Mode Selection Criteria in Mobile Ad hoc Networks using Heterogeneous Antenna Technologies

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Abstract

Smart antenna technology is a new focus area of research for capacity improvements in wireless ad hoc networks. Smart antennas come in different flavors varying from switched beam to adaptive beam forming antennas, single beam or multiple beam directional antennas. It is expected that smart antenna techniques will be adopted for future wireless devices for optimum utilization of available resources. In this work we use OPNET to study the behavior of IEEE 802.11 DCF in a heterogeneous network, where nodes can communicate in omni-directional or directional mode. Using some toy topologies we formulate mode selection criteria for heterogeneous networks where nodes exploit different smart antenna technologies for enhancing the network capacity. This also forms the basis of developing efficient medium access protocols for such type of networks.

I. INTRODUCTION

Mobile Ad hoc networks (MANETs) have gained increased attention over the past decade. Such nodes employ omni directional antennas for communicating with neighboring nodes. However, omni-directional communication results in poor spatial reuse thus adversely affecting the network capacity [1]. Directional antenna on the other hand reduces co-channel interference, increases spatial reuse and provides range extension. Directional communication also introduces new problems such as deafness, location tracking and increase the hidden terminal problem. The use of directional antennas can lead to severe performance degradation in some scenarios due to the aforementioned problems. Recent research is widely focused on applicability of directional antennas in mobile ad hoc networks [2-7].

IEEE 802.11 DCF [8] has emerged as the de-facto medium access control (MAC) standard for wireless LAN and mobile ad hoc networks. Distributed Coordination Function (DCF) was designed for omni-directional communication and thus its suitability for directional communication has to be evaluated. Almost all asynchronous on-demand protocols for omni-directional or directional antennas are based on this standard.

In this work we consider heterogeneous networks where nodes have the capability of transmitting in omni-directional or directional mode. With the help of some toy-topologies we present criteria for a node to dynamically switch between various smart antenna technologies to achieve optimal performance. This work forms the basis for a hybrid MAC protocol based on IEEE 802.11 DCF for such type of networks. We have developed antenna modules to be interfaced with wireless LAN MAC available in OPNET.

The rest of the paper is organized as follows. In Section II we give an overview of IEEE 802.11 DCF and directional MAC protocols and their associated problems. We present developed modules for OPNET in Section III. The performance evaluation is done in Section IV. Mode selection criteria are formulated in Section V. Section VI concludes the paper.

II. AN OVERVIEW OF IEEE 802.11 DCF BASED MAC

A. IEEE 802.11 DCF:

IEEE 802.11 distributed coordination function (DCF) is based on the CSMA/CA channel access mechanism in which nodes contend for the channel [8]. Before transmitting a packet, each node senses the channel. If the channel is sensed busy it waits for the current transmission to complete. If the channel is idle for DIFS duration, the transmitting node then selects a random slot based on its contention window for transmitting the packet. During the backoff period, if the channel is sensed busy, the node freezes its backoff counter and waits till the channel is idle again and repeats the above procedure. This is to ensure that the two neighboring nodes that have sensed channel for DIFS duration at the same time do not start their transmission concurrently. DCF also has an optional four-way handshake mechanism involving control messages (RTS/CTS) preceding the data communication. This is used in addition to the physical carrier sensing, if the frame size exceeds certain threshold. This minimizes the data packets collisions. A node overhearing the control messages (RTS or CTS) sets its Network Allocation Vector (NAV) to defer its transmission until the end of the ongoing data transmission. This is termed as virtual carrier sensing and avoids collision with any hidden transmissions.

B. Directional protocols based on IEEE 802.11 DCF:

Several existing MAC protocols for directional antennas are based on IEEE 802.11 DCF [2-7]. Most of these protocols differ in the way control messages are exchanged. While in some protocols RTS/CTS messages are transmitted directionally, some prefer omni-directional transmission. Directional communication enhances the range and network connectivity, thus reducing the number of hops needed from a source to destination node. Omni-directional transmission of control packets on the other hand greatly reduces the hidden terminal and deafness problems [4]. In directional mode of communication each node maintains a Directional Network Allocation Vector (DNAV) based on directional virtual carrier sensing (DVCS) which holds the information regarding deferring transmission in a particular direction until the end of corresponding data communication. This is similar to NAV in omni-directional protocols.

