Performance Improvement of Ad Hoc Networks Using Directional Antennas and Power Control

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Abstract

To improve the system performances of wireless ad hoc networks, researchers have proposed many approaches including the use of directional antennas and power control mechanisms. However, most of these works consider only directional transmission, while directional antennas could be used for both transmitting and receiving. Moreover, there is a lack of work that evaluates the impact of power control in heterogeneous ad hoc networks where directional antennas are partially deployed. In this paper, we propose a power controlled directional MAC protocol which enables both directional transmission and reception of all control and data packets. We evaluate our protocol in heterogeneous ad hoc scenario and show how much performance enhancement can be achieved as a result of using both directional antennas and power control.

1. Introduction

The past decade has witnessed a remarkable interest in wireless ad hoc networks that operate without any infrastructure support. The IEEE 802.11 Distributed Coordination Function (DCF) is the dominant MAC protocol in such network. However, the DCF method cannot utilize shared channel efficiently. Therefore, various methods have been developed to improve the utilization of shared channels and increase network throughput, which mainly involve replacing the omni antennas with directional antennas and controlling packet transmission power adequately.

Directional antennas (also called smart antennas) offer many benefits and play a key role in 3G and 4G systems. They have been broadly used in various wireless communication systems. However, to simply use directional antennas with the conventional 802.11 protocol for ad hoc networks does not result in substantial network improvement and sometimes even deteriorates network performance due to several problems, such as the exposed and hidden terminal problems and the deafness problem. Consequently, the design of new MAC protocols that could better exploit the advantages of directional antennas becomes an interesting research issue. The author in [1] proposed two Directional MAC (DMAC) schemes. DMAC simply utilizes GPS as an additional device to get location information. It transmits RTS (request to send), DATA and ACK directionally and alternatively transmits CTS (clear to send) omnidirectionally depending on whether the antenna pattern of the transmitter is blocked. A Multi-hop RTS MAC (MMAC) scheme is introduced in [2] to exploit the higher transmission gain of directional antennas for transmission on multi-hop paths. The MMAC scheme can be considered as an enhancement of the DMAC protocol. A new carrier sensing mechanism called DVCS (Directional Virtual Carrier Sensing) is designed in [3]. DVCS supports both directional transmission and directional reception. Instead of relying on GPS devices to locate each node, DVCS estimates the node location information by running Direction of Arrival (DoA) algorithms.

Integrating transmission power control algorithms into directional MAC protocols is another method to improve the performance of ad hoc networks. In recent years, directional antenna-based power control mechanisms have been proposed in a handful of papers (e.g., [4, 5, 6, 7, 8]). However, most of these proposals are based on directional MAC protocols that consider only directional transmission, while directional antennas could be used for both transmitting and receiving, and in order to demonstrate the improvement in SDMA (space division multiple access) efficiency. In the simulation studies, those research projects usually assume the same communication range for omni and directional antennas. Apparently this assumption is not supported in realistic situations. Besides, heterogeneity is inherent in wireless ad hoc networks. It is common
that not all nodes in the network are equipped with directional antennas [9]. There is a lack of work that studies the impact of power control in the practical scenario with partially-deployed directional antennas.

In this paper, we propose a power controlled directional MAC protocol that enables both directional transmission and reception of both control and data packets (RTS/CTS/DATA/ACK packets). We evaluate by computer simulations the performance of our protocol in both homogeneous (all the users have directional antennas) and heterogeneous (some users have directional antennas) ad hoc scenarios and use different values for the gain of omni and directional antennas so as to recognize that directional antennas have longer communication ranges than omni ones.

The rest of the paper is organized as follows. Section 2 describes the proposed MAC protocol. Simulation results and performance comparisons with other MAC protocols are presented in Section 3. Finally, Section 4 concludes the paper.

