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Performance Improvement of Ad Hoc Networks by Deployment of Directional Antenna

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Ad hoc network which requires no infrastructure equipment such as access points is paid great attention in recent years. In ad hoc network, each host controls its wireless access in a distributed fashion. Generally, carrier sensing is used for detecting channel availability. By using RTS and CTS control frames, MAC sub-layer predicts the channel use and resolves hidden-terminal problem. Broadcast nature of RTS and CTS control frames leads to inefficient spatial reuse. One promising solution for this inefficient spatial reuse is usage of directional antenna. In ad hoc networks, heterogeneous network configuration is general, which means each host is equipped with different network facilities. For antennas, it will be general situation that not all hosts are equipped with directional antenna. This paper evaluates throughput performance of the ad hoc network in this realistic situation and shows how much performance improvement deployment of directional antenna will bring to the network.

1. Introduction

A wireless ad hoc network is now attracting great attention because it enables communication among wireless hosts without any fixed network infrastructure [1]. Almost MAC (medium access control) sub-layer of wireless ad hoc networks uses a carrier sensing mechanism to identify the channel availability. The hidden terminal problem is a major technical problem for MAC using carrier sensing. When one host can receive from two other nodes which cannot hear each other, these two nodes may transmit their frames simultaneously, which results in collisions. In order to resolve this problem, virtual carrier sensing, i.e., RTS (request to send)-CTS (clear to send) mechanism, has been used. The sender sends a RTS control frame when it intends to send a data frame. This RTS frame is sent by omni-directional antenna, and all nodes receiving this frame will set its NAV (network allocation vector). NAV specifies the earliest time that the node is permitted to attempt its transmission. This silence enforcement mechanism of virtual carrier sensing has not only a positive aspect, i.e., resolving hidden terminal problem, but also a negative aspect, exposed terminal problem. A node may be blocked of its transmission due to transmission of a nearby node even though blocked transmission causes no collision, which is the exposed terminal problem. The exposed terminal problem extremely reduces spatial reuse of ad hoc networks. One promising way for improving spatial reuse in ad hoc network is the directional antenna.

IEEE 802.11 DCF [2] is originally designed for omni-directional antenna, so it cannot be directly applied to directional antenna. A lot of MAC protocols for directional antenna have been proposed thus far. These include directional busy tone-based MAC [3], DMAC (Directional MAC) [4], MMAC (Multi-hop RTS MAC) [5] and SWAMP [6]. Almost of these MAC protocols for directional antennas assume that all nodes in the ad hoc networks are equipped with directional antenna. Ad hoc networks have great advantage of requiring no infrastructure facilities and constructing a self-organized network. This means that there will be no strict management of network facilities, which means heterogeneity of network elements. So, it should be natural that ad hoc network includes different types of nodes. For antennas, this is also the case, which means it is general that the ad hoc network includes not only nodes with omni-directional antenna but also nodes with directional antenna. From the deployment aspect, this is also the case. Most of present wireless nodes are implemented with omni-directional antenna, so it will be general on the deployment process of directional antenna that not all nodes are equipped with directional antennas.

DVCS (directional virtual carrier sensing) MAC protocol [7] is one example which can be applied to general situation of partial deploy-

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ment of directional antenna. DVCS adds several additional functions for directional antennas, e.g., directional NAV setting and angle of arrival setting. Other than these additional functions, DVCS makes use of original IEEE 802.11 DCF MAC protocol. Thus, it can work with nodes of omni-directional antenna.

In this paper, we evaluate network capacity of ad hoc networks in a general situation that directional antenna is partially deployed in the network. For MAC protocol, we use DVCS which works well in this partial deployment scenario. We evaluate throughput performance of UDP and TCP and give some insights for deployment strategy of directional antenna in ad hoc networks from the viewpoint of improvement of network capacity.