C. Hidden Terminal and Deafness:

Problems due to hidden terminals and deafness often arise with directional antennas due to the inability of a node to sense other ongoing transmission(s) in the neighborhood. These problems have been thoroughly studied in literature [4], [9], [10]. These occur primarily due to another data communication

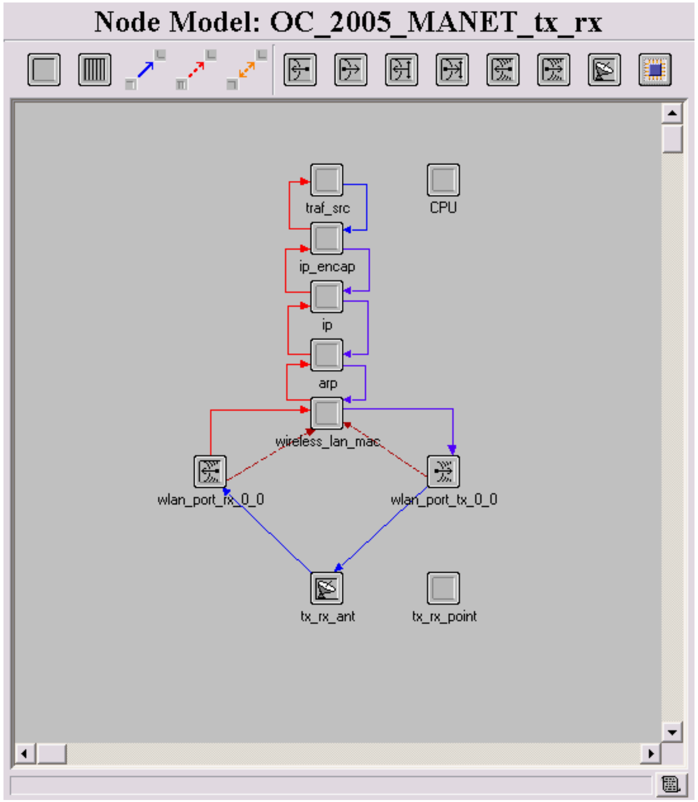


Figure 1: The Node Model

occurring in the neighborhood about which the current transmitter is unaware about. Knowledge of neighboring transmissions can enhance the overall system performance by avoiding unnecessary collisions, however it can also degrade the system throughput in some cases (for example, exposed node problem). In this work we systematically investigate the cases where performance is enhanced and where it can degrade. We propose that the nodes based on the neighborhood information, should dynamically decide when to communicate in omni-directional mode and when to communicate in directional mode for boosting the overall network performance.

III. OPNET MODELS

We perform a simulation based study in order to develop mode selection criteria for performance improvements. We have used OPNET as our simulation tool for testing different topologies.

A. Node Model

We have modified the advance node model of MANET station available in OPNET to incorporate the capability of directional communication as shown in figure 1. When the node is transmitting or receiving in directional mode the antenna (tx_rx_ant) points in the desired direction with the help of antenna pointing processor (tx_rx_point). The data rate of the wireless channel is set to 2 Mbps. Table I describes the various simulation parameters.

B. Antenna Model

In this paper, we consider a node with capability of operating in both omni-directional and directional modes. In directional mode its range is kept same as that of omni-directional mode.

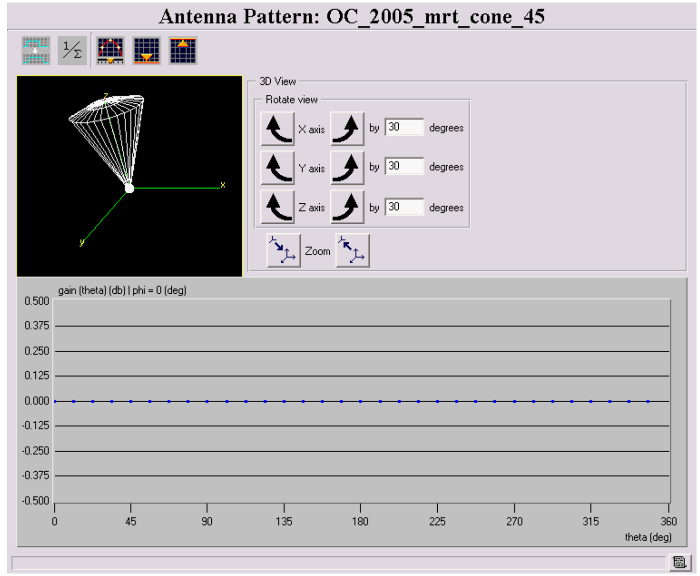


Figure 2: The Directional Antenna Pattern

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Data rate	2 Mbps
Data packet size	1500 bytes
Packets Inter-arrival time	Constant (5 milliseconds)
Packet reception-Power Threshold	-95 dBm
Buffer size	32 Kbytes (~21 Packets)
Transmission power	0.5 mW

This is achieved by controlling transmitting power and antenna gain while in directional mode. To achieve this, a conical directional antenna pattern of beam-width 45 and gain of 0 dBi for main lobe is created using the antenna pattern editor as shown in figure 2. The gain in remaining spherical region is confined to -20 dBi. We focus on gains from spatial reuse *exclusively* and not by extending the range of directional beams. In idle mode, the receiver remains in omni-directional mode while sense the channel.