2. The Proposed MAC Protocol

We propose a power controlled directional antenna-based MAC protocol by incorporating a power control scheme into DVCS protocol and name our protocol Power Controlled Directional Virtual Carrier Sensing protocol (PCDVCS). We choose DVCS because it provides high performance in heterogeneous ad hoc networks. It allows nodes equipped with directional antennas to be interoperable with nodes running the 802.11 MAC with omni antennas. The power control algorithm to be incorporated is similar to [4, 5]. However, our scheme supports power control for both control packets (CTS and ACK) and data packets.

In order to explain the operation of the PCDVCS protocol clearly, we use a simple scenario with only two nodes in the system as illustrated in Fig. 1.

![Figure 1: Packets transmission using PCDVCS](image)

We assume that node A intends to send data to Node B, and it finds an estimated AOA (angle of arrival) for node B in its cache. The first step is: Node A adjusts its antenna pattern towards the direction of the cached AOA, which may be a little different than the exact direction of node B since node A or B probably changed their relative locations due to mobility. Following this, node A sends the Directional RTS (DRTS) to node B at a maximum power and encapsulates this transmission power $T_x_{\text{Power\_dBm}}$ (noted $T_p$) inside the DRTS packet. To do this, the format of DRTS packet has to be modified.

Node B senses the DRTS packet and adjusts its antenna pattern to maximize the receiving power. Upon successful reception of DRTS, node B locks the pattern for further transmission and checks the received RTS power $R_x_{\text{Power\_dBm}}$ (noted $R_p$) and must use it to extract $T_x_{\text{Power\_dBm}}$ from the DRTS packet. Note that in order for node B to receive the packet, the received power must be greater than $R_x_{\text{Sensitivity}}$ (noted $R_s$), which represents the minimum power threshold required to receive the packet correctly.

\[ R_p = T_p + T_g - P_{PL} + R_g - R_N - P_{fm} \]  \hspace{1cm} (1)

where $T_g$, $P_{PL}$, $R_g$, $R_N$ and $P_{fm}$ denote the transmit antenna gain, the power lost due to the path-loss, the receive antenna gain, the power lost due to the noise at the receiver and the fading margin respectively.

Then, node B computes the difference between the received power and its threshold. We denote this value as $\gamma$. So, $\gamma = R_p - R_s$. Node B then encapsulates $\gamma$ into its DCTS packet and transmits this DCTS back to node A using a reduced power $P_{\text{CTS}}$.

During the second step, when node A receives the DCTS packet, it re-adjusts its antenna pattern to maximize the receiving power and then locks it until the completion of the transmission of the ACK packet. The AOA of node B stored in node A will also be updated. The operation of beamforming on both sides correctly adjusts the directional antennas. Following this, node A extracts the value of $\gamma$ from DCTS packet and computes the appropriate power for transmitting data packets (denoted $P_{\text{Data}}$) using (2).

\[ P_{\text{Data}} = \text{dBTomW}(T_p - \gamma)A_{\text{Data}} \]  \hspace{1cm} (2)

where dBTomW represents a function used to transfer dB value to mW value, dBTomW($x$) = $10^{x/10}$, and where $A_{\text{Data}}$ denotes the amplified coefficient used for data transmission. The intention of using amplified coefficients is to take account of various negative effects, which include unexpected interference, fading and mobility.

Node B then starts data transmission using $P_{\text{Data}}$. The same method is used as mentioned in the second step for computing the required power for CTS and
ACK transmissions except that we used a larger value for the amplified coefficients \((A_{\text{CTS}} \text{ and } A_{\text{ACK}})\) when calculating the required power for CTS and ACK \((P_{\text{CTS}} \text{ and } P_{\text{ACK}})\) resp.) aiming to decrease the probability of CTS and ACK corruption.

The third step comes after the completion of the ACK transmission, when both transmitter and receiver sides unlock their beam patterns.

