# A Power-Efficient MAC Protocol with Two-Level Transmit Power Control in Ad Hoc Network Using Directional Antenna


Dola Saha[1], Siuli Roy[1], Somprakash Bandyopadhyay[1],
Tetsuro Ueda[2], Shinsuke Tanaka[2]

[1] Indian Institute of Management Calcutta
Diamond Harbour Road, Joka Calcutta 700104, India
{dola, siuli, somprakash}@iimcal.ac.in
[2] ATR Adaptive Communications Research Laboratories
2-2-2 Hikaridai, Keihanna Science City, Kyoto 619-0288, Japan
{teueda, shinsuke}@atr.co.jp



**Abstract.** The use of directional antenna in wireless ad hoc networks largely reduces radio interference, thereby improving the utilization of wireless medium and consequently the network throughput, as compared to omni-directional antenna, where nodes in the vicinity of communication are kept silent. In this context, researchers usually assume that the gain of directional antennas is equal to the gain of corresponding omni-directional antenna. However, for a given amount of input power, the range R with directional antenna will be much larger than that using omni-directional antenna. In this paper, we propose a two-level transmit power control mechanism in order to approximately equalize the transmission range R of an antenna operating at omni-directional and directional mode. This will not only improve medium utilization but also help to conserve the power of the transmitting node during directional transmission. The performance evaluation on QualNet network simulator clearly indicates the efficiency of our protocol.


## 1 Introduction

Usually, in ad hoc networks, all nodes are equipped with omni-directional antenna. However, ad hoc networks with omni-directional antenna uses RTS/CTS based floor reservation scheme that wastes a large portion of the network capacity by reserving the wireless media over a large area. Consequently, lot of nodes in the neighborhood of transmitter and receiver has to sit idle, waiting for the data communication between transmitter and receiver to finish. To alleviate this problem, researchers have proposed to use directional (fixed or adaptive) antennas that direct the transmitting and receiving beams toward the receiver and transmitter node only. This would largely reduce radio interference, thereby improving the utilization of wireless medium and consequently the network throughput [1-6]. As shown in Fig. 1, while node n is communicating with node m using omni-directional antenna, node p and r have to sit idle. However, with directional beam forming, while node n is communicating with node m, both node p and r can communicate with node q and s respectively, improving the medium utilization or the SDMA (space division multiple access) efficiency. We can even improve this SDMA efficiency by controlling power of directional transmission to make the directional transmission range almost equal to omni-directional transmission range. Due to the high gain of the main lobe of directional antenna, the directional transmission range is much larger than that of omni-directional transmission range. So, directional transmission creates unnecessary interference in the area beyond the omni-directional transmission range and SDMA suffers. By almost equalizing the omni- and directional transmission range, drastic improvement in medium utilization and SDMA efficiency can be achieved resulting in improved average throughput. In Fig. 1, the power controlled directional transmission range is shown in dotted lines. With power controlled directional transmission of node n, nodes x, y or z can start communication improving SDMA efficiency, which was not possible with full power directional transmission of node n.

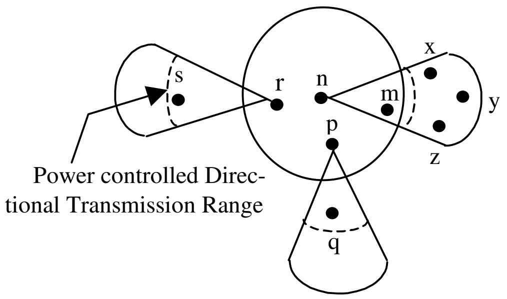


**Fig. 1.** Improving SDMA efficiency with Directional Antenna and power-controlled Directional Transmission

## 2 Related Work

In spite of the advantages of directional antennas, work on developing efficient MAC protocol using directional antennas in the context of ad hoc networks is limited because of the inherent difficulty to cope up with mobility and de-centralized control in ad hoc networks. Some researchers have tried to address this challenge in several ways. In recent years, several MAC protocols that rely on RTS-CTS type handshaking as in IEEE 802.11 have been suggested with directional antennas.