This paper is structured as follows. Section 2 explains the exposed terminal problem and its solution of using directional antenna. Section 3 gives short introduction of DVCS. In section 4 and 5, we evaluate UDP and TCP throughput in ad hoc network under the situation of partial deployment of directional antenna. For evaluation, we change the ratio of nodes which are equipped with directional antennas. From simulation results of UDP and TCP throughput, we try to give some insights for deployment strategy of directional antenna in ad hoc networks. Section 6 concludes the paper.

2. Exposed Terminal Problem and Directional Antenna

In wireless networks, the exposed terminal problem occurs when a node is prevented from sending packets to other nodes due to a neighboring transmitter. Consider an example of 4 nodes labeled R1, S1, S2, and R2, where the two receivers (R1 and R2) are out of range from one another (**Fig. 1**). And the two transmitters (S1 and S2) are in range of each other and for each corresponding receiver. When node S1 starts transmission of data to R1, node S2 is prevented from transmitting to R2. Even these two transmissions can occur simultaneously without collision, S2 is blocked from its transmission to R2 by carrier sensing, which causes ineffective reuse of wireless channel. One promising solutions for this exposed terminal problem is directional antenna.

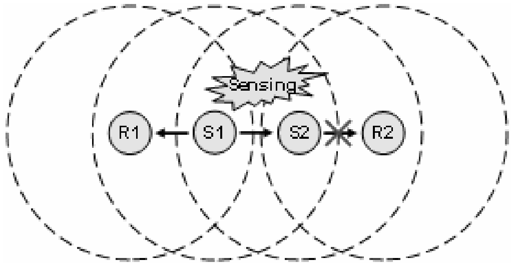

Fig. 1 The exposed terminal problem.

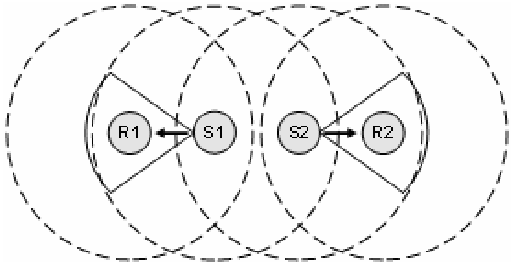

Fig. 2 Directional antenna resolves exposed terminal problem.

As shown in **Fig. 2**, these two transmissions can occur simultaneously by using directional antennas because transmission from S1 to R1 affects nothing in wireless transmission from S2 to R2. Thus, directional antenna is expected to improve network performance of the ad hoc networks.

3. DVCS (Directional Virtual Carrier Sensing) Protocol

DVCS [7] assumes that nodes in the ad hoc networks implements directional antenna with spatial diversity antennas. Diversity gives possibility of directional analysis of arrived signal, which makes it possible to identify relative direction of the neighboring nodes. By using this directional function, DVCS [7] adds the following three additional functions to the original IEEE 802.11 MAC protocol.

- AOA caching
  When each node hears any signal, it caches estimated angle of arrivals (AOAs) from neighboring nodes (**Fig. 3**). When the node has data to be sent to the neighboring node and also its cached AOA for this node, it adjusts beam direction of its directional antenna to the cached angle and sends the RTS control frame. If it has no cached AOA for this node, the RTS control frame is sent by omni-directional antenna.
- Beam Locking and Unlocking
  When the node receives the RTS control frame, it adjusts direction of its directional antenna so that it maximizes the received power. And the node locks the direction

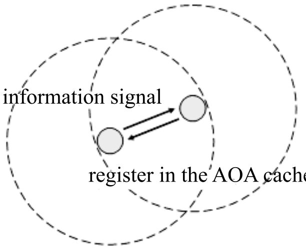

Fig. 3 AOA (Angle of Arrival) caching.

