Effects of Directional Antennas on 802.11e

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Abstract— **Nodes, using CSMA/CA type medium access control (MAC) protocols (e.g. IEEE 802.11e) and omnidirectional antennas, in an ad-hoc network may not be able to transmit packets to each other concurrently due to spatial contention for the shared wireless medium. The maximum network performance depends on the maximum number of possible concurrent transmissions. This can be maximized in a multi-hop ad-hoc network using directional antennas. Neighboring nodes falling outside the transmission region are less vulnerable to co-channel interference. Directional antennas allow increased transmission range by reducing noise, interference and multi-path fading. We emphasize the interference reduction capability of directional antennas in the context of suburban ad-hoc networks (SAHN). We build an analytical model, based on the basic channel access mechanism of IEEE 802.11, to show the effect of interference on network performance along multiple hops using three antenna schemes; multiple fixed directional antennas, omnidirectional antennas with multiple frequency channels and omnidirectional antennas with single frequency channel. We extend our analyses for IEEE 802.11e to accommodate different traffic classes. We also verify our analyses with extensive simulations.**

Keywords– Ad-Hoc Network, SAHN, 802-11e, Directional Antenna, Peak Performance

I. Introduction

In this paper we focus our discussions on network[1] performance using the IEEE 802.11e and multiple fixed directional antennas. Only interference related effects on network performance are presented. Results are compared with the performance of networks using three different antenna schemes. **(1) Scheme O:** Each node is equipped with a single network interface card (NIC) connected to an omnidirectional antenna. Moreover the whole network is operated using the same frequency channel. **(2) Scheme MO-x:** Here x NICs are connected to an omnidirectional antenna. Each NIC is allocated a dedicated frequency channel. **(3) Scheme MD-x:** It comprises of x NICs, each of which has a dedicated directional antenna. The direction and range of transmission and reception are set so that the transmission from an antenna can be heard only by the designated receiver. Therefore the network performance is not affected by the frequency channel allocations of the corresponding MD-x scheme.

An omnidirectional antenna scheme may provide more connecting links than a directional antenna scheme if nodes in a network are located within each other's transmission range. However, closely located nodes are very likely to face co-channel interference during simultaneous transmission. The number of collisions and packet drops increases and hence the network performance degrades. A directional antenna scheme may provide fewer links in a network. This may seem to cause poor routing performance, but we believe that using directional antenna schemes can outperform omnidirectional antenna schemes. Our simulation results support this.

Omnidirectional antennas radiate energy in all directions. For a given transmission power, the range using omnidirectional antennas is lower than when using directional antennas. Ad-hoc routing algorithms with omnidirectional antennas and fixed transmission power have an upper bound to the number of intermediate hops between a pair of source and destination. Directional antennas may resolve this problem using the same amount of transmission energy. They can focus beams at narrow angles. This can decrease channel interference of other nodes falling beyond the transmission angle, increase the transmission range and contribute to bridging voids in a network. Gain of a directional antenna over its omnidirectional counterpart depends on how narrow the primary beam (lobe) is. Interference by secondary lobes can reduce the effective transmission range of the primary lobe. In this paper, we ignore the effects of secondary lobes.

We discuss some related works in Section II and give an outline of our simulation setup in Section III. Then in Section IV we present a simple, yet efficient, analytical model to investigate the effects of various antenna schemes on the network performance related to a SAHN. We extend our investigation with extensive simulations in Section V. Finally we conclude our paper with future research directions.

II. Related Work

Nasipuri et al [7] have used directional antenna elements intelligently in order to minimize routing overhead. Ramanathan [8] has discussed the possibilities of taking advantage of higher transmission ranges of beam-forming antennas. Bandyopadhya et al [9] have proposed a proactive routing algorithm over an ESPAR (Electronically Steerable Passive Array Radiator) antenna.

Roy et al [10] have optimized DSR (Dynamic Source Routing [11]) to efficiently perform in ad-hoc networks using directional antennas. Furthermore, a simple MAC protocol, called DiMAC, was proposed to enhance the performance of the routing protocol.

Marvin [12] has proposed a combined routing and

[1]Networks such as SAHN[1][2][3][4][5][6].

scheduling procedure to improve performance of STDMA (Spatial Time Division Multiple Access) in multi-hop adhoc networks (both rough and flat terrain) with smart antennas. He has also investigated the possible performance gain in CSMA with handshaking using a simple Switch Beam antenna system as the smart antenna technology.