In [1], a directional MAC scheme has been proposed where directional or omni-directional RTS is sent depending on the on-going communication in the vicinity. In [2], a MAC protocol to achieve multihop efficiency has been proposed with multi-hop-RTS-singlehop-CTS using directional antenna. In this mechanism, using larger range of directional beam, a destination is reachable in less number of hops as compared to that using omni directional antenna. In both the schemes [1-2], the mobile nodes are assumed to know the physical locations of themselves and their neighbors using GPS. With the use of directional RTS and directional CTS, several issues like a *new hidden terminal problem* due to asymmetry in gain & due to unheard RTS/CTS, *deafness* and *higher directional interference,* as depicted in [2], remains unsolved. In [3], the proposed MAC protocol need not know the location information; the source and destination nodes identify each other's direction during omni-directional RTS-CTS exchange in an on-demand basis. It is assumed that all the neighbors of s and d, who hear this RTS-CTS dialog, will use this information to prevent interfering with the ongoing data transmission. However, because of omnidirectional transmission of RTS and CTS packets, this protocol provides no benefits in the spatial reuse of the wireless channel. However, it still improves the throughput over a MAC using omni-directional antennas due to the reduced amount of interference caused by the directional data transmission. In our earlier work, we have developed a MAC protocol [4], where each node keeps certain neighborhood information dynamically through the maintenance of an Angle-SINR Table. In this method, in order to form AST, each node periodically sends a directional beacon in the form of a directional broadcast, sequentially in all direction at 30 degree interval, covering the entire 360 degree space. The nodes, which receive these signals at different angles, determine the best received signal strength and transmit the information back to the source node as data packet with RTS/CTS handshake. However, the overhead due to control packets is very high in this method [4].

In this paper, we will illustrate a receiver-oriented location tracking mechanism to reduce the control overhead and a simple MAC protocol for efficient medium utilization. On this directional MAC, we will show that power controlled directional transmission is a necessity and it improves network throughput by conserving power. We have done extensive performance evaluation using QualNet to demonstrate its effectiveness.

## 3 System Description

### 3.1 Antenna Model

There are basically two types of smart antennas used in the context of wireless networks: switched-beam or fixed beam antennas and steerable adaptive array antennas. A switched-beam antenna generates multiple pre-defined fixed directional beam-patterns and applies one at a time when receiving a signal. In a steerable adaptive array antenna which is more advanced than a switched beam antenna, the beam structure adapts to Radio Frequency (RF) signal environment and directs beams towards the signal of interest to maximize the antenna gain, simultaneously depressing the antenna pattern (by setting nulls) in the direction of the interferers.

We have developed a wireless ad hoc network testbed using smart antenna [5] where each user terminal uses a small, low-cost smart antenna, known as ESPAR (Electronically Steerable Passive Array Radiator) antenna. The ESPAR antenna consists of one center element connected to the source (the main radiator) and several surrounded parasitic elements (typically four to six passive radiators) in a circle (Fig. 2).