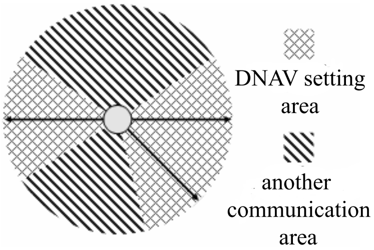

Fig. 4 DNAV (Directional NAV) setting.

of beam of the directional antenna. When the node (the node sent the RTS frame) receives the CTS control frame, it re-adjusts beam pattern of its directional antenna to maximize the received power. This node may have cached AOA of the node sent the CTS frame, but there is a chance that direction of the node may be slightly changed due to mobility. So, there is a necessity to re-adjust the direction. Beam locking of both sides is unlocked after ACK control frame transmission.

- DNAV setting
  DVCS protocol uses DNAV (directional NAV) instead of NAV in IEEE 802.11 MAC protocol. Each DNAV has its direction and width. Each node can have multiple DNAV and each DNAV has its own timer. When a timer expires, the corresponding DNAV is removed. The node cannot send any signal to the angle of DNAV setting, but it can send signal to the angle without DNAV. **Figure 4** shows the case where there are three DNAVs of the angle of 0, 180 and 315 degrees where each DNAV width is 60 degrees. In DVCS, spatial reuse of wireless channel is achieved because signal can be sent to the angles without DNAV.

DVCS protocol adds nothing to original IEEE 802.11 MAC protocol without the above three functions, which means DVCS can work well even with the node which has omni-directional antenna. When node A sends data to node B, DVCS works as follows (**Fig. 5**)

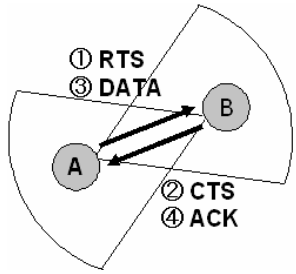

Fig. 5 Data transmission using DVCS.

(1) When node A intends to send data to node B and it has cached AOA for node B, it adjusts beam of its directional antenna to the angle of B's AOA and sends the RTS control frame (This angle of directional antenna may be a little different to the real direction of node B, because node A and/or B may change its location due to their mobility).
(2) When node B receives the RTS control frame, it adjusts beam of its directional antenna so that receiving power is maximized. Node B locks the beam direction of directional antenna and sends the CTS control frame.
(3) Node A receives the CTS control frame and re-adjusts its directional antenna so that the receiving power is maximized. B's AOA stored in node A is also revised. By beamforming operation at both sides, directional antennas are correctly adjusted and data frames are transmitted.
(4) After ACK transmission, both sides (node A and B) unlock their beam locking of directional antenna.

When the angle of node B is not stored in AOA of node A, node A will send RTS with omni-directional antenna. In the case that node B has only the omni-directional antenna, node B can respond to the RTS control frame sent by directional antenna of node A. In this case, node B can send the CTS by omni-directional antenna and node A can receive it by directional antenna. Thus, DVCS can work well in the situation that not all nodes implement directional antenna.

4. Performance Evaluation of UDP Throughput

Deployment of directional antenna will resolve the exposed terminal problem, which will improve spatial reuse of wireless channel. So, directional antennas are expected to bring significant performance improvement for the ad hoc networks. Ad hoc network has a self-organizing nature and each node may have different network facilities. For antenna specification, this is also the case, which means it is natural that not all nodes are equipped with directional antennas. So, we would like to evaluate performance improvement by deployment of directional antennas in the ad hoc networks. In this section, we evaluate UDP throughput performance.

