2007 IEEE International Symposium
on Signal Processing and Information Technology

A Directional Routing Protocol for Ad Hoc Networks with Angle-of-Arrival Estimation

Kun Liu[1], Amr Youssef[2], and Walaa Hamouda[1]
[1]Department of Electrical and Computer Engineering
[2]Concordia Institute for Information Systems Engineering
Concordia University
Montreal, Quebec, H3G 1M8, Canada
e-mail: {ku_liu,youssef,hamouda}@ece.concordia.ca

Abstract— **Using adaptive antennas, both the transmission range and spatial reuse of wireless systems can be enhanced. In this paper, we propose a reactive source routing protocol for ad hoc networks using directional antennas. Signal parameter estimation via the rotational invariance technique (ESPRIT) is used for direction-of-arrival (DOA) estimation and hence, alleviating the need for global positioning system (GPS). This also makes our protocol suitable for both outdoor and indoor applications. By maintaining the status of the topology and ongoing neighborhood communications, the routing path is chosen to minimize the interference with any on going transmission. Simulation results demonstrate a clear performance improvement relative to IEEE 802.11.**

Index terms— Mobile ad-hoc networks, adaptive antennas, ESPRIT, 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. The quick deployment capability, and robustness against topological changes make ad hoc networks attractive for a large number of applications. For such networks, the network control is distributed among the mobile nodes. Thus an ad hoc network can be described as a self-organizing and self-configuring multihop wireless network where 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.

The routing protocols in ad hoc networks [1] can be generally classified into two categories: reactive (source-initiated on demand) and proactive (table-driven) protocols. Unlike proactive protocols (e.g., [2]) where each node maintains a route to all possible destinations, reactive protocols (e.g., [3], [4]) perform route discovery only when there are packets that need to be sent and no route is available to the destination. Reactive protocols achieve low routing overhead at the cost of extra route discovery delay.

The use of directional antennas in mobile ad hoc networks has shown to offer large potential gains relative to omni-directional antennas. Recently, several researchers have focused on the potential throughput gains achieved using directional antennas in ad hoc networks. When compared to omnidirectional antennas, directional antennas are more attractive option in terms of power and bandwidth efficiency. On the other hand, when used in ad hoc networks, directional MAC (DMAC) protocols usually require all nodes, or part of the nodes, to be aware of their exact locations. This location information is typically provided to the DMAC protocol from upper network layers, for example, by using a Global Positioning System (GPS). Other problems that face these DMAC protocols are the deafness problem and the hidden terminal problem. Solving these problems is at the core of designing any DMAC protocol. At the same time, DMC protocols should not sacrifice channel bandwidth to deal with theses problems.

The rest of the paper is organized as follows. In the next section, we briefly review the directional MAC protocol which was previously proposed by the authors in [9]. Section III outline the proposed routing protocol. The simulation results and analysis are presented in Section IV.

II. THE DIRECTIONAL MAC PROTOCOL

The underlying directional MAC protocol [9] employs two frequency division multiplexed channels. 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. There are two different values for 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 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. The detailed process of this DMAC protocol can be divided into four steps:

(i) RTS transmission: If channel one is sensed idle, the source node sends an RTS frame to the destination node in the omni mode using channel one. All mobile nodes remain in the omni mode when they are idle, listening to channel one.

(ii) RTS reception and CTS transmission: in this step, all the mobile nodes determine the DOA of the incoming signal using certain directional-of-arrival (DOA) estimation algorithm. Having received the RTS from the source node, the destination node can determine the direction to send its CTS response. This CTS frame is transmitted using omni mode (OCTS) in channel one. At the same time of the OCTS transmission, the destination node sends another CTS using the directional mode (DCTS) in channel two. Accordingly, all other nodes, except the source node, update their DNAV table.

(iii) CTS reception and DATA transmission: when the source node 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. Since the transceiver has known the direction of each other, the DATA transmission over channel two can use the directional mode.

