Evaluation of Directional (Transmitting and Receiving) Algorithms in Wireless Ad Hoc Networks with Directional Antennas

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ABSTRACT

In the literature, we showed the simulation results of an all directional transmission and reception algorithm, proposed in Zhang (2015), (named as LiSL/d for a link scheduler) in mobile wireless ad hoc networks with directional antennas. Mainly these methods of algorithms were proposed for military purposes and utilize the beam forming capabilities of smart antennas to tailor resource access according to the services desired for individual traffic flows while some limiting interference, probability of detection and jamming in the network. Especially, the proposed protocol serves four significant advantages: (1) it assumes specially directional transmission/reception (no omni-directional or omni-capability is assumed at all), (2) it is distributed, that is, it utilizes local information only, (3) which administer different slots to link dynamically based on demand, (4) power control is easily carried out during neighbour discovery, reservation as well as data trans- mission period with very little overhead. To analyze the performance of this algorithm against with IEEE 802.11 omni protocol and the directional virtual carrier sensing (DVCS) protocol, exhaustive simulations have been done in QualNet, especially for the Lakehurst framework and some random network topologies. Results of simulation show that without jamming both LiSL/d and DVCS improve the network performance to the extent of 3 times and LiSL/d also out performs DVCS. Whenever there is jamming, mainly depending on the power level of jamming nodes, the percentage of packet received under LiSL/d can be 7 times higher than that of DVCS and IEEE 802.11 with omni-directional antennas."

Keywords - Directional Antennas, Ad hoc Networks, MANET, MAC, Neighbour Discovery.

1. INTRODUCTION

Recently there has been very strong interest among researchers to utilize high-gain, directional antennas for both transmission and reception in wireless-ad hoc-networks. Directional antennas used in both ends felicitate more transmission range and higher data rate. They strongly reduce signal interferences in unnecessary directions and reduce jamming susceptibility and lesser probability of detection (LPD) by limiting the dispersion and detection of energy to desired regions. The additional gain provided by directional transmission and reception can enable communication between distant nodes, thereby reducing the diameter of a network. Additionally, space usage is more likely to increase because multiple paired transactions cannot be set up at the same time.

Therefore, a mobile wireless network with smart antennas is expected to be able to reap significant improvements in performance in terms of the quality of service (end-to-end delay and throughput) provided to individual traffic flows and its capability to thwart jamming and detection by hostile entities. However, the profitability of a particular network depends on the capabilities of the antenna, transmitter, receiver, and algorithm used. Extensive research has been done on control algorithms (MAC) in wireless ad hoc networks using directional antennas. However, all the previous work predicts omni-directional reception at some stages of the algorithms (neighbour discovery, reservation or scheduling). The omni-receive requirement, however, makes the convention vulnerable to jamming. Also, in some communication networks, an omni-antenna might not be available. If there is even one omni-directional frame in the convention between transmitter and receiver, then the directional transmission must be in prescribed limit for the coverage of the omni antennas. It becomes therefore necessary to design some algorithms for directional transmission and reception in wireless ad hoc networks. Previous literatures on MAC in networks with directional antennas have covered a range of approaches including slotted ALOHA (Zander, 1990) CSMA/CA (Ko *et al*., 2014), as well as TDMA (Dyber and Farman, 2015; Bao and Garcia-Luna-Aceves, 2015). These TDMA approaches in (Dyber and Farman, 2015; Bao and Garcia-Luna-Aceves, 2015) make slot reservations based on traffic load but do not dynamically adjust reservations as load change; neither approach provides acknowledgements for data packets received. Mainly all of the literature on scheduling multi- point transmissions has been done in the context of TDMA-based networks with omni-directional antennas. Various researchers focus on the distributed scheduling algorithms that can accommodate changes in a node's neighbourhood (caused by movement, obstruction or interference) without global recalculation of transmission schedules (Bao and Garcia-Luna-Aceves, 2016; Ali *et al*., 2016; Steenstrup, 2016). In (ElBatt *et al*., 2017), switched beams antennas (fixed and pre-defined) are considered. They identify a few problems with the previous MACs and propose that RTSs are sent out only on unblocked beams. Nodes receive omni-directionally. Reservation packets carrying “directional info” are sent to as many neighbours as possible (instead of only a subset).