Takata et al [13] have proposed a MAC protocol, IEEE 802.11 distributed coordination function (DCF), called SWAMP for ad-hoc networks using smart antennas. SWAMP uses a dual access mode. It takes the advantages of the spatial reuse capability of wireless channels and longer transmission ranges offered by smart antennas. Simulation results show that SWAMP exhibits high throughput, low end-to-end delay and low overhead compared to the IEEE 802.11 and DiMAC.

Fahmy and Todd [14] have proposed a MAC protocol for ad-hoc networks with adaptive smart antennas. The protocol uses omnidirectional transmission with directional reception and is referred to as selective CSMA with cooperative nulling (SCSMA/CN). The proposed protocol accommodates the active nulling of co-channel interferers which may arise while transmissions are in progress. This is achieved using a three-way handshake where neighboring nodes cooperate during link activations and thus allow the designated receiver to dynamically null potential future interfering packet transmissions.

Kong et al. [15] and Robinson and Randhawa [16] have proposed analytical models based on discrete Markov processes for in-depth understanding of the working mechanism of IEEE 802.11e. Though these models can be used as a predictive tool for QoS provisioning in single-hop adhoc networks, it is not obvious how they can be applicable in the context of multi-hop ad-hoc networks and directional antennas with different classes of traffic.

Islam et al [4] have investigated the effects of various antenna schemes, based on the legacy IEEE 802.11, on a routing protocol for SAHN. It does not present any analytical model that can be used to capture the effect of interference on routing performances along multiple hops for using different antenna schemes.

Apart from building an analytical model to show the effect of interference on routing performances along multiple hops for using different antenna schemes, we want to get the maximum performance results achievable to consider as a benchmark for evaluating various MAC and routing protocols optimized for a SAHN. None of the previous works has explored these areas within the context of multiple hops, IEEE 802.11e and SAHN.

III. Simulation setup

Throughout this paper, if not mentioned explicitly, we have considered the following setup for our analyses and simulations. We have used GloMoSim (version 2.02) for simulating various layers and wireless media. Nodes are separated by at most 240 meters, use the same transmission power with a transmission range of 240 meters and use IEEE 802.11e in the link layer. The physical layer modulates/demodulates signals using OFDM (Orthogonal Frequency Division Multiplexing) with a transmission rate of 54 Mbps. Each session consists of CBR (Constant Bit Rate) traffic using UDP and routed using DSR.

IV. Performance Evaluation (Phase 1)

In this section we build an analytical model, based on the basic channel access mechanism of IEEE 802.11, to show the effect of interference on network performance along multiple hops using three antenna schemes. Then we extend our analyses for IEEE 802.11e to accommodate different traffic classes.

First of all we build an analytical model based on a single session S, established between A and G in Figure 1. Then we discuss our model for IEEE 802.11e by considering two sessions with different ACs and verify the analyses with simulation results.

Consider the network shown in Figure 1(a). Here each node communicates with its neighbors using the antenna scheme O. Transmission range (represented by the dotted circle) of each node is same and can be heard by at most one neighbor in each direction. Since the network operates under the same frequency channel and each node transmits and receives using an omnidirectional antenna, each data packet exchange between two neighbors (say B and C) prevents other nodes, neighboring the communicating neighbors (i.e. A and D), from transmitting and receiving. Each rectangular box in Figure 1 shows the span of such interference for exchanging a single data packet between two neighbors. With an omnidirectional antenna both the communicating neighbors transmit in all directions. Therefore the interference zone for transmitting a single packet in the O and MO-x scheme spans up to 240×3 meter in diameter. In our work we assume that the overlapping of two interference zones, having the same frequency channel, within the same time space causes a collision and hence results in loss of packets.

The steps in Figure 1(a) indicate that packet transmissions of S (denote S by S_O for the antenna scheme O) can avoid collisions if each packet is sent at an interval no less than $T_4 - T_1$. Ideally if the number of intermediate nodes was reduced to 1, the session could send packets at an interval of $T_2 - T_1$ without any collisions. This would allow three times more load than the previous one. Therefore, due to the nature of the antenna scheme O, the achievable performance of a session may decrease as the number of intermediate nodes increases.