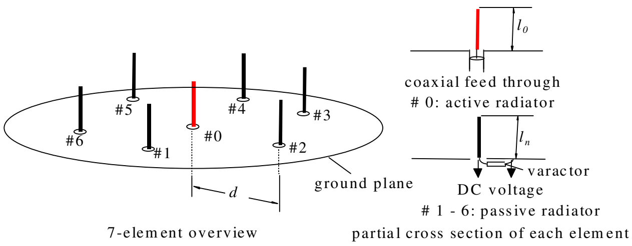


**Fig. 2.** Configuration of ESPAR antenna

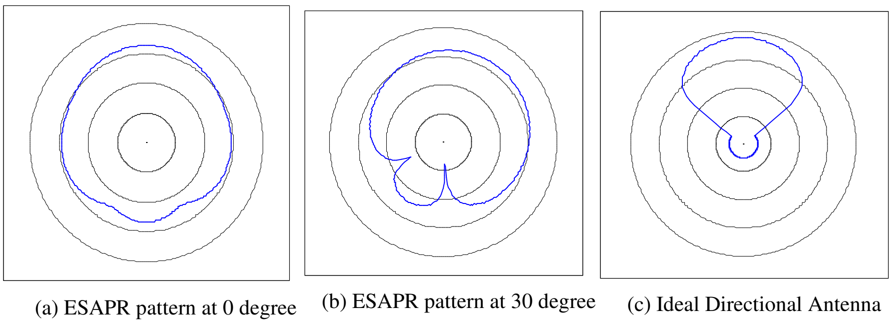


**Fig. 3.** Different Directional Antenna Pattern Used in our Simulation

Developing suitable MAC protocols with adaptive antenna in ad hoc networks is a challenging task. That is why, most of the works in the context of ad hoc networks assume to use simpler switched beam antenna. In this work also, we are using smart ESPAR antenna as a switched beam antenna. ESPAR antenna can also be used as a generalized switched beam antenna or quasi-switched beam antenna [5], by selecting the value of reactance for one specific directional beam among multiple directional beam patterns, without using multiple receiver chains (frequency converters and analog-digital converters). Since ESPAR antenna would be a low-cost, low-power, small-sized antenna, it would help to reduce the power consumption of the user terminals in WACNet and would be able to deliver all the advantages of switched beam antenna.

The antenna pattern of ESPAR antenna with 60 degree beam width is shown in Fig. 3(a) and 3(b). Fig. 3(a) shows pattern at 0 degree: a beam pattern formed at each antenna element at an interval 0 to 60 degree, 60 to 120 degree and so on, thus forming 6 beams. Fig. 3(b) shows pattern at 30 degree: a beam pattern formed at each in-between antenna elements at an interval 30 degree to 90 degree, 90 degree to 150 degree and so on, thus forming 6 more pattern. Together they constitute 12 overlapping pattern at 30 degree intervals. Fig. 3(c) shows an ideal directional antenna with

45 degree beam-width with insignificant side-lobes. As will be demonstrated in performance evaluation, the performance of ideal directional antenna is the best (as expected); at the same time, ESPAR performance is also comparable to that of ideal directional antenna.

### 3.2 A Few Assumptions and the Rationales

- When the antenna of a node operating in omni-directional mode, it is capable of transmitting and receiving signal from all direction with a gain, say, $G^{omni}$. While idle, a node operates in omni-directional receive mode.
- When the antenna of a node operating in directional mode, a node can points its beam (main lobe) towards a specified direction with a beam width *w* and with a gain, say $G^{dir}$ ($G^{dir} >> G^{omni}$ ).
- Consequently, for a given amount of input power, the transmission range $R^{dir}$ with directional antenna will be much larger than that with corresponding omni-directional antenna ($R^{omni}$ ).

## 4 A Directional MAC with Location Tracking Mechanism

In this work, our MAC protocol is basically a *Receiver-oriented, Rotational Sector Based Directional MAC protocol* which also serves as a Location Tracking mechanism. Here, each node waits in omni-directional-sensing-mode while idle. Whenever it senses some signal above a threshold, it enters into *rotational-sector-receive-mode*. In rotational-sector-receive mode, node n rotates its directional antenna sequentially in all direction at 30-degree interval, covering the entire 360-degree space in the form of the sequential directional receiving in each direction and senses the received signal at each direction. After one full rotation, it decides the best possible direction of receiving the signal with maximum received signal strength. Then it sets its beam to that direction and receives the signal.

However, in order to enable the receiver decoding the received signal, each control packet is transmitted with a preceding tone with a duration such that the time to rotate a receiver's rotational receive beam through 360 degree is little less than the duration of the tone (200 microseconds in our case). The purpose of this transmitted tone before any control packet is to enable the receiver to track the best possible direction of receiving the signal. Once it sets its beam to that direction, the purpose of tone signal is over and subsequently the control packet is transmitted.

In this proposed framework, we have used three types of omni-directional control packets: Beacon, RTS (Request to send) and CTS (clear to send) for medium access control. Another control packet ACK is directional control packet. Data is transmitted directionally after RTS/CTS handshaking is done. Beacon is a periodic signal, transmitted from each node at a pre-defined interval. As indicated earlier, beacon is transmitted with a preceding tone signal that helps the receivers to detect the best possible direction of receiving the signal. Then each receiver sets its beam to that direction and receives and decodes the packet. Since RTS is a broadcast packet and contains source address, nodes can decode that RTS also to form the Angle-Signal Table. So, we have used RTS as beacon. If an RTS is sent, beacon timer is reset. The use of RTS as beacon is advantageous at high traffic where overhead due to beacon is minimized. This is because, the transmitting nodes don' t have to send an additional beacon to inform its neighbors of its presence.