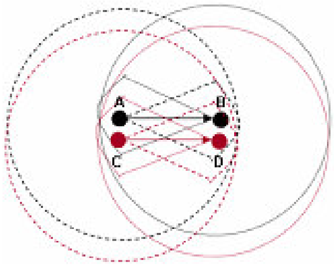
IV. PERFORMANCE EVALUATION

A. Evaluation Methodology and Considerations

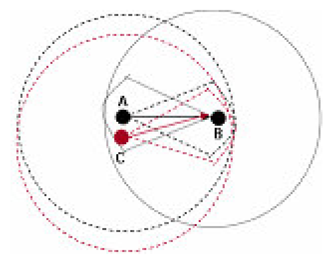
In our simulation we compare the performance of nodes in directional and omni-directional modes with regard to throughput, delay and BER at receiver, and retransmission attempts made by the transmitter. Important simulation parameters are listed in Table I. Each simulation is run for 100 seconds. CBR traffic is considered with a packet inter-arrival time of 5 milliseconds. Hence, each transmitter on an average generates 200 packets per second. A node can transmit about 130 packets per second with the given data rate and packet size leading to a loaded network. Further, in directional mode of transmission all packets RTS/CTS/DATA/ACK are transmitted directionally and the channel is considered to be symmetric.

B. Analysis of different Scenarios

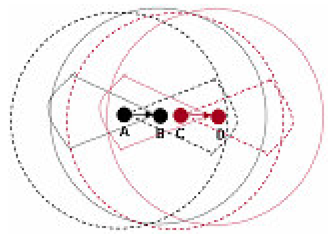
The use of directional antennas reduces co-channel interference, enhances spatial reuse and provides range extension. However, it also introduces certain problems such as deafness, location tracking and the hidden terminal problem. In contrast to omni-directional mode, in directional mode nodes have relatively less knowledge of neighborhood transmissions.



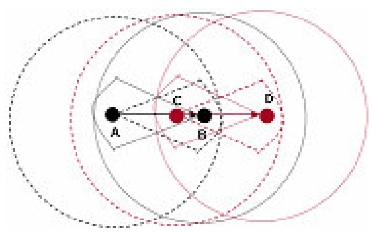
(a) Deaf communicating pair



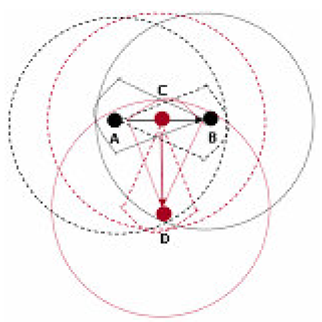
(b) Common receiver



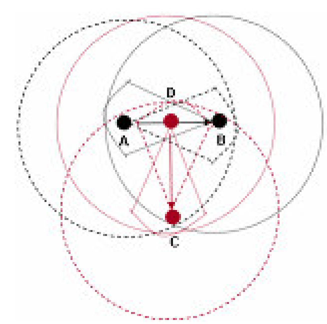
(c) Linear_Pair_SameBeam



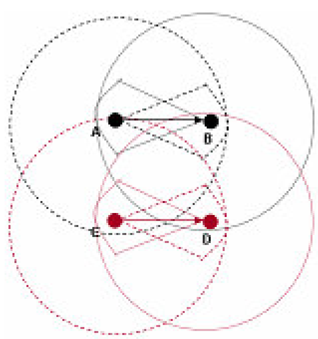
(d) Tx_0



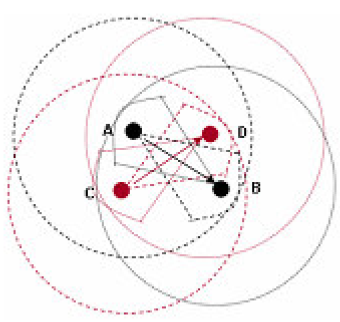
(e) Tx_90



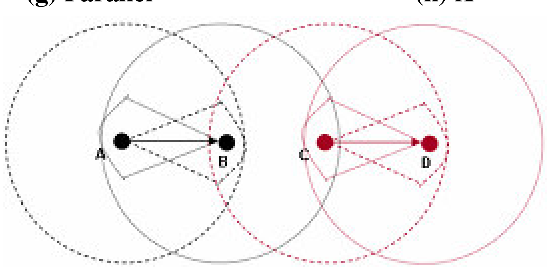
(f) Rx_90



(g) Parallel



(h) X



(i) Linear

Figure 3: Sample Scenarios

This lack of information can lead to severe performance degradation in some scenarios. To analyze these effects in the form of hidden terminal and deafness problems, we evaluate different possible scenarios that are common in MANETs. However, these scenarios may not comprehensively cover all the possible communication scenarios in MANETs. Figure 3 shows the different scenarios considered for evaluation. We consider two pairs of communication nodes A-B and C-D. Both the transmitters (A and C) generate similar traffic with identical packet inter-arrival times. We analyze how each flow can interfere with the other and affect the overall network performance.

Topology (3.a): Deaf communicating pair scenario

- Receivers in same beam of the transmitter
- Transmitters in same beam of the receiver
- Both the transmitters are deaf to each other communication

In this topology with directional communication either transmitter cannot sense the communication by the other transmitter. Thus both the transmitters are deaf to each other's transmission and can transmit simultaneously. However at the receiver side, both the transmissions overlap and thus interfere with each other resulting in a large number of packet drops at the receivers. Thus simultaneous communication results in very poor performance of both the flows as shown in figure 4.a. The average throughput in directional mode is about 15% lower than in omni-directional mode. A large number of retransmissions (figure 4.b) are attempted by both the transmitters, thus leading to unnecessary collisions and consequently higher energy consumption. Omni-directional mode performs better in such topologies.