Now we will see how network performance is affected using an MO-2 antenna scheme. Figure 1(b) and 1(c) represent two such networks with different channel allocations. The number of non-overlapping channels in each case has been restricted to two. Both networks could perform similarly to MD-2 if the channels were allocated in a way so

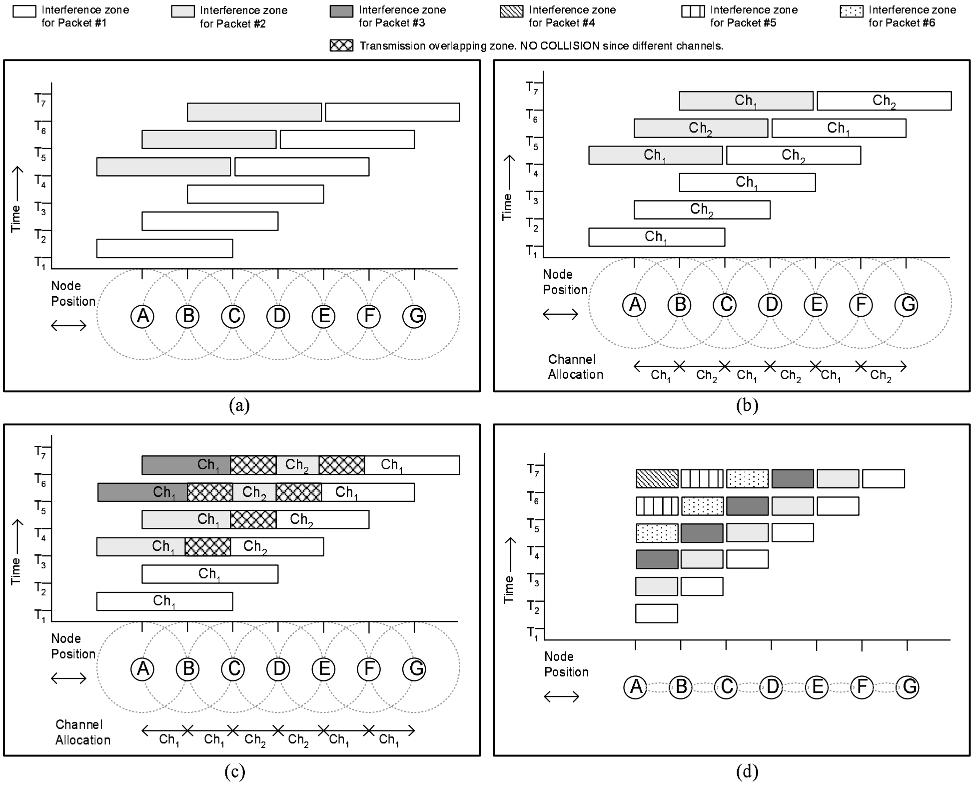


Fig. 1. An analytical model, based on the basic channel access mechanism of IEEE 802.11, that shows the effect of interference on routing performances along multiple hops for using O, MO-2 and MD-2.

that channel reuse was permitted at 4-hop neighbours instead of 3.

Let the variant of S, used in Figure 1(b) and 1(c), be denoted by S_{MO-2}. Due to the channel allocations of Figure 1(b), the MO-2 scheme cannot offer more load to S_{MO-2} than S_O. The alternate channel allocation of Figure 1(c) solves the problem to some extent since here S_{MO-2} can send packets at $T_3 - T_1$ time units intervals which is 3/2 the load offered to S_O. Though the transmissions in Figure 1(c) at $T_3 - T_1$ time units intervals overlap (shown with cris-crossed rectangle), they do not collide since these transmissions use different frequency channels.

An MD-2 scheme can improve the performance of S if the antennas are beam formed in such a manner that transmission of one node node can be heard by at most one neighbor. The dotted ellipses in Figure 1(d) shows the interference zone of each antenna element. Let S_{MD-2} denote the variant of S used in Figure 1(d). Due to the spatial separation of interference zones by directional beams, it is possible to send a new packet from a node just after the previous one reaches its neighbor. Hence the packet transmission interval can be reduced to $T_2 - T_1$ which can offer three times more load to S_{MD-2} than S_O. This also indicates that increasing the number of intermediate nodes may not degrade the network performance except for adding additional transmission and queuing delays.