Whenever node n wants to start data communication with, say j, it checks the medium and if it is free, n issues an omni-directional RTS. The target node j on receiving RTS, issues omni-directional CTS. The objective of RTS/CTS here is not to inhibit the neighbors of n and j from transmitting or receiving (as is the case with omni-directional antenna) but to inform the neighbors of j and n that j is receiving data from n. It also specifies the approximate duration of communication. All the neighboring nodes of n and j keep track of the communication between n and j by setting their Directional Network Allocation Vector (DNAV) towards n and j. Thus, nodes in the neighborhood of n and j can initiate communication in other directions *without disturbing the existing communication between n and j.* The source and destination nodes wait for Acknowledgement and Data respectively in directional receive mode.

## 5 Power Controlled Directional MAC Protocol

Most researchers [6-7] used power control schemes, which suitably vary transmit power to reduce energy consumption. But, this scheme has a shortcoming, which increases collisions and degrades network throughput, as pointed out in [7]. So, Jung et. al. [7] proposed to transmit each data packet at maximum power level periodically, for just enough time, so that nodes in carrier sensing zone can sense it. This work has been implemented using omni-directional antenna. But the scenario is completely changed when we use directional antenna to transmit and receive signals. In [6], RTS/CTS handshake at full power is used to decide transmission power for subsequent data and acknowledgement packets. But the marked difference between omni- and directional antenna gains has not been taken into account. So, the concept of controlling power, as suggested in [6] does not work in real scenario, which is illustrated below.

In order to demonstrate the advantage of using directional antenna in gaining SDMA efficiency, researchers usually assume that the gain of directional antennas is equal to the gain of corresponding omni-directional antenna. Under this assumption, it is easy to visualize improvement in SDMA efficiency: the coverage area or the area of the $transmission\_zone_n(\alpha)$ of a node n forming a transmission beam with a beam-angle $\alpha$ ($\alpha << 360°$) and a transmission range R with respect to n is $\alpha R^2/2$ which is much low when $\alpha = 45$ degree(say) compared to that when $\alpha = 360$ degree ( i.e. omni-directional). If the transmission zone of a node is small, it implies that the number of transmission zones that can be formed in a given area by a given number of nodes is high, giving rise to higher SDMA efficiency. However, in real situation, this assumption is invalid. For a given amount of input power, the range R of a user terminal using directional antenna will be much larger than that using omni-directional antenna. This implies that, narrower the beam-width, higher would be the gain of main lobe of the directional antenna and consequently the range would be larger. So, the transmission range R is not same in both the cases and is inversely proportional to $\alpha$. Consequently, SDMA efficiency will not improve as much as it is expected. For example, in Fig. 1, nodes x, y and z are outside the omni-directional transmission range of node n, but in the directional transmission range of node n. So, even if they don' t receive RTS from node n, they are captured by the directional transmission of node n and cannot start a communication in other directions. On the other hand, since node m is within omni-directional transmission range of node n, proper reception of signal at node m does not require higher directional transmission range of node n towards the direction of node m. If we reduce the power to reduce the directional transmission range, as shown in dotted line, nodes x, y and z can start communication in directions other than the direction of node m which is blocked by DNAV. Thus, SDMA efficiency is improved resulting in increased throughput.

In this paper, we study power control for the purpose of improving SDMA efficiency and as a result energy consumption is minimized. We propose a two-level transmit power control mechanism in order to approximately equalize the transmission range R of an antenna operating at omni-directional and directional mode. In other words, if P is the full power used during omni-directional transmission, a reduced power level p will be used during directional transmission so as to equalize the range of transmission approximately in both the cases. This will not only improve the SDMA efficiency but also help to conserve the power of the transmitting node during directional transmission of data. In this scheme, control packets like beacon, RTS and CTS are omni-directional and use full power P for their transmission. On the other hand, directional transmission of ACK (Acknowledgement) packets and data packets are done with reduced power p.

Since directional transmission range depends mainly on antenna pattern and the gain of its main lobe, the reduced power p will be different in different antenna patterns. If a node knows with which antenna it is equipped with, it can control its power accordingly during directional transmission to approximately equalize its directional transmission range with omni-directional transmission range.