(iv) DATA reception and ACK transmission: upon successfully receiving the DATA, the destination node sends an ACK using the directional mode over channel two. Due to the use of directional antennas, new transmissions can be set up in the vicinity of ongoing transmission if it is not covered by the range of the directional antenna. In summary, the transmission process will occupy channel one in the stage of RTS+OCTS, and channel two in the DCTS+DATA+ACK stage.

A. DOA Estimation Using ESPRIT

Estimation of Signal Parameter via 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 also suitable the indoor environment.

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 ([12]-[16]). Examples of these techniques include the MUltiple SIgnal Classification (MUSIC) [16], Root-MUSIC [13], Unitary Spectral MUSIC, Unitary Root-MUSIC, Estimation of Signal Parameter via Rotational Invariance Technique (ESPRIT) [10], TLS ESPRIT [14] and Unitary ESPRIT [15]. Among the above algorithms, ESPRIT is one of 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 [14].

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 imply that one has to have two separate arrays. The array geometry should be such that the elements could be selected to have this property [14]. For example, if the antenna array above has five identical elements with an inter-element spacing, it may be thought 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 [14]:

1) Take measurements from two identical sub-arrays, which are displaced by d/λ.
2) From the measurements, estimate the correlation matrices between the two sub-arrays and find their eigenvalues and eigenvectors.
3) Find the number of directional sources K.
4) Form the two matrices with their columns being eigenvectors associated with the largest eigenvalues of each correlation matrix. Let these be de-

noted by Γ_x and Γ_y. For a uniform linear array with M array elements, this can be done by first forming an $(M-1)\times K$ matrix Γ by selecting its columns as the K eigenvectors associated with the largest eigenvalues of the estimated array correlation.

5) Compute the eigen-decomposition of the $2K\times 2K$ matrix
$$\begin{bmatrix} \Gamma_x^H \\ \Gamma_y^H \end{bmatrix} [\Gamma_x \; \Gamma_y] = V\Lambda V^H$$
(H denotes complex transpose), then find its eigenvectors. Let these eigenvectors be the columns of a matrix V.

6) Partition V into $K\times K$ sub-matrices as
$$\begin{bmatrix} V_{11} & V_{12} \\ V_{21} & V_{22} \end{bmatrix}$$

7) Calculate the eigenvalues ϕ_k of the matrix,
$$\phi_k = -V_{11}\;V_{22}^{-1}, k = 1, 2.., K.$$

8) Estimate the direction of arrival,
$$\theta_k = \cos^{-1}\left(\frac{\arg(\phi_k)}{2\pi d/\lambda}\right), k = 1, 2, .., K.$$

In our simulations, 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.

III. Proposed Directional Routing Protocol

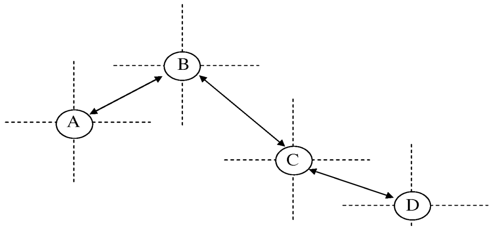
A. Route discovery

Similar to many other reactive routing protocols (e.g., [4],[7]), the route discovery mechanism employs route request (RREQ) and route reply (RREP) packets for path creation. Every node maintains a directional routing table (DRT). Using the information provided by the underlying ESPRIT-based DMAC and the RREQ/RREP packet, each node can determine the direction of every neighbor and store in its DRT.

Suppose node A (see Fig. 1) needs to send packets to the receiver node D, which is not in its DRT. Node A broadcasts a RREQ packet to all its neighbors. When node B receive this request, B checks its DRT and if D does not exist in this table, B will forward this RREQ to its neighbor. By relaying the RREQ packet, D will receive this RREQ that followed the path {A, B, C, D} and sends back a RREP.

When C relays this RREP to B, C attaches the path cost from C to D in its RREP. The method of how the path cost is evaluated will be outlined in the next section. The same process will be followed by B. Once A receives this RREP, the route cost value of A's DRT will be updated.