4.1 Simulation Model

Aim of the paper is to evaluate basic performance improvement for deployment of directional antenna, so we use static network model where no mobility is taken into account. For routing protocol, we use AODV [8]. For simulation tool, we use Qualnet. We use node location model which takes into account of location homogeneity (In Qualnet, they call "semi-automated node placement"). In this node placement, square field is divided into cells and one node is located randomly in each cell. When we use pure random model, there may be some heterogeneity of connectivity among ad hoc nodes. We would like to avoid evaluating network throughput in this extremely heterogeneous situation, because measured throughput is too low in the situation that many nodes are placed in some narrow space in simulation field due to high interaction of wireless channel among ad hoc nodes. Even though in some part node is placed sparsely and a node has small number of neighboring nodes, network throughput may be too low because of congestion at this bottleneck node. 40 nodes are placed in square simulation field by this node location model of taking account of location homogeneity. 8 nodes are randomly selected as the source of UDP or TCP traffic and each destination node is also randomly selected from 40 nodes. Other simulation parameters are described in **Table 1**.

Table 1 Simulation parameter.

Number of Node	40 Nodes
Traffic	CBR traffic generation
Data size	512 Bytes
Omni directional beam communication radius	300 m
Directional beamwidth	45-degree
Directional beamlength	390 m
Wireless band	2 Mbps

In the ad hoc networks, geographical density of nodes affects throughput performance. We define the following node density parameter R.

$$R = \frac{N \times \pi \times r^2}{m^2}$$

where N, r and m is the number of nodes (40), omni-directional beam radius [m] and length of each side of simulation field [m], respectively. We evaluate two different densities, $R = 1.8$ and 3.0. Length of each side of square field is 1,900 and 2,500 [m] for $R = 1.8$ and 3.0, respectively.

4.2 UDP Throughput

Figures 6 and **7** show UDP throughput characteristics for $R = 1.8$ and 3.0, respectively.

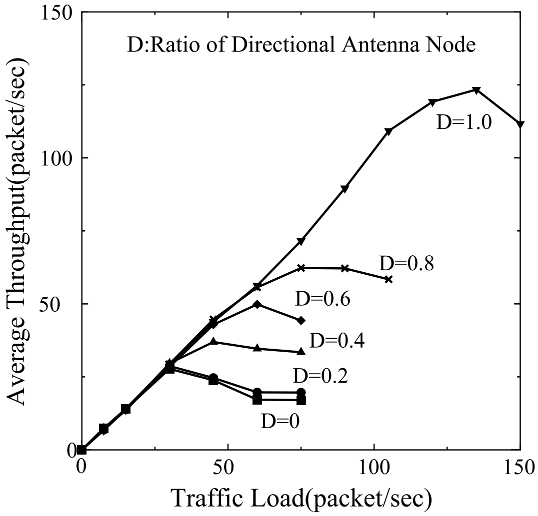

Fig. 6 UDP throughput performance ($R = 1.8$).

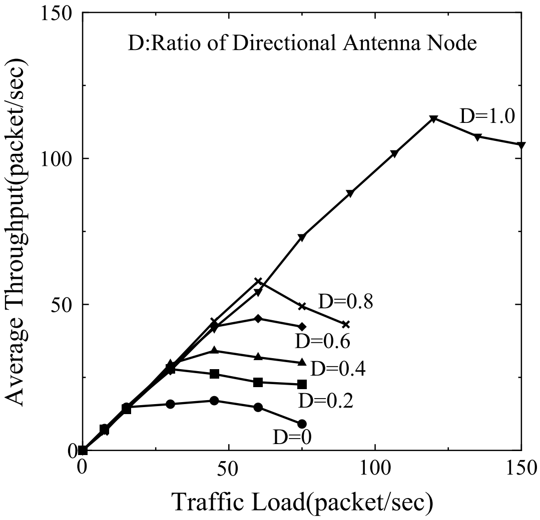

Fig. 7 UDP throughput performance ($R = 3.0$).

Horizontal axis shows traffic load (average arrival rate) of each node and vertical axis shows average throughput of UDP for each node. A parameter D is ratio of nodes with directional antennas. When $D = 0.6$, 60% of nodes in the network are equipped with directional antenna and the other 40% nodes are with omni-directional antennas. In our simulation, we assume that each packet has 512 byte length, so 100 packet/sec is about 400 kbps. Both simulation results show that with increase of traffic load, throughput of UDP increases at first. And after it has maximum value, it decreases slightly. The reason why throughput of UDP increases at first is that throughput increases linearly with increase of input traffic beyond network capacity. Thus, the maximum value of average throughput of UDP shows network capacity of ad hoc networks. After throughput shows maximum value, it decreases slightly because of overhead for control packet transmission.

