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ESPRIT-Based Directional MAC Protocol for Mobile Ad Hoc Networks

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Abstract— **The use of directional antennas in mobile ad hoc networks has shown to offer large potential throughput gains relative to omnidirectional antennas. When used in ad hoc networks, directional medium-access-control (DMAC) protocols usually require all nodes, or part of nodes, to be aware of their exact locations. This location information is typically provided using a global positioning system (GPS) which, typically, requires a line of sight in order to avoid the large signal attenuation and hence is not suitable for indoor applications. Moreover, as the inaccuracy associated with the GPS position estimation increases, the system throughput dramatically degrades.**

In this paper, we propose an efficient two-channel two-mode DMAC protocol. Our protocol employs two frequency division multiplexed channels: channel one used for omni-mode transmission and channel two for directional mode transmission. Signal parameter estimation via the rotational invariance technique (ESPRIT) is used for direction-of-arrival (DOA) estimation. By avoiding the reliance on GPS for obtaining the position information, our protocol is suitable for both outdoor and indoor applications. Under different operating conditions and channel models, our simulation results clearly show the throughput improvement achieved using the proposed protocol relative to the IEEE 802.11.

Index terms— Mobile ad-hoc networks, adaptive antennas, direction-of-arrival estimation.

I. INTRODUCTION

An ad hoc network is a collection of, possibly mobile, devices or nodes that are able to establish wireless communications with each other without any pre-existing infrastructure. In Ad hoc networks, each node functions not only as a host but also as a router that maintains routing paths and relays data packets for other nodes in the network that may not be within the direct wireless transmission range.

Normally, all ad hoc nodes are assumed to have only omni-directional antennas and many existing ad hoc MAC protocols are designed based on this assumption [1]. When using omni-directional antennas, the electromagnetic energy of the signal is spread over all directions around the transmitter while only a small portion of it is received by the intended receiver. This may also cause interference for other unintended recipients. Directional antennas have been proposed as a method to solve this energy/bandwidth waste problem and hence improve the capacity of wireless networks. Many works have already focused on how to utilize the benefits of directional antennas in ad hoc MAC protocols (e.g., [2]-[10]). The most important feature of directional antennas is due its capability to avoid co-channel interference. Thus, using directional antennas allows multiple transmissions to co-exist in the same neighborhood. Due to this characteristic, directional antennas constitute an attractive component for all wireless applications, including ad hoc networks. On the other hand, besides the device portability factor, some problems may arise when directional antennas are used in ad hoc networks. These include: deafness, hidden terminal problem and the need for location awareness. The deafness and hidden terminal problems are studied extensively in [2]. The location awareness is a natural requirement since the transmitter must know the position or direction of the intended receiver in order to focus the main lobe of its antenna beampattern towards the appropriate direction.

To solve the above problems, the majority of directional MAC (DMAC) protocols need to obtain the position information and exchange this information by some proposed frames. Several DMAC protocols (e.g., [6], [10]) assume that all nodes are equipped with a global positioning system (GPS) to be able to determine the position information of the intended user. While the cost of GPS hardware is getting lower, GPS typically requires a line of sight in order to avoid the large signal attenuation and hence is not suitable for indoor applications.

Another practical problem that is also ignored by most of the previously proposed GPS-based DMAC protocols is the inaccuracy associated with the GPS position estimation. Moreover, as the position estimation error increases, the system throughput dramatically degrades when using a large number of antenna elements.

In this work, we propose a 2-channel 2-mode DMAC protocol that achieves a large throughput gain relative to other DMAC protocols [2]-[5]. Estimation of signal parameter via rotational invariance technique (ESPRIT) is used for direction of arrival (DOA) estimation [14]. By employing directional antennas, not only to transmit data frames but also as a tool to estimate the signal DOA, the position estimation is achieved at no additional hardware cost. Moreover, by avoiding the reliance on GPS for obtaining the position information, our protocol is also suitable for indoor environments. By varying

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the ESPRIT parameters and the number of antenna elements, we are also able to avoid any system capacity degradation caused by inaccurate DOA estimation.

The rest of the paper is organized as follows. In Section II, we give a description of our proposed MAC protocol. In Section III, we briefly review the ESPRIT DOA estimation algorithm. Our (Matlab) simulation results are presented in section IV. Finally, conclusions are given in Section V.