Topology (3.b): Common receiver scenario

- Two or more transmitters with common receiver
- Usually both the transmitters are deaf to each other communication

This topology is very similar to deaf communication pair topology described above. In directional mode transmitting nodes waste considerable amount of time in retransmission attempts (figure 5.b) and thereby backing off. This results in throughput degradation at the common receiver as evident from figure 5.a. This topology also requires all nodes to be in omni-directional mode for better performance.

Topology (3.c): Linear_Pair_SameBeam

- Another communicating pair in the same beam of the transmitter
- Throughput of C-D pair suffers due to interference from A-B ongoing communication in directional mode

In this topology node A being deaf to node C, interferes with the communication between node C and node D leading to collisions at node D. This is evident from high BER observed at node D (figure 6.d). Hence while packet reception at node B is almost 100% (figure 6.a), throughput of node D is highly degraded as shown in figure 6.b. Also due to collisions at node D, retransmission attempts by node B increase considerably (figure 6.c). By switching node C to omni-directional mode we can attain near optimal performance as shown in figure 6.

Topology (3.d): Tx_0

- Another node transmitting in same direction

In this topology, performance improvement can be achieved by switching node C to omni-directional mode while keeping the other nodes in directional mode as can be seen from figure 7.

Topology (3.e and 3.f): Tx_90 and Rx_90

- Another non-interfering transmitter or receiver in the communicating beams

This is a situation in which the two transmitter's beams do not overlap at the receivers. Thus in such a case if we use directional mode of communication then simultaneous transmission of both flows is feasible without affecting each other. However, with omni-directional antennas, nodes overhear each other's transmission and consequently both the transmitters cannot transmit simultaneously. Thus in this scenario if nodes select directional mode then a higher performance can be achieved. Figure 8 shows the predicted performance improvement. Similar results are obtained for Rx_90 scenario.

Topology (3.g, 3.h and 3.i):

- Only the intended receiver or transmitter in the communicating beams
- Both the transmitters are deaf to each other communication
- No other communicating node in those beams

In such case directional mode of communication outperforms omni-directional mode. In these cases also results obtained are similar as shown in figure 8.

V. MODE SELECTION CRITERIA

As we can notice from the above topologies, naïve directional communication or naïve omni-directional communication results in sub-optimal performance in certain cases. Optimal network performance in all scenarios can only be realized with the help of intelligent antenna mode selection. Based on the above scenarios we formulate the following mode selection criteria:

- All nodes should use omni-directional mode in the following cases:
  - Deaf communicating pair scenario
    - Receivers in same beam of the transmitter
    - Transmitters in same beam of the receiver
    - Both the transmitters are deaf to each other communication
  - Common receiver scenario
    - Two or more transmitters with common receiver
- Intermediate transmitting node should employ omni-directional mode while other nodes should be directional mode for the following cases:
  - Another communicating pair in the same beam of the transmitter
  - Another node transmitting in same direction
- All nodes should use directional mode, in the remaining cases including:
  - Another non-interfering transmitter or receiver in the communicating beams
  - Only the intended receiver or transmitter in the communicating beams

VI. CONCLUSIONS

Smart antenna technology has become a new focus area of research for capacity improvements in wireless ad hoc networks. We have used OPNET to study the behavior of IEEE 802.11 DCF in a heterogeneous network, where nodes can communicate in omni-directional or directional mode. Directional mode leads to better spatial reuse, enhances system capacity but also introduces problems of deafness and hidden terminal. Omni-directional antenna on the other hand suffers from poor spatial reuse. However there are some cases where omni-directional mode performs better. Mode Selection Criteria forms the basis of developing MAC protocols for MANETs using heterogeneous antenna technologies. Dynamically switching a node from directional to omni-directional or vice versa depending on the neighboring nodes can enhance the system performance considerably.

The above concept can also be applied directly to multiple beam antennas [11] where optimal performance can be achieved by transmitting control packets in beams having transmitters and receivers only. As part of future work we plan to consider multiple beam antennas and perform extensive study with more communicating pairs and increasing node densities. We also plan to extend this work for multi-hop topologies and develop Game Theoretic strategies in determining the mode selection criteria for such scenarios.