Figures 8 and **9** show the number of re-floodings for route request generated by both of the source nodes and intermediate nodes. Vertical axis shows the number of re-flooding of route request packets in the whole networks and horizontal axis shows ratio of directional antenna nodes. Three bars for each deployment ratio show the number of re-flooding characteristics of different three traffic loads (30, 80 and 120 packet per second). When 7 consecutive failures of RTS transmission happen before a frame transmission, IEEE 802.11 DCF discards the corresponding frame[9]. AODV in the network layer interprets this frame loss as route failure, which causes re-flooding of a route request packet. With low percentile deployment of directional antenna, wireless interference among adjacent nodes causes lots of failures of RTS transmission. As shown in Figs. 8 and 9, the number of re-floodings of route request packets decreases with increase of directional antenna deployment ratio. This decrease of control packets (flooding packets of route request) is the reason why the increase of average throughput of UDP with increase of deployment ratio.

Simulation results in Figs. 6 and 7 show that UDP capacity (maximum throughput) seems to increase linearly with increase of ratio of directional antenna when D is between 0 and 0.8. Capacity improvement (increase of maximum throughput) between $D = 0.8$ and 1.0 is very large, compared with capacity improvement of other increase of 0.2 in D (e.g., from $D = 0.2$ to $D = 0.4$). When there is even one node with omni-directional antenna on the session (path from the source to the destination), interaction of wireless channel around this omni-directional antenna node reduces total throughput of this session. When ratio of directional antenna, D, is below 0.8, probability that there is at least one node of omni-directional antenna in each session increases, which is the reason why performance improvement brought by directional antenna deployment is not so high in this region.

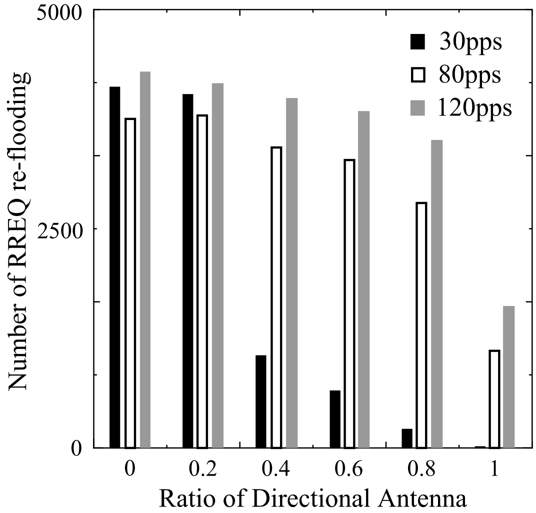

Fig. 8 RREQ re-flooding performance ($R = 1.8$).

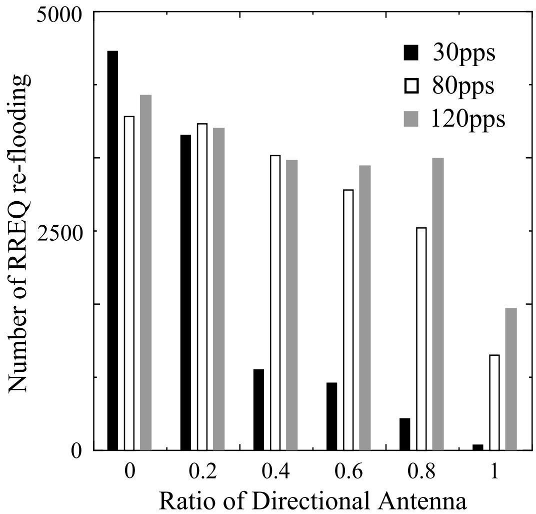

Fig. 9 RREQ re-flooding performance ($R = 3.0$).