II. Proposed Directional MAC PROTOCOL

Our proposed protocol is a two-channel two-mode (omni and directional) DMAC protocol. In channel one, all packets are sent in omni mode. In channel two, all packets are sent in directional mode. The mobile nodes are assumed to be equipped with directional antennas. We use two different values for the network allocation vector (NAV). The first is referred as omni-NAV (ONAV) which counts the period during which a node cannot use channel one to transmit packets (similar to function of NAV table in IEEE 802.11). The second one is a directional-NAV (DNAV) which counts the period during which a node cannot use channel two in certain direction. Thus, the DNAV can be seen as a table that keeps track of the blocked directions and the corresponding durations toward which a node must not initiate a transmission. If a node wishes to send a directional packet over channel two, and this direction is blocked by DNAV table, then it needs to defer this transmission. However, a transmission intended towards other directions that are not blocked by DNAV table can still be initiated. In order to illustrate this, consider the scenario shown in Fig. 1. Assume that node A and B communicate with each other using directional antennas. Also assume that all nodes are in the radio range of each other.

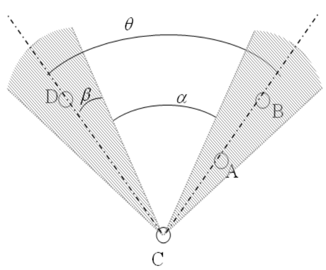

Fig. 1. An example of the function of the DNAV table.

During the period of communications between node A and B, if node C has a packet to send to D, then it must check its DNAV table to see if it is safe to transmit in this direction. Since node C has already received a directional packet from node B only, it updates its DNAV table. Therefore, node C finds it is safe to transmit in the direction of D. We assume that the directional beamwidth is 2β degrees. Let θ be the new initial transmission direction apart from the direction of ongoing transmission. That is, $\theta = 2\beta + \alpha$ where α is the angular separation of the range edges of the beamformers. If α is negative, then the two beamformers might overlap. In our protocol, we must make sure that α is greater than or equal to zero before any ongoing transmission can proceed.

To illustrate the basic steps in our new proposed MAC protocol, consider the scenario shown in Fig. 2 which consists of 6 mobile nodes, A, B, C, D, E and F. The nodes in our protocol can operate in two modes; omni-mode and directional mode. This scenario is designed to clarify the communication process between all possible neighboring pairs. In particular, it illustrates the communication process for the 3 types of neighboring pairs: (i) omni node, omni node, (ii) omni node, directional node, and (iii) directional node, directional node.

In the above scenarios, we consider nodes A and B as the transmitting pairs, nodes C and D as omni nodes, nodes E and F as directional nodes. We separate the whole process into four steps; “RTS transmission”, “RTS reception and CTS transmission”, “CTS reception and DATA transmission” and “DATA reception and ACK transmission”. In what follows, we describe the details of each one of these four steps.

(i) RTS Transmission:

Assume that node A wishes to initiate a transmission with node B as shown in Fig. 2. If channel one is sensed idle, node A sends a RTS frame to B in the omni mode using channel one. All mobile nodes remain in the omni mode when they are idle, listening to channel one. Thus node C, D, E, and F will update their ONAV. This stage is the same as in the IEEE 802.11.

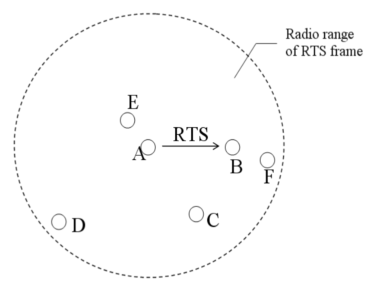

Fig. 2. RTS transmission stage.