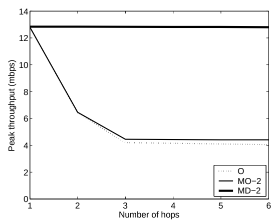
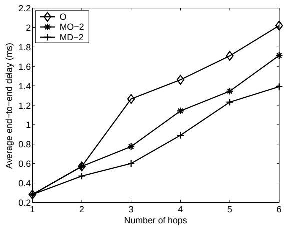


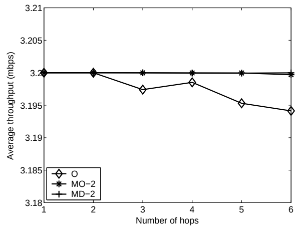
Fig. 2. Peak throughput with varying hops and antenna schemes.

We have verified the above analyses by simulating S_O, S_{MO-2} and S_{MD-2} separately over multiple hops. AC and packet size for each session was AC_VO and 400 bytes respectively. With this configuration the theoretical peak throughput for a single hop network is almost 13.6[2] mbps. Simulation results (Figure 2) show that this peak performance was achieved with the S_{MD-2} scheme regardless of the number of intermediate nodes. However, for S_O and S_{MO-2} the peak throughput degraded with increasing

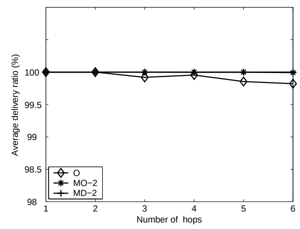
[2] $T_{DATA} = 20 + 4 \times \lceil \frac{16+6+8\times(34+400)}{216} \rceil = 88$ μsec [17], $T_{RTS} = T_{CTS} = T_{ACK} = 24$ μsec, aSlotTime = 9 μsec and $T_{SIFS} = 16$ μsec. So total time taken for a single packet transmission is 208 μsec and the peak throughput is around $\frac{400*8}{AIFS[AC\_VO]+CW_{min}[AC\_VO]/2+208} = 13.6$ mbps.



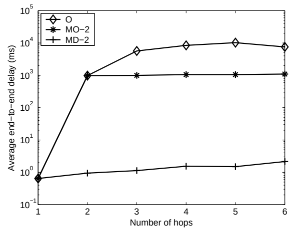
(a)Results for AC_VO



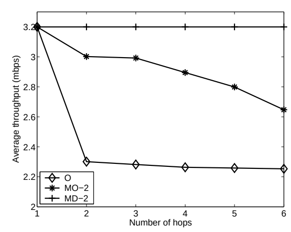
(b)Results for AC_VO



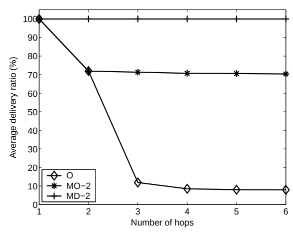
(c)Results for AC_VO



(d)Results for AC_BK



(e)Results for AC_BK



(f)Results for AC_BK

Fig. 3. Comparing the effects of O, MO-2 and MD-2 on network performance with varying hop counts.

number of intermediate nodes and converged to almost 1/2 and 1/3 of the initial peak value respectively.

So far we have considered only a single session. Now we will discuss different antenna schemes with multiple sessions that originate from the same node and operate in different ACs. For simplicity let us consider two sessions denoted by $\mathrm{S_{AC1}}$ and $\mathrm{S_{AC2}}$ where AC1 denotes a higher AC than AC2.

Assume that all sessions transmit packets at an interval of $\mathrm{T_4 - T_1}$. From the previous analyses we can claim that with the indicated load there should not be any collision for a single session. However in 802.11e if there are packets in both output queues of AC1 and AC2, the packet with AC2 faces a virtual collision and waits for a random time (based on the contention window size and back-off counter) before it can be transmitted. Since the waiting time of packets in different ACs differs due to virtual collisions, there could be instances where packets of different ACs can compete for the channel within the time interval less than $\mathrm{T_4 - T_1}$. This may result in real collisions and create further randomness in the transmission schedule. Consequently there could be more collisions and the performance of each session will degrade depending upon the offered load. We have already seen that for $\mathrm{S_O}$, $\mathrm{S_{MO-2}}$ and $\mathrm{S_{MD-2}}$ the critical period for collisions (CPC) are $\mathrm{CPC_O = T_4 - T_1}$, $\mathrm{CPC_{MO-2} = T_3 - T_1}$ and $\mathrm{CPC_{MD-2} = T_2 - T_1}$ respectively. Since $\mathrm{CPC_O > CPC_{MO-2} > CPC_{MD-2}}$, for a given load and the same number of multiple intermediate nodes, $\mathrm{S_{AC1}}$ and $\mathrm{S_{AC2}}$ are expected to perform worst for the antenna scheme O and best for the antenna scheme MD-2.