Since it is possible to have more than one routing path from the source node to the destination node, the successful routing path, which is selected according to the cost of every reachable route, is used for data transmission. The routing path which has the lowest value of path cost will be used for the data transmission.



DRT in node A

Destination	Route	Cost
B	{A(30), B status flag}	1
C	{A(30), B}	2
D	{A(30), B, C}	3

DRT in node B

Destination	Route	Cost
A	{B(210), A status flag}	1
C	{B(315), C status flag}	1
D	{B(315), C}	2

DRT in node C

Destination	Route	Cost
A	{C(135), B}	2
B	{C(135), B status flag}	1
D	{C(330), D status flag}	1

Fig. 1. An example for the DRT

B. The optimum route

Besides the above typical function of RREQ/RREP packets, our protocol also requires each node to attach its current working status, i.e., active or idle in these packets.

The cost of each hop is determined based on the number of the potential interfering nodes, i.e., the nodes that are covered by the radio range of the transmitter's directional antenna. Only the active potential interfering nodes are counted. In other words, if the interfering node was originally idle, it is not counted. The total cost of a reachable route is the sum of its associated interfering nodes. If there is more than one reachable path with the same path cost, the path with the lower hop count is selected as the routing path from source to destination.

From Figure 2-a, the cost associated with the path from node A to B is set to 1. On the other hand, in

Figure 2-b, this cost is set to 2 if node C was in the active state, i.e., Node C was already processing data at the time of the routing path finding stage, otherwise, the cost is set to 1 if node C is idle.

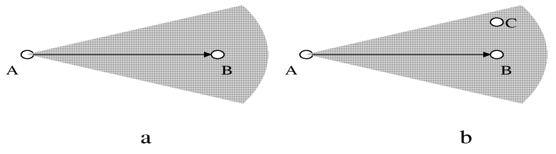


Fig. 2. An example for counting the number of interfering nodes

In order to determine whether a node is covered by the radio range of a given transmitter, the transmitter needs to determine the beamwidth of the main lobe of its directional antenna. This beamwidth is a measurement of the antenna's radiation pattern, and it is defined as the angle between the half-power (3dB) points of the main lobe. In order to simplify our analysis, we do not take the side lobe of directional antenna into consideration, i.e., we only consider the null-to-null beamwidth of the main lobe calculation which is given by

$$\theta_{BW} = 2sin^{-1}(\frac{\lambda}{Nd})$$

where λ is the wavelength of the radio wave, N is the element number of antennas and d is the distance between the antenna elements.

IV. PERFORMANCE ANALYSIS

Throughout the first set of experiments, we consider a scenario which consists of 30 nodes randomly scattered in a 1 Km × 1 Km area and calculate the average system throughput for 20 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 250 meters. The total throughput is the average throughput from all node. That is the total throughput = frame length × number of frames transmitted successfully per second. The control frames, such as RTS/CTS/ACK, are not included in the throughput calculation. Simulations are performed for additive white Gaussian noise (AWGN) 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, i.e., if the BER 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 3-elements uniform-linear array with antenna spacing $d = \lambda/2$, where λ is the wavelength of the transmitted signal. The simulation time is set to 1 second, and the channel rate is set to 1 Mbps with data frame length = 4,000 bits. We also assume that all data that need to be transmitted have already been available in the buffer of the nodes before the simulation begins.

For the purpose of comparison, we also present the corresponding simulation results for both IEEE802.11 and the single hop case, i.e., the case where the DMAC protocol is used but a node is declared unreachable if it is not within one hop reach of the source.