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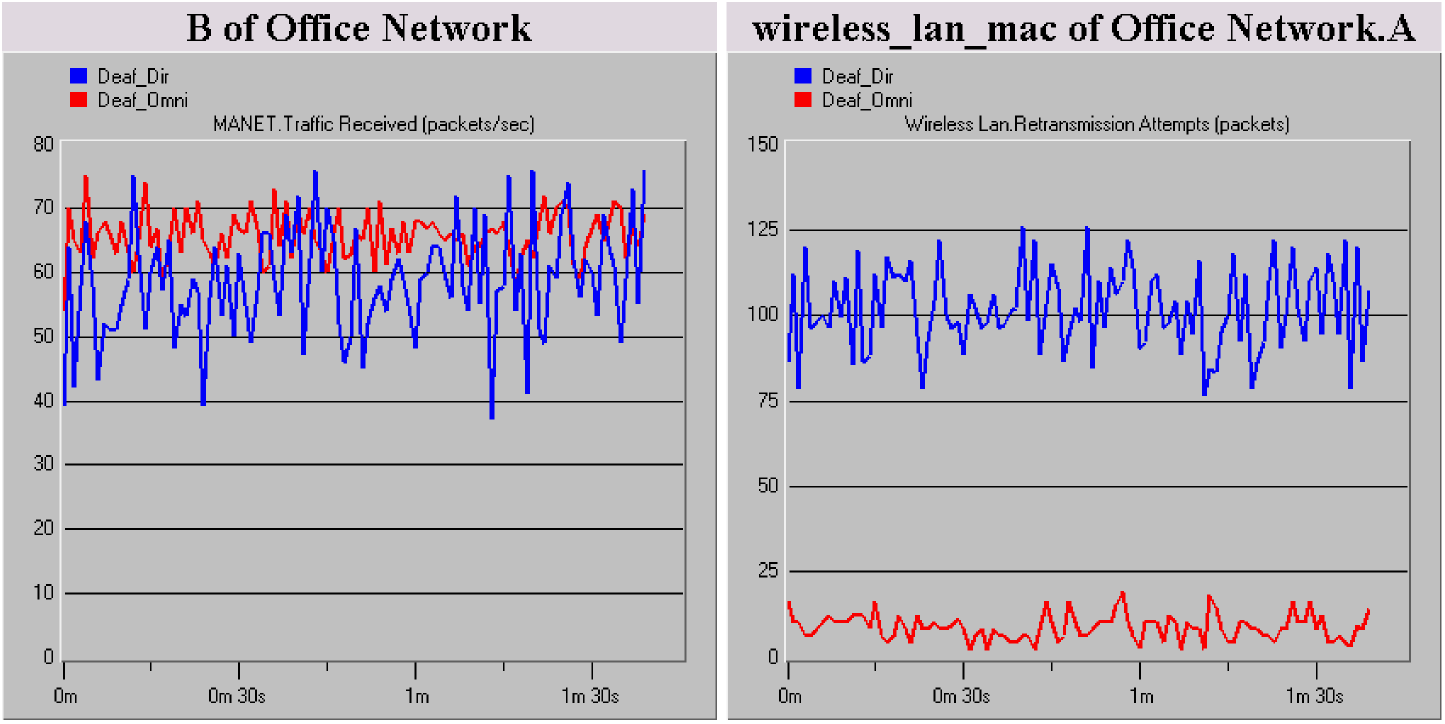
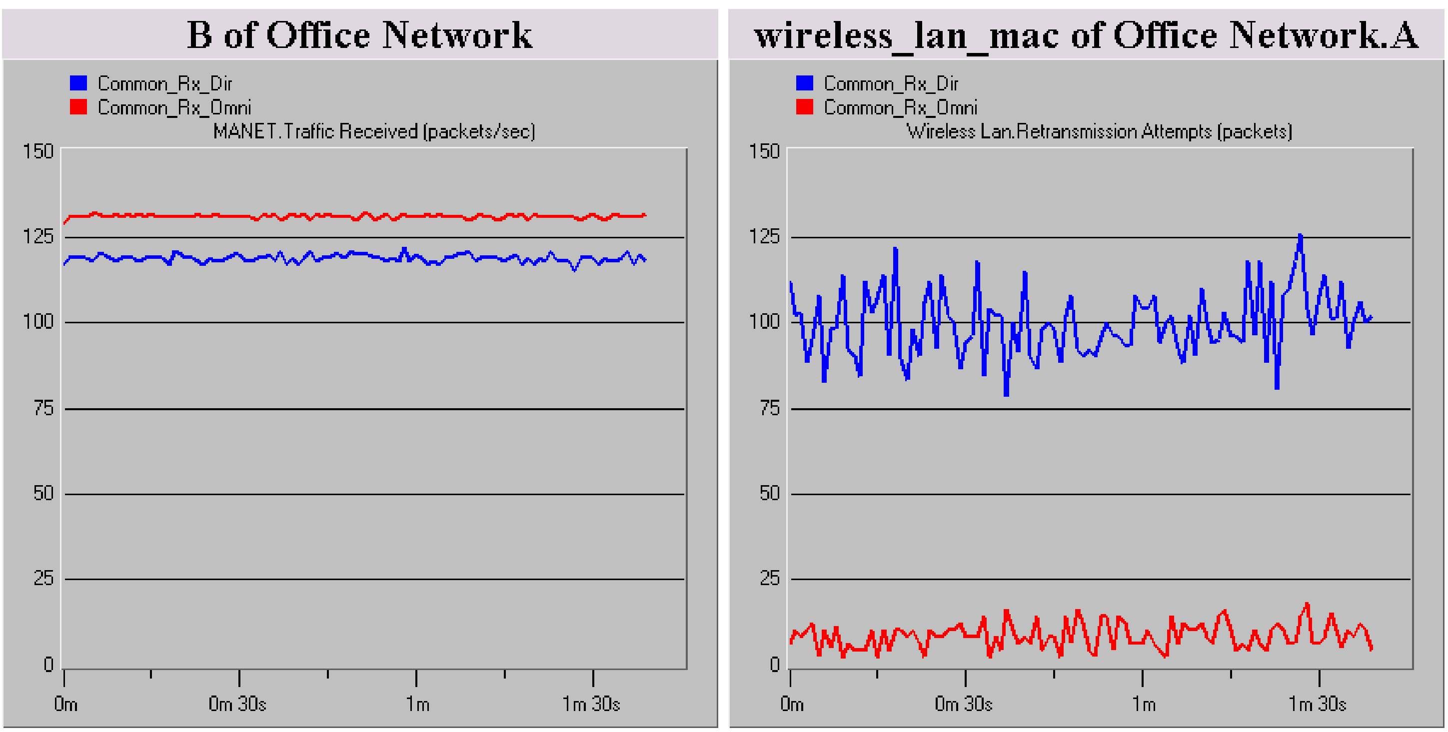