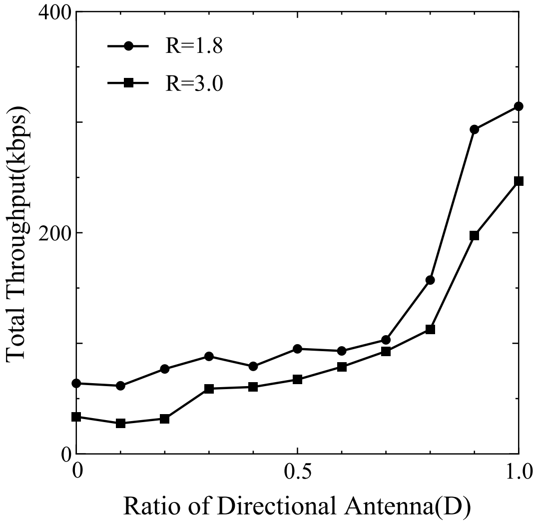

Fig. 10 TCP throughput performance.

5. TCP Throughput Performance

TCP is widely used for the transport protocol. In this section, we evaluate TCP throughput performance of the ad hoc network with partial deployment of directional antenna. For simulation model, we use almost the same model as UDP evaluation. Only the difference is traffic model. We use greedy model for TCP traffic source model. This means application layer already has data to be sent and transmission rate of the source is decided by congestion control behavior of TCP.

Figure 10 shows TCP throughput characteristics for node density of $R = 1.8$ and 3.0. Horizontal axis of the figure shows ratio of nodes with directional antennas (D) and vertical axis shows total throughput of 8 sessions. Simulation results show that little performance improvement is obtained when D is less than 0.8. When D is larger than 0.8, performance improvement of TCP throughput is very large with increase of ratio of directional antenna nodes. TCP is originally designed for wired networks, which means main reason for packet loss is buffer overflow at a router, i.e., congestion in the network. So, TCP uses packet loss as the signal of congestion inside the network. Packet losses induce congestion control, e.g., congestion window reduction due to timeout. In the ad hoc network, there are several reasons for packet losses other than congestion. These include low communication quality of wireless channel and mobility of ad hoc network. TCP at the end host misunderstands packet losses due to these reasons as the signal of congestion. Especially for ad hoc network, contention at MAC layer induces long delay for packet transmission, which causes timeout of TCP. When D is less than 0.8, the probability of at least one omni-directional antenna node included in a session becomes high and interaction on the wireless channel around these omni-directional antenna nodes induces contention at MAC layer, which will be the reason why TCP throughput cannot be improved with increase of directional antenna in this situation. However, when D is larger than 0.8, most of sessions include no omni-directional antenna on their paths, so TCP performance is significantly improved.

6. Conclusions

In the paper, we evaluate performance improvement brought by deployment of directional antennas in the ad hoc networks. In the ad hoc network, it is general that each node has heterogeneous capabilities, so we assume the realistic situation that not all nodes in the network are equipped with the directional antennas. We evaluate UDP and TCP throughput performance with various ratios of nodes equipped with directional antennas in the network. Simulation results show that UDP throughput is improved with increase of directional antenna nodes. This improvement is significantly large when this ratio is larger than 0.8. For TCP throughput, there is little improvement where this ratio is below 0.8. In the case that this ratio is larger than 0.8, throughput improvement of TCP brought by deployment of directional antenna is very large. From these simulation results, in the case that streaming services using UDP are provided in the ad hoc networks, gradual deployment of directional antennas will bring smooth performance improvement. However, in the case that reliable data transmission services using TCP are provided in the ad hoc networks, gradual deployment will bring little improvement for the user and bulk deployment is preferable.

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