(ii) RTS Reception and CTS Transmission:

In this step, all the mobile nodes determine the DOA of the incoming signal using the ESPRIT DOA estimation algorithm. Having received the RTS from A, node B can determine the direction that it uses to send its CTS response. After checking its DNAV table, node B can also determine whether it is safe to use the direction of A in channel two. If it is safe, the physical layer at node B senses channel one for SIFS time slots. If channel one remains free during this interval, a CTS frame is transmitted using omni mode (OCTS) in channel one. At the same time of the OCTS transmission, node B sends another CTS using directional mode (DCTS) in channel two. As indicated in Fig. 3, node A, C, E, F will receive the OCTS and update their ONAV table (similar to IEEE 802.11). On the other hand, only nodes A and E will receive DCTS, and hence node E will consequently update its DNAV table. Compared to the IEEE 802.11, our proposed protocol uses a DCTS besides

OCTS. The function of this DCTS is to update the DNAV table for all nodes which are located in the radio range of the ongoing transceiver's directional antenna in channel two. Hence these nodes will not try to send any signals that may interfere with ongoing transmissions. As shown in Fig. 4, node E will update its DNAV table when it receives DCTS from B. The shadowed part is the blocked range in E's DNAV table, which means that node E cannot initiate any transmission that is directed to this blocked area. For example, node E cannot set up any DATA transmission to node F during the period of DATA transmission between nodes A and B. Once node A and B finish the handshake stage in channel one, they start transmitting their DATA frames over channel two using the directional antenna mode. In particular, similar to the one it used to send DCTS, node B will use the directional beampattern to receive data from node A, and keep the null part in other directions to eliminate any potential interference.

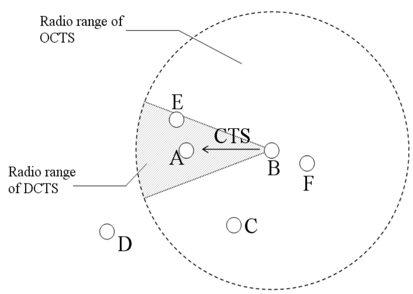

Fig. 3. CTS transmission stage.

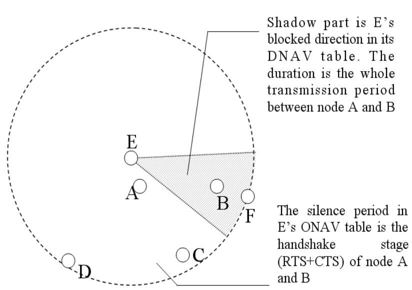

Fig. 4. The blocked direction in the DNAV table.

(iii) CTS Reception and DATA Transmission:

The sender (node A) waits for the CTS using the omni mode. If no feedback arrives within the timeout duration, node A will retransmit a new RTS packet. When node A receives the CTS, knowing the direction of receiver from DOA estimation, it initiates the DATA transmission using the directional mode over channel two provided that this direction passes the examination of its DNAV table. The antenna beamforming is demonstrated in Fig. 5. Since nodes A and B have known the direction of each other, node A can send DATA over channel two using the directional mode. Similarly, node B can point its directional antenna to node A so that the interference from other directions may not affect the ongoing DATA transmission.

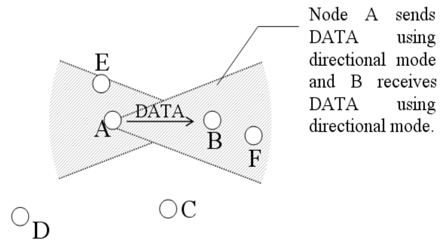

Fig. 5. DATA transmission stage.

(iv) DATA Reception and ACK Transmission:

On receiving the DATA successfully, node B sends an ACK using the directional mode over channel two. The antenna beamforming in this case is demonstrated in Fig. 6. Node A will then point its directional antenna to node B to receive ACK. Due to the use of directional antennas, new transmissions can be set up in the vicinity of node A or B if it is not covered by the range of the directional antenna. As a result, the whole system capacity will be dramatically increased compared to the original IEEE 802.11 protocol. In summary, the transmission process will occupy channel one in the stage of RTS+OCTS, and channel two in the DCTS+DATA+ACK stage.

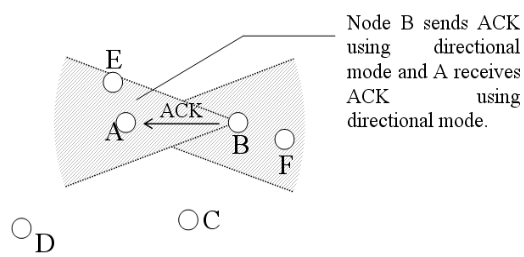

Fig. 6. ACK transmission stage.