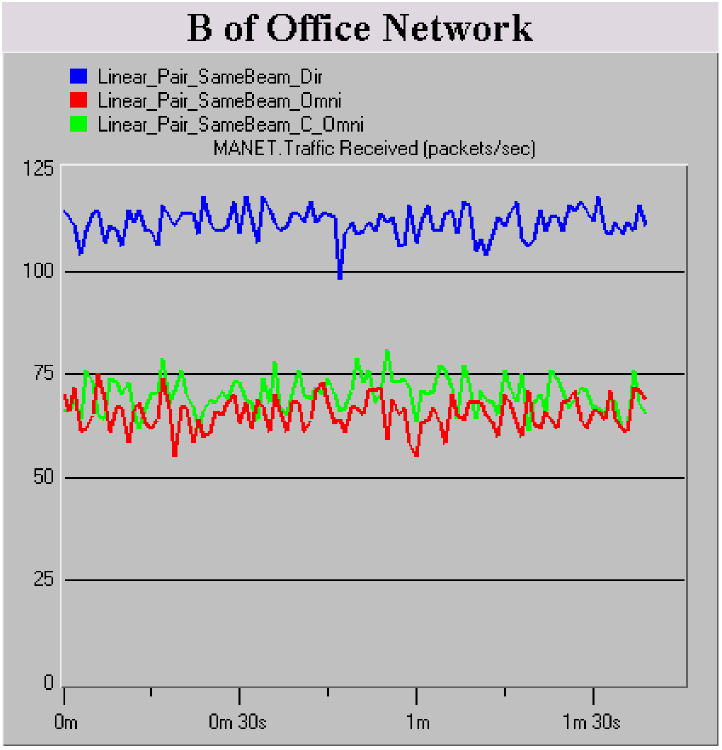
(a) Packets received by receiver node B vs. time **(b) Retransmission Attempts by transmitter node A vs. time**

Figure 4. Results for Deaf Communication Pair Scenario

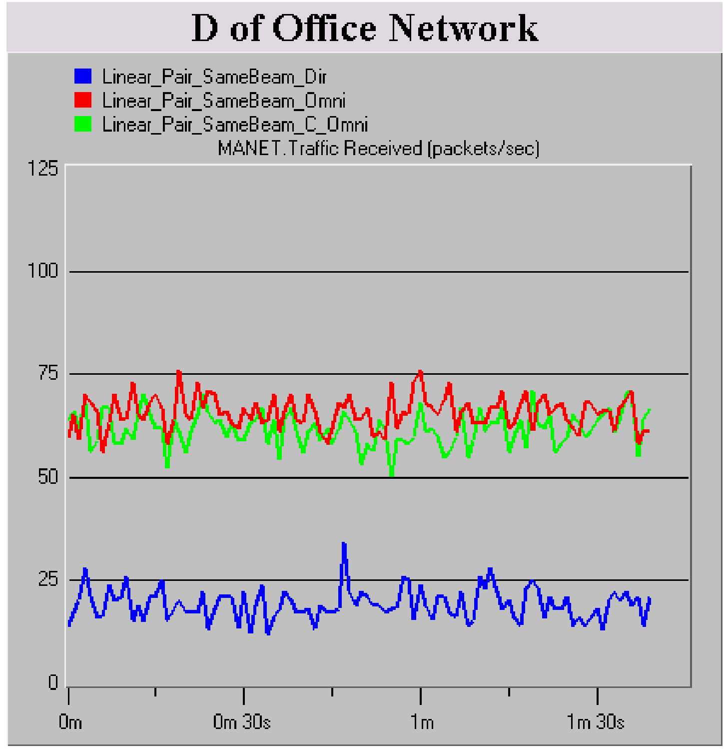


(a) Packets received by receiver vs. time **(b) Retransmission Attempts by transmitter node A vs. time**