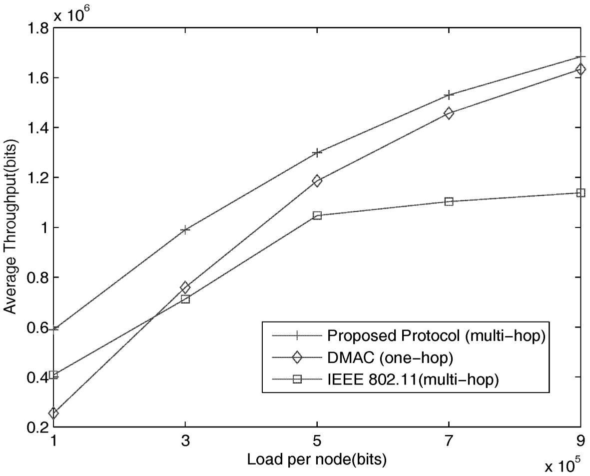


Fig. 3. Performance comparison for different loads per node. Number of antenna=3, SNR=20dB

Figure 3 shows how the system throughput varies as the load per node increases from 0.1 Mbps to 0.9 Mbps. From the figure, it is clear that the performance gap between the single hop case and our proposed protocol decreases as the load per node increases. This can be explained by noting that, for heavy loads, less nodes can act as routers. On the other hand, for light loads, several nodes can finish transmitting their load during the 1 second simulation time and start acting as routers for other nodes and hence provide a larger number of possible routes for data transmission. We also note that, for very light loads, the performance of the IEEE protocol with multi-hop is better than the DMAC protocol with one-hop. The reason is that the number of possible routing paths is more important if all packets have plenty of time to finish their transmission.

Figure 4 shows the system throughput versus the signal-to-noise (SNR). As shown in the figure, when

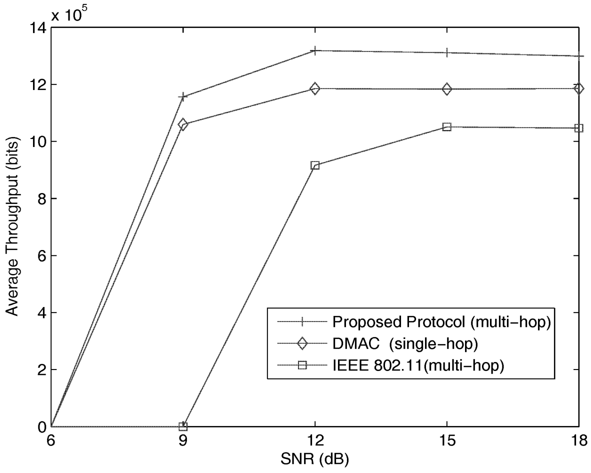


Fig. 4. Average throughput for different SNR. Load/node=0.5 Mbps, Number of antennas=3

the SNR is lower than 6 dB, the three protocols can not transmit any data because even short packets, such as RTS/CTS, fail to be transmitted. When the SNR increases, the DMAC protocol offers a substantial throughput gain compared to the IEEE 802.11 protocol. For example, while the IEEE 802.11 throughput is almost zero at SNR=9dB, the proposed protocol achieves a throughput of over 1 Mbps under the same SNR condition.

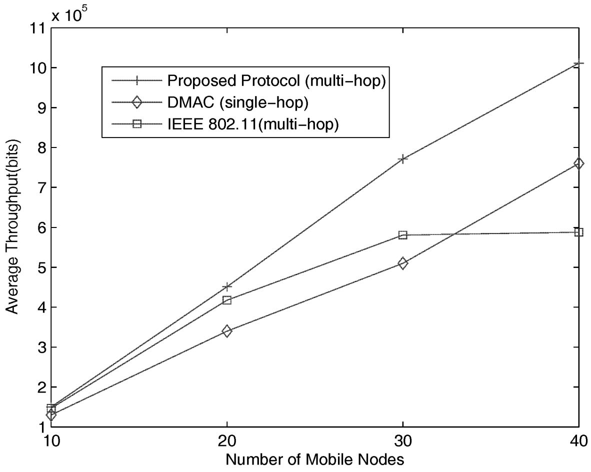


Fig. 5. Average throughput at different number of nodes. Load/node=200 kbps, SNR=20dB