3. Performance Evaluation

We now evaluate the performance of the PCDYCS protocol and contrast it with DVCS protocol (without power control) and IEEE 802.11b protocol. Simulation software used in this paper is QualNet 4.5.1 [10] which is distributed by Scalable Network Technologies, Inc. By using the QualNet simulation program, our work is evaluated with a more actual directional antenna model and full IP protocols. In our simulation, the field temperature is 290K. The two-ray model is used as the path-loss model. The radio type is 802.11b. We don’t use auto rate fallback and set data rate to 2Mbps with DBPSK (differential binary phase shift keying) modulation. To simulate the different communication ranges of omni and directional antennas, the directional antenna gain is set to 15 dBi. AODV (Ad Hoc On-Demand Distance Vector Routing) is used as the routing protocol. The transmission power is 16 dBm. Receiver sensitivity is 89.0 dBm. The CBR packet size is 512 bytes. The amplified coefficient for CTS and ACK is set to 1.15 while the amplified coefficient for Data is set to 1.10. The other parameters are: the height of both omni antennas and steerable directional antennas are set to 1.5 meters. Directional NAV delta Angel is 37 degree. AOA cache expiration time is 2s. Directional beamwidth is 45 degrees.

We conduct simulations under two scenarios, a randomly generated homogeneous topology, and a more realistic heterogeneous ad hoc scenario. In the randomly generated homogeneous topology, 45 nodes are randomly placed over a 1500 x 1500 m flat terrain. One out of ten nodes is randomly selected as the source and each destination node is also randomly selected from 45 nodes. The directional antenna used is an electronically steerable antenna which includes a circular antenna array with 6 isotropic antenna elements. In the heterogeneous scenario, 50 nodes are randomly placed over a 1500 x 1500 m flat terrain. 17 nodes are equipped with omni antennas and run the 802.11b protocol. The other 33 nodes are equipped with steerable directional antennas and run PCDYCS or DVCS protocol. Nine CBR traffic flows are set randomly.

In our simulation, we measure the average throughput which is the mean value of the throughput of all the traffic flows in the network. For power consumption, we take into consideration only the power consumed for the purpose of transmission. We also measure the average power consumption which is the mean value of the power consumed for the transmission of RTS/CTS/DATA/ACK packets of all the nodes in the network.

The performance comparison for the randomly generated homogeneous topology is shown in Fig. 2 and 3. Fig. 2 depicts the network throughput. It is shown that PCDYCS achieves up to 99.3% increase in throughput over IEEE 802.11b and 16% over DVCS. This increase is due to the increase in the number of simultaneous transmissions and the largely mitigated interference. Meanwhile, as can be seen in Fig. 3, the power consumption in PCDYCS is about 36% of that of DVCS and 17% of that of 802.11b scheme. This power saving is attributed to the directional antenna gain and to the power control mechanism.

![Figure 2: Network throughput in scenario 1](image1)

![Figure 3: Power consumption in scenario 1](image2)
In this paper, a power controlled directional MAC protocol that could work well in both homogeneous and heterogeneous ad hoc networks and enabled both directional transmission and reception of both control and data packets was proposed. The performance of the proposed protocol was evaluated using QualNet in realistic situations and compared with the IEEE 802.11b protocol and the DVeS protocol. Simulation results demonstrated that the proposed pCDVCS achieves an increase of around 99.3% over the throughput of the IEEE 802.11b scheme and up to 35% over the throughput of the DVeS protocol. Meanwhile, it reduces power consumption by up to 83% compared with the 802.11b protocol and up to 66.5% compared with the DVeS protocol.

4. Conclusions

In this paper, a power controlled directional MAC protocol that could work well in both homogeneous and heterogeneous ad hoc networks and enabled both directional transmission and reception of both control and data packets was proposed. The performance of the proposed protocol was evaluated using QualNet in realistic situations and compared with the IEEE 802.11b protocol and the DVeS protocol. Simulation results demonstrated that the proposed pCDVCS achieves an increase of around 99.3% over the throughput of the IEEE 802.11b scheme and up to 35% over the throughput of the DVeS protocol. Meanwhile, it reduces power consumption by up to 83% compared with the 802.11b protocol and up to 66.5% compared with the DVeS protocol.

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