To verify the aforementioned analyses related to multiple sessions with different ACs, we have simulated $\mathrm{S_{AC1}}$ and $\mathrm{S_{AC2}}$ simultaneously with varying hop counts and antenna schemes. Figure 3 shows the simulation results. AC1 and AC2 were replaced with AC_VO and AC_BK respectively. Each session was offered a load of 3.2 mbps. With this setup the MD-2 scheme showed almost stable performance compared to the other schemes with varying hop counts. The average end-to-end delay for the MD-2 scheme seemed to increase with increasing the number of intermediate nodes since each additional intermediate node is responsible for adding extra queuing and transmission delays to the overall end-to-end delay.

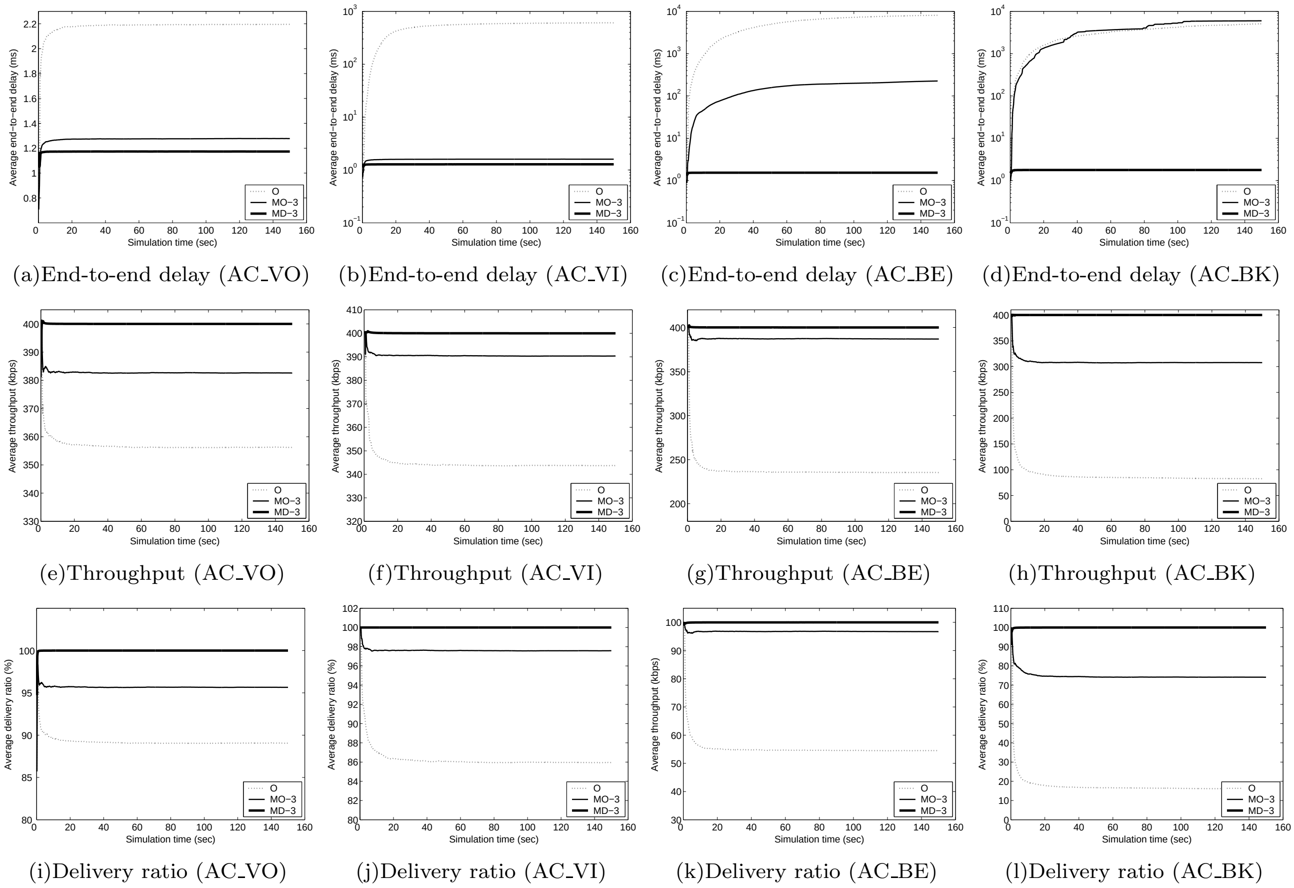
V. Performance Evaluation (Phase 2)