Now, we consider the new transmission if there is an ongoing transmission in its vicinity. All nodes, if they have packets to send, can contend over channel one after sensing channel one free for SIFS time slots. Consider the mobile nodes C and D in Fig. 7. The ongoing DATA transmission of nodes A and B will not affect their transmission. Thus both nodes C and D can initiate transmission during the period of DATA transmission of A and B. This is simply because none of them receive packets in channel two (i.e. DCTS or DATA). On the other hand, the situation is different for node E and F. Node E is able to hear the DCTS from node B as discussed above. Thus node E will update its DNAV table in the direction to B. Also node F can hear the DATA packets form A so that node F will not initiate any transmission in the direction of node A. As shown in Fig. 7, node E can initiate a transmission to node D even though both of nodes are in the omni range of A. This type of transmission is impossible in the IEEE 802.11. Node E can also transmit data to node C even if the transmission direction is pointing to node A. This is forbidden in most of other DMAC protocols because node A is part of an ongoing transmission. Obviously, node E cannot transmit data to node F since F is in the blocked range of E (given in its DNAV table). Another difference between our protocol and other DMAC protocols (e.g., [2], [15]) is that we also take interference into consideration when forming the antenna beampattern. For example, if node E initiates a transmission to D, node E will take the direction of B from the DNAV table as an unintentional direction when it forms its antenna weights. In this case, the antenna beampattern of node E will eliminate the interference part that points to B.

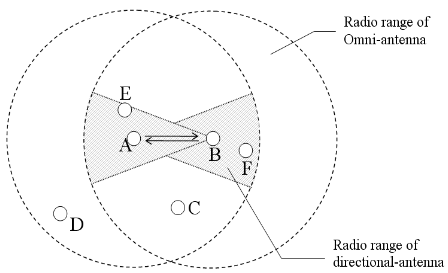

Fig. 7. Antenna beamforming for an ongoing transmission (shadowed part is the radio range of the directional antenna).

III. Direction-of-Arrival Estimation Using ESPRIT

The goal of DOA estimation is to use the data received at the antenna array to estimate the signal direction of arrival. The results of DOA estimation are then used by the array to design the adaptive beamformer which is used to maximize the power radiated towards the intended receiver, and to introduce nulls to combat interference as was explained in the previous section.

Various techniques of DOA estimation have been developed in the literature [16],[17]. Examples of these techniques include the MUltiple SIgnal Classification (MUSIC), Root-MUSIC, Unitary Spectral MUSIC, Unitary Root-MUSIC, Estimation of Signal Parameter via Rotational Invariance Technique (ESPRIT), TLS ESPRIT and Unitary ESPRIT. Among the above algorithms, the ESPRIT technique is one of the most widely used algorithms for DOA estimation. This is due to the many advantages it offers, few to mention are, (i) ESPRIT is more effective from computational point of view, (ii) Unlike different MUSIC algorithms, ESPRIT does not suffer from the false peaks in the spatial spectrum [17]. In our work, we use a uniform linear array (ULA) consists of M equally spaced elements that receive signals transmitted from $K < M$ narrowband sources which are in the far-field of the array. These received signals are assumed to be impinging on the array from directions $\theta_1, \cdots, \theta_K$. The idea behind ESPRIT is to divide the antenna array into two equivalent sub-arrays separated by a known displacement. It uses two identical arrays in the sense that array elements need to form matched pairs with an identical displacement vector. That is, the second element of each pair ought to be displaced by the same distance and in the same direction relative to the first element. Although ESPRIT needs two equivalent sub-arrays, this does not mean that one has to have two separate arrays. The array geometry should be such that the elements could be selected to have this property [17]. For example, if the antenna array above has five identical elements with an inter-element spacing, it may be thought of as two arrays of four matched pairs, one with the [1 2 3 4] elements and one with the [2 3 4 5] elements. The two arrays are displaced by the distance d. The way that ESPRIT exploits this sub-array structure for DOA estimation is now briefly described [17]: (I) Make measurements from two identical sub-arrays which are displaced by d/λ. (II) Estimate the two array correlation matrices from the measurements and find their eigenvalues and eigenvectors. (III) Find the number of directional sources K. (IV) Form the two matrices with their columns being eigenvectors associated with the largest eigenvalues of each correlation matrix. Let these be denoted by Γ_x and Γ_y. For a ULA, this could be done by first forming an $(M-1) \times K$ matrix by Γ selecting its columns as the K eigenvectors associated with the largest eigenvalues of the estimated array correlation. (V) Compute the eigen-decomposition of the matrix $\begin{bmatrix} \Gamma_x^H \\ \Gamma_y^H \end{bmatrix} [\Gamma_x \ \Gamma_y] = V \Lambda V^H$, where H denotes the Hermitian conjugate of the matrix, then find its eigenvectors. Let these eigenvectors be the columns of a matrix V. (VI) Partition V into $K \times K$ sub-matrices as $\begin{bmatrix} V_{11} & V_{12} \\ V_{21} & V_{22} \end{bmatrix}$. (VII) Calculate the eigenvalues ϕ_k of the matrix, ϕ_k=$-V_{11} \ V_{22}^{-1}$, $k = 1, 2.., K$. (VIII) Estimate the direction of arrival, $\theta_k = \cos^{-1}\left(\frac{\arg(\phi_k)}{2\pi d/\lambda}\right)$, $k = 1, 2, .., K$.

