore, the receiver node started to receive interference from the jammer node and the SNR at the receiver approached zero.

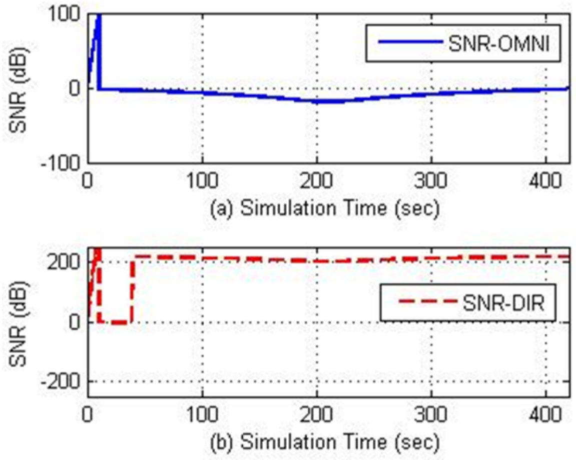

Fig. 5: (a) SNR of Isotropic Antenna, (b) SNR of Directional Antenna.

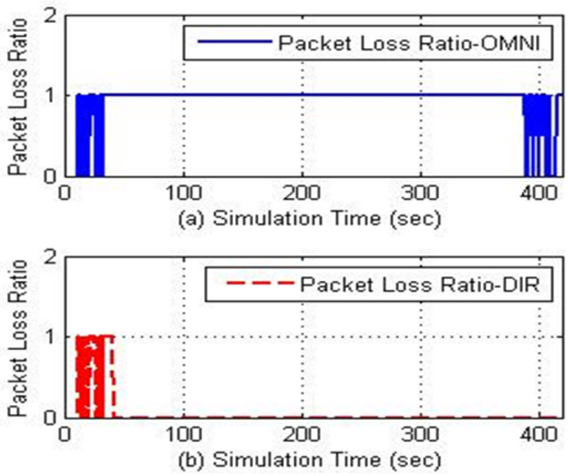

Fig. 6: (a) Packet Loss Ratio Using Isotropic Antenna, (b) Packet Loss Ratio Using Directional Antenna.

Fig. 6 shows the packet loss ratio using isotropic antenna and directional antenna. As the jammer moves along the prescribed path, it can be seen from Fig. 6 part (a) that the packet loss ratio of the UAV_2_RX node increases as the distance to the UAV_JAM node decreases. On the other hand, as the UAV_ JAM passed the UAV_1_TX, the direction vector between the UAV_JAM antenna and the UAV_2_RX antenna is no longer in line with the direction of greatest gain for the UAV_2_RX antenna. Therefore, the packet loss ratio is zero.

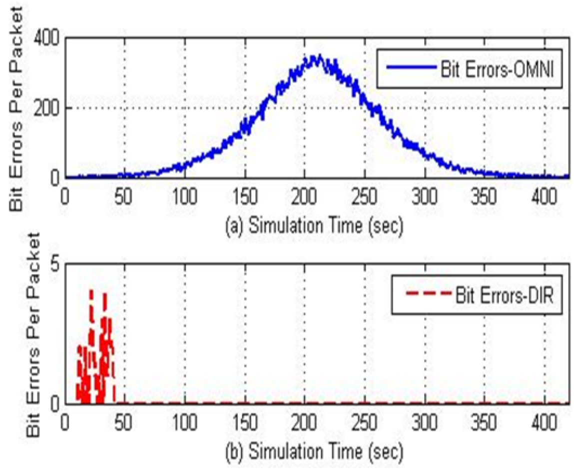

Fig. 7: (a) Bit Error Using Isotropic Antenna, (b) Bit Error Using Directional Antenna.

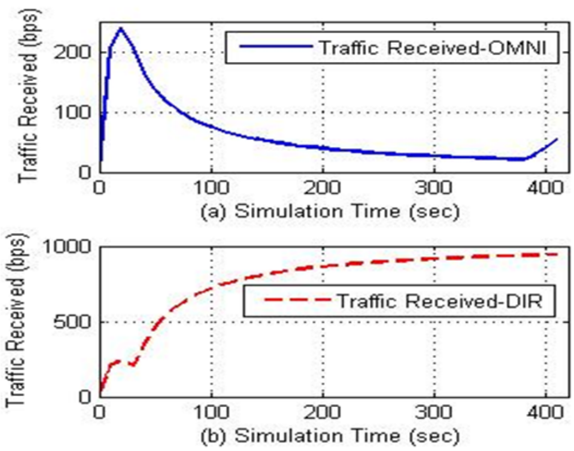

Fig. 8: (a) Traffic Received Using Isotropic Antenna,

Fig. 7 shows the bit errors per packet. Using the isotropic antenna pattern, the bit errors per packet at the UAV_2_RX node gradually increases as the distance between the UAV_JAM and UAV_2_RX nodes decreases. Using the same antenna pattern, Fig. 8 and Fig. 9 show that the traffic received as well as the throughput gradually decrease as the distance between the UAV_JAM and UAV_2_RX nodes decrease.

These results show that UAV_JAM node degrades communication quality and increases frame loss rate. They show that with two simultaneous transmissions, the UAV_2_RX node is not able to detect the intended transmission or it may receive corrupted frames. On the other hand, to avoid the interference caused by the UAV_JAM and to make the link between nodes more secure, the UAV_2_RX node needs to use a directional antenna with a higher gain and smaller beam width.

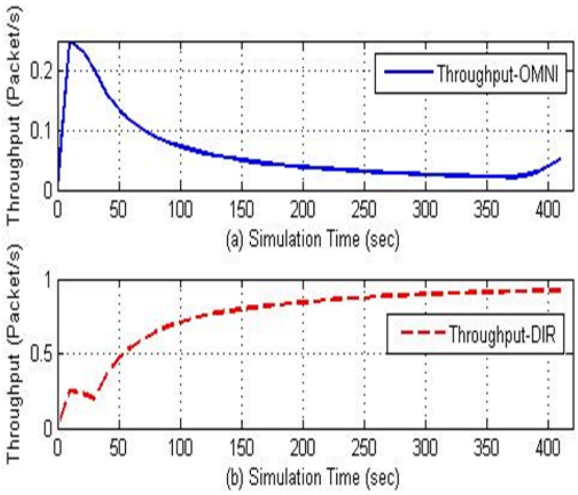

Fig. 9: (a) Throughput using isotropic Antenna, (b) Throughput using directional Antenna.

Conclusion:

Recently, unmanned aerial vehicles are widely being used in military applications such as: search and rescue, real time surveillance and reconnaissance operations. All military UAVs that communicate through a wireless link and form a MANET are using Omni directional antenna. Omni directional antennas radiated signals in all directions; this gives a hostile UAV the opportunity to detect the transmitter and thus become unsafe. On the other hand, to make it safe; the transmitted beam should be narrow so that only nodes located in that direction could receive the signal. Directional antenna can provide this beam so we can reduce the probability in detecting the signal by a hostile UAV. In this paper, we explore the use of directional antenna for military UAVs as one case of enhancing the security level. We developed a security estimation model that is capable for calculating the probability of detecting transmitters closed to the receiver and then using these results to learn the node which direction is safe for transmission. We have constructed our directional antenna pattern using antenna pattern editor provided by OPNET. Using the OPNET simulator, we observed that using directional antenna in UAV ad-hoc network provided better security than Omni directional antenna.

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