Here we investigate effects of different antenna schemes on multiple sessions with different ACs and hop counts.

77 nodes were placed on a 3000 meter by 3000 meter flat terrain where each node had at most 6 neighbors. We have used all three antenna schemes (namely O, MO-3 and MD-3) with the same transmission range. In the whole network three distinct non-overlapping frequency channels were used for the MO-3 scheme. Allocation of channels to MO-3 antenna elements was done randomly. On average, each antenna component had two neighbors. The number of links in the network remained the same. However, in the MD-3 scheme a node was allowed to communicate with at most three neighbors which effectively reduced the degree of connectivity per node.

For each source and destination pair we have four sessions with different initiation times and ACs (namely AC_VO, AC_VI, AC_BE and AC_BK). Each session had a load of 400 kbps where each UDP payload was 400 bytes long. New sessions were introduced every 20 ms.

The comparisons were conducted by keeping the number of sessions and their initiation time, and the communicating node pairs and their total numbers fixed. Though the



(a)End-to-end delay (AC_VO) (b)End-to-end delay (AC_VI) (c)End-to-end delay (AC_BE) (d)End-to-end delay (AC_BK)

(e)Throughput (AC_VO) (f)Throughput (AC_VI) (g)Throughput (AC_BE) (h)Throughput (AC_BK)

(i)Delivery ratio (AC_VO) (j)Delivery ratio (AC_VI) (k)Delivery ratio (AC_BE) (l)Delivery ratio (AC_BK)

Fig. 4. Effects of O, MO-3 and MD-3 on network performance. Hop count of each session for O and MO-3 is 3 and for MD-3 is 5.2.

hop count for each node pair was fixed for O and MO-3, it was increased to some extent while using MD-3 due to its reduced connectivity.