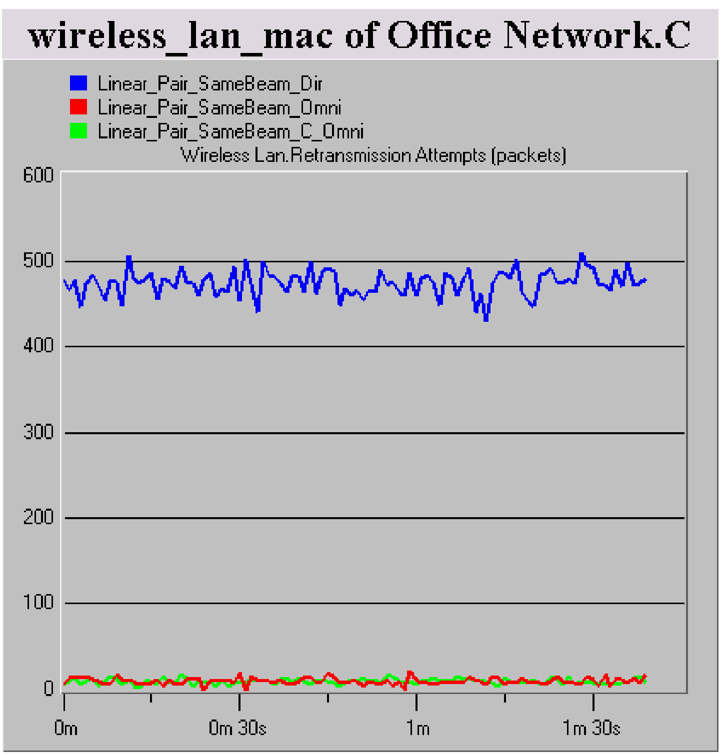
Figure 5. Results for Common Receiver Scenario



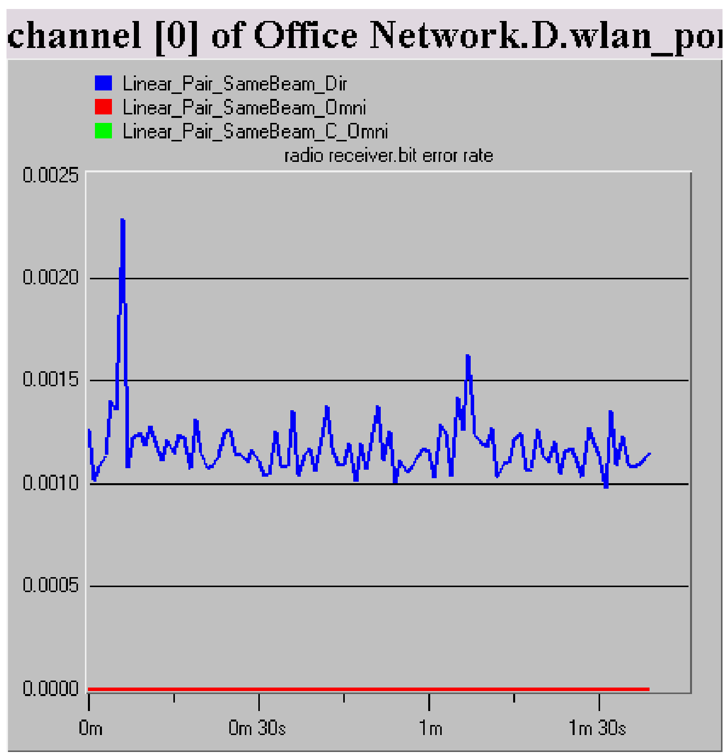
(a) Packets received by receiver node B vs. time