DVCS (Directional Virtual Carrier Sensing) proposed in (Takai *et al*., 2014) is an extension of 802.11 MAC (CSMA/CA: time- asynchronous). Each node caches estimated AOA (angle of arrival) of neighbours when hearing from other nodes. If AOA is known, a node transmits RTS control frames directionally, otherwise, omni-directionally. Nodes listen omni-directionally when idle. AOA is updated every time a new signal is received and is deleted if it fails to get CTS after four directional transmissions. Data are transmitted directionally after CTS is received (beam locking). Directional NAV is associated with a direction and beam width.

Multiple directional network allocation vectors (DNAV) can be set for a node. The multi-hop RTS MAC (MMAC) protocol proposed in (Choudhury *et al*., 2014) is a technique of using smart antennas to establish a multi-hop link through the RTS/CTS hand- shake. In multi-hop RTS MAC convention, nodes keep profiles of the neighboring trans-receiver directions. Whenever a new data request arrives at the MAC layer, the MAC initiates carrier sensing in the direction of the intended receiver. If the channel is idle in that direction, the MAC then issues a directional RTS to the next hop in the path to the destination. Nodes on the path to the destination forward this RTS message directionally until the RTS reaches its destination. (The intermediate nodes on the path are neighbours discovered using omni-directional reception.) The destination then replies with CTS directly to the sender and the two establish data communication.

In (Cain *et al*., 2016), the authors propose an architecture that includes a high-speed mission data channel with an adaptive TDMA link scheduling protocol and an omnidirectional neighbor detection channel. The programming protocol is designed to take advantage of high gain directional antennas. Link planning adapts to changes in neighboring topologies caused by node mobility and link failures. However, the protocol still requires a separate omnidirectional control channel and is vulnerable to detection and interference.

The algorithm proposed by the researchers in (Zhang, 2015) prepares link as opposed to node scheduling, it needs information/data only from one hop neighbours to schedule a transmission; only the available slots at the both ends are required to generate a transmission schedule for the link that is conflict-free. The main features that distinguish our search engine algorithm from others mentioned in the research article are its considerations on the direction of transmission / reception (no omni-antennas or omni-activated devices) in the system and the possibility of select the gaps. When choosing a place to reserve, examine the space coverage, consider the placeholders, and use information that comes from parts of the house the person was left behind or from an unintended recipient.

2. REVIEW OF LiSL/D

In this section, we will review the key components of the LiSL/d (Link Scheduler for Directional antenna) protocol proposed in (Zhang, 2015; Steenstrup, 2016). The protocol consists of neighbour discovery and link scheduling. Readers are referred to (Zhang, 2015) for more details.

2.1 FRAME STRUCTURE

Time is divided into frames, and each frame is divided into 3 sub-frames. As illustrated in Figure 1 the first sub-frame is devoted for neighbour discovery for detecting new nodes or nodes moved away. The second sub-frame is used for two nodes to reassure their connection detected during the neighbour discovery and to make data reservation. The third sub-frame is used for actual data transmission. Each sub- frame is divided into slots. Each slot within the neighbour discovery/reservation period consists of multiple mini-slots.In both he neighbour discovery and reservation periods we need a three-way handshaking for the purpose of power level negotiation and reservation confirmation. Each mini-slot can accommodate three-way handshaking messages used in both the neighbour discovery and reservation. We assume that there are n mini- slots in the first sub-frame and r mini-slots in the second sub- frame. The values of n and r may be different and can be con- figured during the network configuration time. The third sub- frame has M slots (see Figure 1).