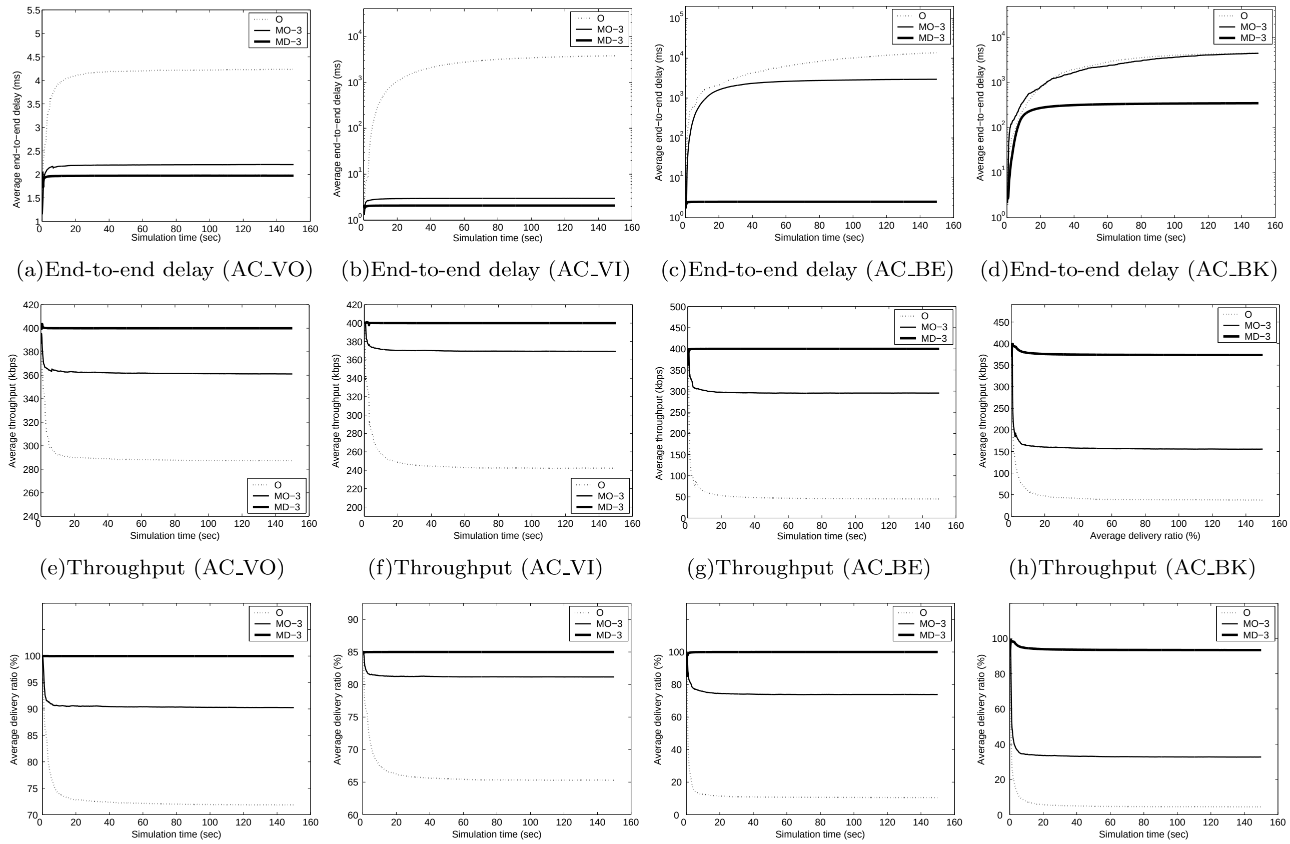
The communicating node pairs were evenly distributed over the whole network. This was to reduce the effect of network congestion on the network performance for overlapping sessions so that only the interference related effects become prominent.

Each simulation was executed for 150 s. We have logged the values of various performance metrics every 200 ms. Each graph in Figures 4 and 5 compares the logged values of the respective performance metric of various antenna schemes. The simulations corresponding to Figure 4 consisted of 27 pairs of sources and destinations with 4 sessions each (i.e. total 27×4 sessions) with a hop count of 3 for O and MO-3. The average hop count for the MD-3 scheme increased to 5.2 due to reduced connectivity. In Figure 5, the total number of sessions, the hop count for O and MO-3 and the average hop count for MD-3 were 19×4, 5 and 8 respectively.

Since only the interference related effects on the network performance were dominant, the performance results corresponding to the MD-3 scheme were fairly stable irrespective of total load of the network and the increased number of hops compared to O and MO-3. The MO-3 scheme showed better performance over the O scheme. However both of them suffered from interference related performance degradation.

VI. Conclusion

We have built an analytical model, based on the basic channel access mechanism of IEEE 802.11 to show the effects of interference on network performances along multiple hops for using three antenna schemes within the context of a SAHN. We have also extended our analyses for IEEE 802.11e to accommodate different traffic classes and verified our analyses with extensive simulation results. It was evident that using directional transmissions and receptions, interference related performance degradation can be reduced considerably. During this study we have used multiple fixed directional antennas and assumed that there is at least one route from a source to its destination. If no route exists in configured directions antennas may need to be redirected. This may be difficult with multiple fixed directional antennas. Moreover, multiple fixed directional antennas may be expensive to buy and install. A smart



(a)End-to-end delay (AC_VO) (b)End-to-end delay (AC_VI) (c)End-to-end delay (AC_BE) (d)End-to-end delay (AC_BK)

(e)Throughput (AC_VO) (f)Throughput (AC_VI) (g)Throughput (AC_BE) (h)Throughput (AC_BK)

(i)Delivery ratio (AC_VO) (j)Delivery ratio (AC_VI) (k)Delivery ratio (AC_BE) (l)Delivery ratio (AC_BK)

Fig. 5. Effects of O, MO-3 and MD-3 on network performance. Hop count of each session for O and MO-3 is 5 and for MD-3 is 8.1.

directional antenna can be an alternative solution at low cost. The performance results encourages us to build a SAHN specific MAC protocol that is capable of integrating smart directional antennas efficiently.

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