Figure 5 shows how the throughput varies with the number of nodes. In this case, we set the load of every transmitter to 0.2 Mbps. As shown in the figure, when the number of nodes is equal to 10, all the three protocols have very low throughput since the probability of establishing a routing path is low, i.e., many nodes will be out of range. As the number of nodes increases, more possible routing paths can be formed. As a result, the performance gap between multi-hop and one-hop of DMAC protocol becomes wider. It should be noted that for the IEEE protocol, at first, the throughput will increase as the number of nodes increases. However, the throughput saturates when the number of nodes reaches 30. This can be explained by noting that the channel will be occupied most of time and large number of nodes only means more nodes have to wait until the channel is free in order to initiate their transmission.

For the other set of experiments, we enlarge the simulation map to 2 km × 2km and increase the number of mobile nodes to 100. We also assume that 20 of the nodes act as transmitters, 20 act as receivers and the other 60 nodes are idle. The rest of the simulation parameters are unchanged.

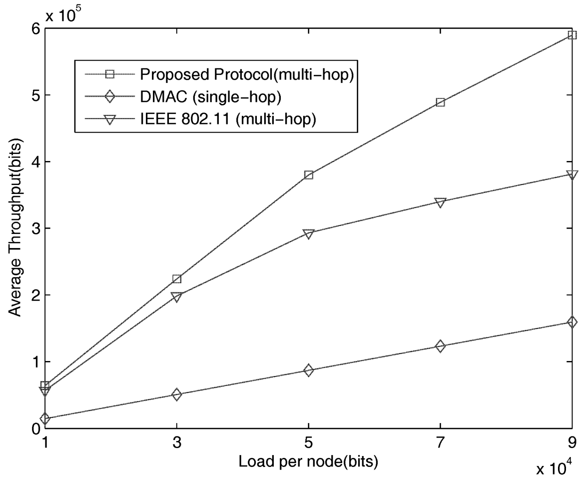


Fig. 6. Performance comparison at different load per node. Number of antennas=3, SNR=20dB, Number of idle nodes=60.

Figure 6 shows how the average throughput varies with the load per node. Unlike the results presented in Figure 3 where we varied the load per node from 100 kbps to 900 kbps, in this case we vary the load per node from 10 kbps to 90 kbps. Employing lower loads ensure that the transmission of packets with large number of hops can be finished during the 1 second simulation time. This is due to the fact that light load means more nodes can act as router during their idle period. Compared with the results in Figure 3, the performance of the one-hop protocol is always lower than the other two protocols. This can be explained by noting that when the nodes are scattered in a large area (i.e, sparse), the existence of reachable path is the dominant factor in determining the throughput.

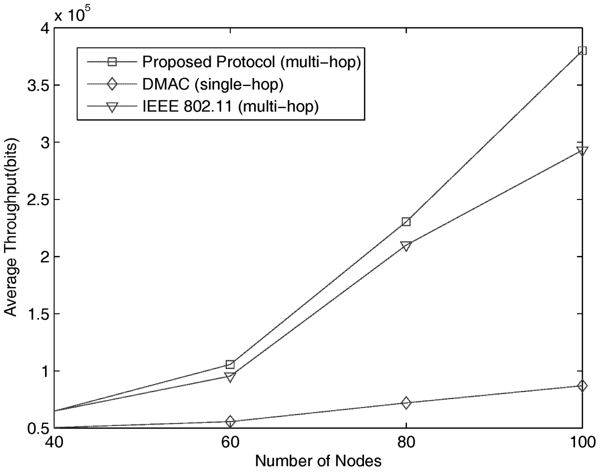


Fig. 7. Average throughput for different number of nodes. Load/node= 50 kbps, SNR=20dB, Number of idle nodes=number of nodes-40

Similar to Figure 5, Figure 7 depicts the system throughout versus the number of active nodes. However, in this case, we assume that 20 of the nodes act as transmitters, 20 act as receivers and the rest of the nodes are idle and hence they can act as routers. In other words, the number of idle nodes varies from 0 to 60 as the total number of nodes varies from 40 to 100. As shown, the system performances of both directional protocols are almost the same when the number of nodes is low. This can be explained by noting that, when the nodes are sparse, the existence probability of reachable routing path is very low and hence the system throughput is also low regardless of the directional protocol used. Also, as the number of nodes increases, the multi-hop protocol outperforms the other two protocols.