## 6 Performance Evaluation

### 6.1 Simulation Environment

The simulations are conducted using QualNet 3.1 [8]. We have simulated ESPAR antenna in the form of a *quasi-switched beam antenna*, which is steered discretely at an angle of 30 degree, covering a span of 360 degree. We have simulated our MAC protocol with (i) Simulated ESPAR Antenna Pattern (ESPAR) and (ii) an Ideal directional antenna pattern without sidelobes (IDEAL) as described in Section 3.1.

We have used simple one-hop randomly chosen communication in order to avoid the effects of routing protocols to clearly illustrate the difference between 802.11 and our proposed MAC. Also, we have used static routes to stop all the packets generated by any routing protocol, whether it is proactive or reactive. In our simulation, we studied the performance of the proposed MAC protocol in comparison with the existing omnidirectional 802.11 MAC protocol by varying the Data Rate and number of simultaneous communications. In studying our MAC protocol, we have used different antenna patterns as described above to ensure the robustness of our proposed MAC protocol. In doing this, we have used ESPAR antenna as one of the antenna patterns, to evaluate the performance of the ESPAR antenna as well.

The set of parameters used are listed in Table I.

**Table 1.** Parameters used in Simulation

| **Parameters** | **Value** |
|---|---|
| Area | 1000 x 1000 m |
| Number of nodes | 40 |
| Transmission Power | 15 dBm |
| Receiving Threshold | -81.0 dBm |
| Sensing Threshold | -91.0 dBm |
| Data Rate | 2Mbps |
| Packet Size | 512 bytes |
| Duration of Preceding Tone | 200 microseconds |
| CBR Packet Injection Interval | 2 ms to 50 ms |
| Number of simultaneous communication | 4 to 12 |
| Simulation Time | 5 minutes |

### 6.2 Results and Discussions

We have used the existing IEEE 802.11 MAC, which we caption as "802.11", as a benchmark to compare and evaluate the performance of our proposed MAC protocol with ESPAR antenna and an ideal antenna, which we caption as "ESPAR" and "IDEAL" respectively. The average Throughput and one-hop average End-to-End Delay is evaluated in random scenarios with increasing data rate (Fig. 4) and with increasing number of simultaneous communications (Fig. 5).

In Fig. 4, it is seen that with increasing data rate, average Throughput of our proposed MAC protocol (E-MAC) with any directional antenna pattern is much better than that of IEEE 802.11. Also, one hop average End-to-End Delay of E-MAC is nearly half of that obtained with IEEE 802.11 protocol. In Fig. 5, it is observed that with increasing number of simultaneous communication, average Throughput decreases in both E-MAC and 802.11, but E-MAC shows significant gain in average Throughput. Also, one hop average End-to-End Delay increases in both IEEE 802.11 and E-MAC, but the increase is much prominent in "802.11" than in E-MAC, irrespective of the directional antenna pattern used. This is because E-MAC does not inhibit neighboring nodes to transmit, but just informs neighbors of the ongoing communication and its direction, so that they can start communication in other directions. Thus, with directional transmission and directional reception, E-MAC performs much better in any random scenario with any directional antenna pattern.

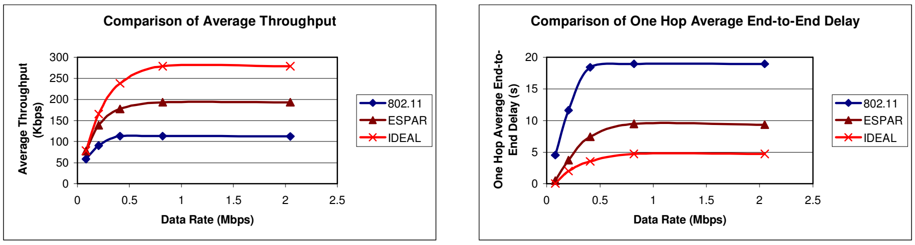


**Fig. 4.** Performance Evaluation of the proposed MAC protocol with directional antenna with increasing data rate

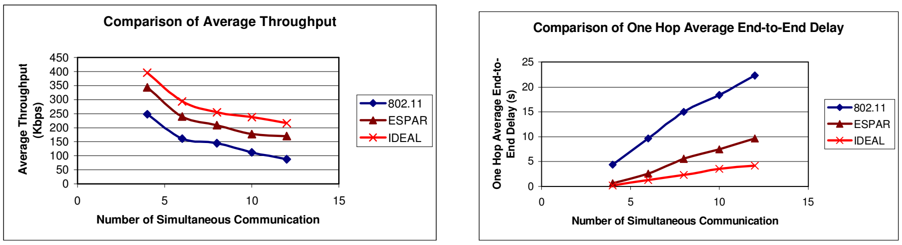


**Fig. 5.** Performance Evaluation of the proposed MAC protocol with directional antenna with increasing number of simultaneous communication