(b) Packets received by receiver node D vs. time

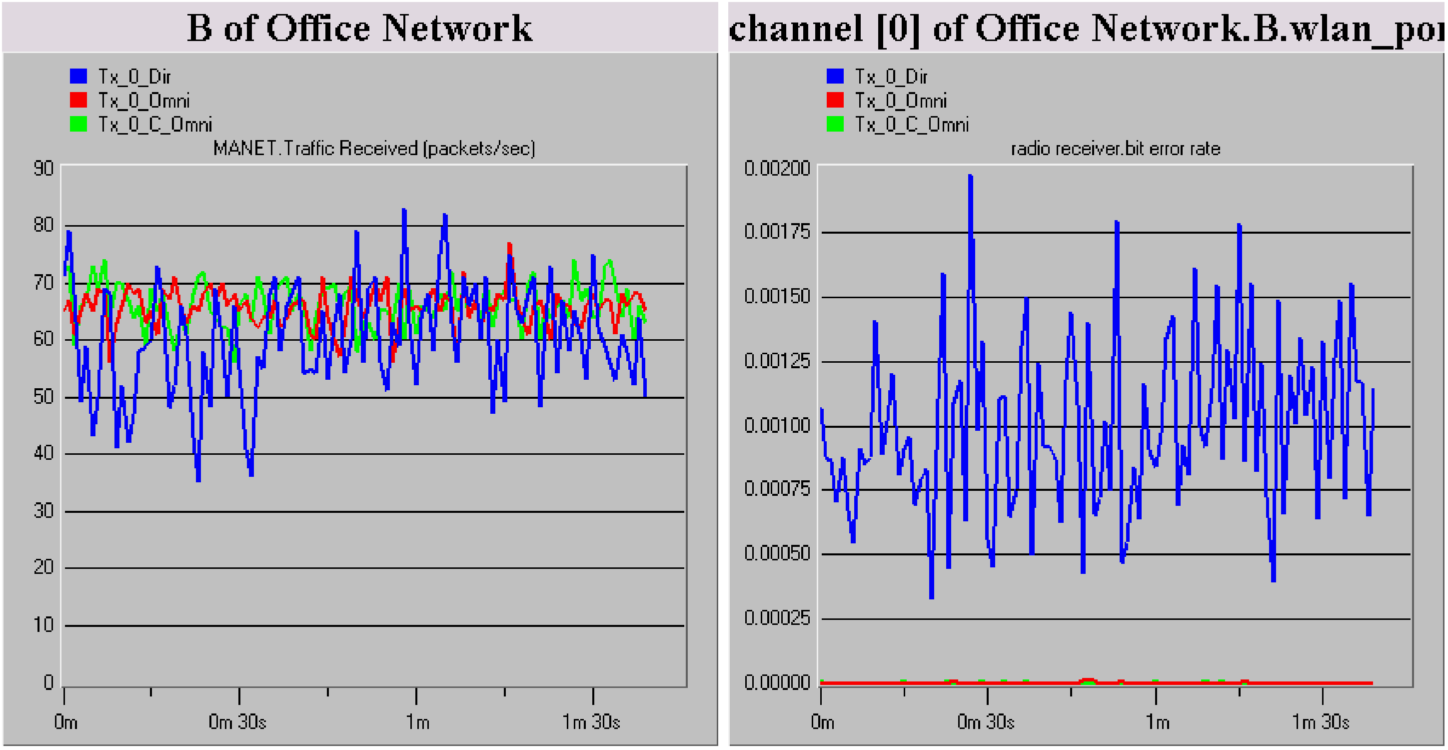


(c) Retransmission Attempts by transmitter node C vs. time



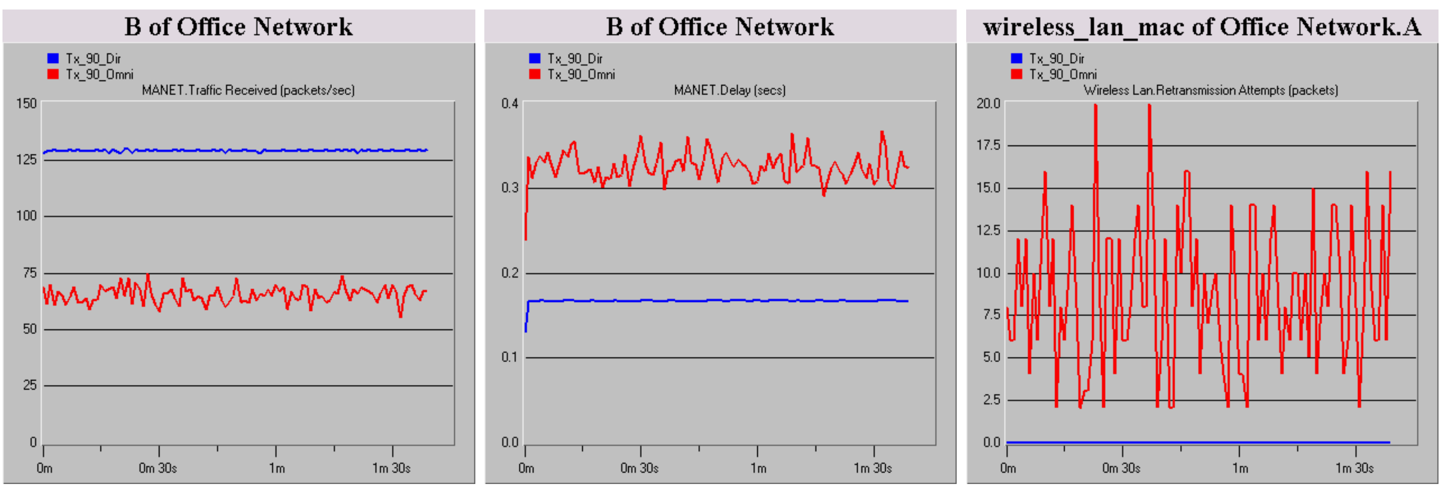
(d) Bit Error Rate at receiver node D vs. time

Figure 6. Results for Linear_Pair_SameBeam Scenario



(a) Packets received by receiver node B vs. time **(b) Bit Error Rate at receiver node B vs. time**

Figure 7. Results for Tx_0 Scenario



(a) Packet received vs. time **(b) Packet Delay vs. time** **(c) Retransmission Attempts vs. time**

Figure 8. Results for Tx_90 Scenario

(Similar results are obtained for Rx_0, Linear, Parallel and X Scenarios)