In what follows, we use the above technique for estimating the DOA of the incoming signals at each mobile node. This DOA is then used for antenna beamforming towards the intended user.

IV. Simulation Results

We consider a scenario which consists of 10 nodes randomly scattered in a 200 meters $\times$ 200 meters area and calculate the average system throughput for 30 randomly generated topologies. We also assume that half of the nodes act as transmitters and the other half as receivers. The transmission range of the antennas in both modes (i.e., omni and directional modes) is fixed to 100 meters. The total throughput is the average throughput from all node. That is the total throughput = frame length $\times$ number of frames transmitted successfully per second. The control frames, such as RTS/CTS/ACK, are not included in the throughput calculation. All simulations are performed for both AWGN and Ricean fading channels. The bit-error-rate (BER) threshold is set to 10^{-5} which is used as a criteria to determine whether the received data frame is acceptable or not. If the BER of a given packet is larger than this threshold, we consider it as a failed packet and do not count it into the total throughput. For the antenna array, we employ a uniform-linear array (ULA) with antenna spacing $d = \lambda/2$, where λ is the wavelength of the transmitted signal.

A. Accuracy of DOA Estimation using ESPRIT

First, we investigate the accuracy of the ESPRIT algorithm [14] as a function of the system parameters, which include the number of array elements, the number of mobile users, angle of arrival, and SNR. Our simulation results will show that the ESPRIT DOA estimation algorithm can provide enough accuracy for DMAC protocols.

Fig. 8 shows the estimated mean DOA error, i.e., $E(|\theta_{estimated} - \theta_{actual}|)$, generated with 3, 5 and 7 array elements. Furthermore, the signal of intention (SOI) is set to 30 degrees, and the number of samples (NOS) is set to 100 [14]. It is evident that using more elements improves the accuracy of the ESPRIT algorithm. This is achieved, however, at the expense of increased computational complexity and added hardware. The simulation range for the number of interfering users and the number of antenna elements is justified by noting that the number of simultaneous signals that the antenna array can estimate must be less than number of elements in the antenna array.

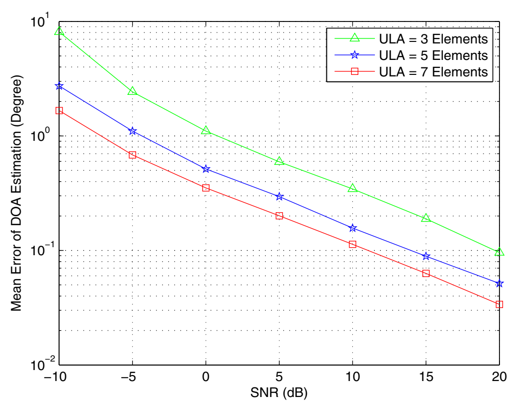

Fig. 8. The effect of SNR on the estimated mean error, SOI=30 degree, and NOS=100.

When we change the number of active users, the number of signals received at the antenna array also changes. Throughout our simulations, we assume that all active users use the channel simultaneously.

B. Throughput Performance

Having examined the accuracy of the DOA estimation using the ESPRIT algorithm, now we assess the throughput performance of our proposed directional MAC protocol under different system parameters.