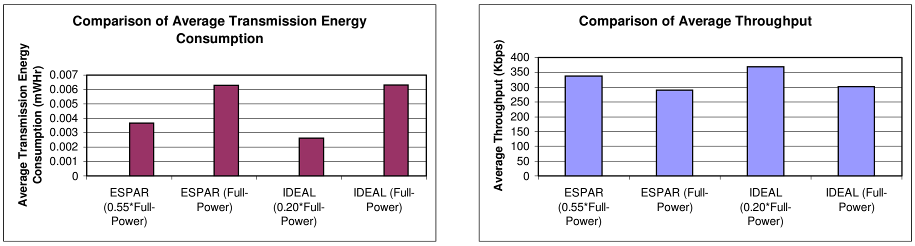


**Fig. 6.** Comparison of Average Transmission Energy Consumption and Average Throughput with and without controlling transmission power

By tuning the directional transmission power, it has been observed that if directional transmission is done with 55% (in case of ESPAR) and 20% (in case of IDEAL) of the full power, the directional transmission range nearly equals to omni-directional transmission range. The results in Fig. 6 show that by controlling power, less transmission energy is consumed than that with full transmission power and corresponding average throughput increases with both ESPAR and IDEAL directional antenna. This is mainly due to SDMA efficiency achieved by reducing the directional transmission power and almost equalizing directional and omni-directional transmission range.

## 7 Conclusion

Use of directional antenna in ad hoc wireless network can drastically improve system performance, if proper MAC protocol can be designed. The success of the MAC protocol highly depends on the directional antenna pattern. Currently, the ESPAR antenna is under development, where we are trying to modify the beam-pattern to get maximum gain from E-MAC. The location tracking mechanism as done in our proposed MAC protocol can be utilized in designing efficient Routing protocol. Presently, we are working on efficient controlling of transmission power dynamically to improve the proposed MAC performance.

## 8 Acknowledgements

This research was supported in part by the Telecommunications Advancement Organization of Japan.

## References

1. Y.B. Ko, V. Shankarkumar and N. H. Vaidya, ``Medium access control protocols using directional antennas in ad hoc networks,' Proc. Of the IEEE INFOCOM 2000, March 2000.
2. Romit Roy Choudhury, Xue Yang, Nitin H. Vaidya, Ram Ramanathan, "Using directional antennas for medium access control in ad hoc networks" Proceedings of the eighth annual international conference on Mobile computing and networking September 2002
3. Nasipuri, S. Ye, J. You and R.E. Hiromoto, "A MAC Protocol for Mobile Ad Hoc Networks Using Directional Antennas", Proc of the IEEE WCNC 2000.
4. S. Bandyopadhyay, K. Hasuike, S. Horisawa, S. Tawara, "An Adaptive MAC Protocol for Wireless Ad Hoc Community Network (WACNet) Using Electronically Steerable Passive Array Radiator Antenna", Proc of the GLOBECOM 2001, November 25-29, 2001, San Antonio, Texas, USA
5. T. Ueda, K. Masayama, S. Horisawa, M. Kosuga, K. Hasuike, "Evaluating the Performance of Wireless Ad Hoc Network Testbed With Smart Antenna", Fourth IEEE Conference on Mobile and Wireless Communication Networks (MWCN2002), September 2002
6. Asis Nasipuri, Kai Li, and Uma Reddy Sappidi, "Power Consumption and throughput in Mobile Ad Hoc Networks using Directional Antennas" in Proceedings of the *IEEE International Conference on Computer Communication and Networks (ICCCN2002),* October 14-16, 2002, Miami, Florida.
7. Eun-Sun Jung and Nitin Vaidya, "A Power Control MAC Protocol for Ad Hoc Networks", ACM International Conference on Mobile Computing and Networking (MobiCom), September 2002.
8. *QualNet Simulator Version 3.1*, Scalable Network Technologies, www.scalable-networks.com