V. CONCLUSIONS

We introduced a new on-demand routing protocol for ad hoc networks with directional antennas. The underlying directional MAC protocol utilizes the ESPRIT algorithm for the DOA estimation. The routing path is determined in such a way to minimize the interference with ongoing transmission. Simulation results confirmed the performance improvement achieved with this protocol.

REFERENCES

[1] E.M. Royer, *A Review of Current Routing Protocols for Ad Hoc Mobile Wireless Networks,* IEEE Personal Communications, Apr. 1999.

[2] T. Clausen, P. Jacquet, A. Laouiti, P. Muhlethaler, and A. Qayyum et L. Viennot, *Optimized Link State Routing Protocol,* IEEE INMIC, pp. 62-68, Dec. 2001

[3] C. E. Perkins, *Ad Hoc On Demond Distance Vector (AODV) Routing,* Internet-Draft, IETF MANET Working Group, Nov. 1997

[4] D. B. Johnson, D. A. Maltz, *Dynamic Source Routing in Ad Hoc Wireless Networks,* Mobile Computing, Vol. 353, pp153-185, 1996

[5] A. Nasipuri, J. Mandava, H. Manchala, and R. E. Hiromoto, *On-Demand Routing Using Directional Antennas in Mobile Ad Hoc Networks,* IEEE International Conference on Computer Communication and Networks, (ICCCN 2000), Oct. 2000.

[6] A. K. Saha, D. B. Johnson, *Routing improvement using directional antennas in mobile ad hoc networks,* Global Telecommunications Conference, (GLOBECOM 2004), Nov. 2004.

[7] H. Gossain, T. Joshi, C. Cordeiro and D. P. Agrawal, *A cross-layer approach for designing directional routing protocol in MANETs,* Wireless communications and Networking Conference, IEEE, Mar. 2005

[8] A. Spyropoulos and C. S. Raghavendra, *Energy efficient communications in ad hoc networks using directional antennas,* IEEE INFOCOM 2002, Jun. 2002.

[9] Kun Liu, Walaa Hamouda, and Amr Youssef, emphPerformance of a MANET Directional MAC Protocol with Angle-of-Arrival Estimation,, to appear in the Journal of Wireless Communications and Mobile Computing.

[10] A. Paulraj, R. Roy, and T. Kailath, *A Subspace Rotation Approach to Signal Parameter Estimation,* Proceedings of the IEEE, vol. 74, no.7, pp. 1044-1045, July 1986.

[11] K. Nagashima, M. Takata and T. Watanabe, *Evaluations of A Directional MAC Protocol for Ad Hoc Networks,* Distributed Computing Systems Workshops, 24th International Conference, 23-24 Mar. 2004.

[12] R. Schmidt, *Multiple Emitter Location and Signal Parameter Estimation,* IEEE Transactions on Antennas and Propagation, vol. AP-34, no. 3, pp. 276-280, 1986.

[13] B. D. Rao, K. Hari, *Performance Analysis of Root-Music,* IEEE Trans. Signal Processing 28, pp. 25-42, 1999.

[14] R. Roy and T. Kailath, *ESPRIT-Estimation of Signal Parameters Via Rotational Invariance Techniques,* IEEE Transactions on Acoustics. Speech, and Signal Processing, vol. ASSP-37, no. 7, pp. 984-995, 1989.

[15] M. Haardt and J. Nossek, *Unitary ESPRIT: How to obtain increase spatial smoothing technique for bearing estimation in a multipath environment,* IEEE Trans. ASSP, vol. 43, pp. 1232-1242, May. 1995.

[16] S. Haykin, Adaptive Filter Theory, 4th edition, Prentice Hall, 1991.