Fig. 9 shows the average throughput as the load varies from 0.1 Mbps to 1 Mbps. When the load per node is equal to 1 Mbps, the average throughput of our protocol is about 2.3 Mbps which is more than the average throughput achieved by the IEEE 802.11 (1 Mbps). The reason for this improvement can be explained by noting that, in our protocol, several simultaneous transmissions can be allowed compared to IEEE 802.11 protocol, especially at high load situations. On the other hand, the average throughput of both protocols are almost the same when the assigned load-per-node is light. The reason is that some nodes can finish their data transmission process when the simulation time is not over. That is to say, these nodes can leave the channel free to other waiting nodes for their data transmission or act as routers for other nodes which may be out of range of each other. As a result, irrespective of the MAC protocol they employ, all buffered data will be finished in time. On the other hand, when the load becomes heavy, those waiting nodes will not have enough time to finish their transmission. It should be noted that the bandwidth of the control channel of our protocol is expected to be much smaller than the data channel bandwidth. Hence, the IEEE 802.11, while it uses only one data channel, still provides a relatively fair baseline for comparison.

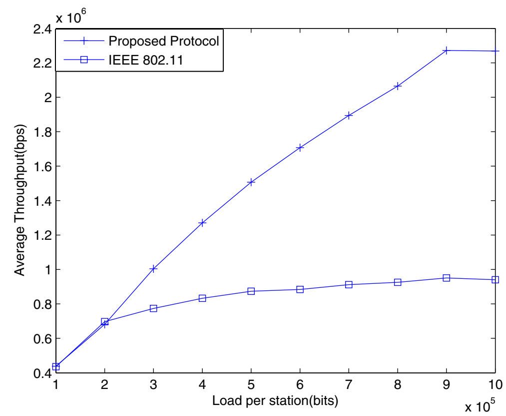

Fig. 9. Average throughput in AWGN channel, 10 mobile nodes, 30 random topologies, SNR = 20dB, and NOE= 6 (not applied to IEEE 802.11).

Fig. 10 shows how the SNR affects the performance of our protocol. When the SNR is lower than 5dB, both the IEEE 802.11 and our protocol cannot transmit any data because even short packets, such as RTS/CTS, fail to be transmitted. Therefore, the transmitter must ensure that the system SNR is kept over 5 dB. One should also remember that the SNR affects the accuracy of our DOA estimation algorithm which consequently affects the system throughput. From Fig. 11, it is clear that the SNR requirement of our DOA estimation algorithm is not so restrictive. Compared to the IEEE 802.11, it is clear that as SNR increases, our protocol offers a substantial throughput improvement. As shown in Fig. 11, the IEEE 802.11 throughput is almost zero at SNR=10 dB. On the other hand, the throughput of our protocol reaches over 2 Mbps over AWGN channel at the same SNR.

Fig. 10 also shows the performance of our MAC protocol over Ricean channels. Here, we assume a Ricean channel with K=6, which is a typical value for indoor office buildings [18]. For this channel, and for SNR=20 dB, the average throughput of the IEEE 802.11 is almost zero. On the other hand, our protocol reaches an average throughput of about 1.8 Mbps. The results clearly show how the use of directional antennas can alleviate the multipath fading effect.

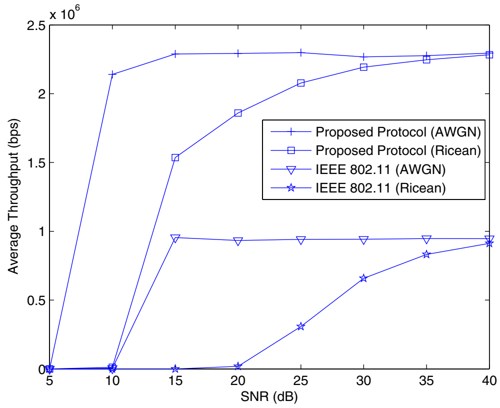

Fig. 10. Average throughput in AWGN and Ricean (K=6) channels, 10 mobile nodes, 30 random topologies, load per station=1 Mbps, and NOE=6 (not applied to IEEE 802.11).

V. CONCLUSIONS

The use of adaptive antennas at mobile ad hoc stations, not only to transmit data frames but also as a tool to estimate the signal DOA, is shown to significantly improve the overall network throughput relative to the case of single omni-directional antenna. This large throughput gain is achieved by allowing more simultaneous transmissions relative to the single-antenna case where interference limits the overall network throughput.

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