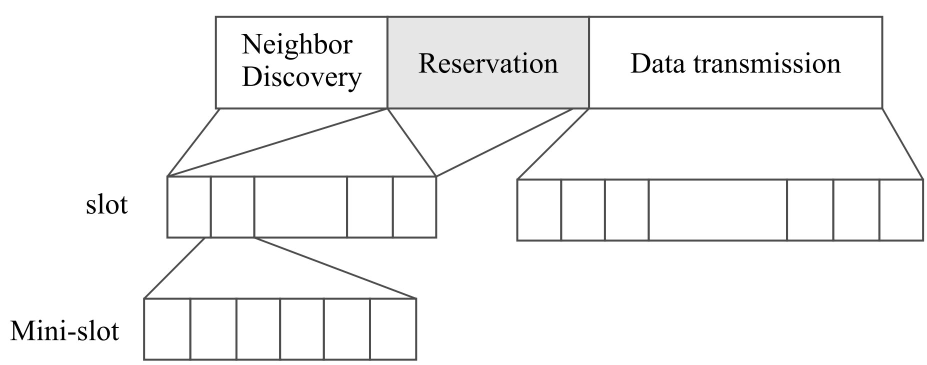

Figure. 1 TDMA frame structure

2.2 NEIGHBOUR DISCOVERY

In this section, we briefly review the neighbour discovery algorithms; details can be found in (Zhang, 2015; Steenstrup, 2016). Ongoing neighbour discovery occurs in the first sub-frame in Figure 1.

2.2.1 SCANNING FOR NEIGHBOURS

For presentation purpose, we assume that a pair of nodes with directional antennas can communicate directly provided that the straight line connecting them is contained within both the current transmit beam of one node and the current receive beam of the other node. It is essential condition that, both the nodes must point their beams towards each other, must in the complementary transmitter /reception mode in this network, communications take place in three dimensions between terrestrial and airborne, along with terrestrial nodes located at various elevations and altitudes. In place of narrow-beam antennas, two nodes require the two beams point in opposite directions, as well as complementary mode. We define a scan that induces a minimal covering distance of the entire search volume (e.g., a hemisphere) and the beams of width ω cantered over each of the pointing direction. Within each scan, nodes follow the predefined sequence, possibly in opposite polarities. When scanning, a node transmits an advertisement in each specified direction. When listening, a node waits for advertisements. If a listening node receives an advertisement, it responds directionally with its own advertisement, and expects to receive an acknowledgement in return, all with a short time interval. Each portion of this three-way handshake can be used to exchange transmission power level information and refine directional information.

2.2.3 MODE SELECTION

A node might detect all of its potential neighbours within a single scan of the sequence of directions, but it will usually require multiple scans to find them. The lower and upper limits on the number of scans necessary for every nodes in the net- work to search all of their potential neighbours depends on the characteristics of the achievable network graph and the algorithm a node uses to select its mode, scanning or listening, for each scan. Here we present a deterministic mode selection algorithm. Each node is initialized with parameters N and j, where $j \in \{0,...,N-1\}$(its unique identifier) and N is the maximum possible number of nodes in the network. Each node's ID, j, is coded into a binary form. If the number of digits is less than [log2 N], 0's is added to the left up to [log2N] digits. For example, if N=16, and j=3, its binary form is 0011. For scan i, if the ith digit is 0, it chooses listening mode and if it is 1, it chooses scan mode. Thus, during the first scan, a node has the opportunity of detecting one-half of its neighbours in the network (if they are within the reachable range). It can be easily proved that, for any two nodes, there is at least one different digit in their binary code, which in turn implies that the two nodes can be detected by each other in at most [log2N] scans if they are within the reachable range.

2.3 LINK SCHEDULING

The frame structure of LiSL/d is shown in the Figure 1. To avoid collision and to reduce waiting time for making reservation, we developed a 2-step reservation algorithm. During neighbour discovery, a time slot is agreed on which a reservation can be made and nodes can re-detect each other (to up- date their location, power level, etc). Actual reservations are made at their agreed time slots during each frame, which ensure that new reservation can be made within one frame time. During the neighbor discovery process, when a scanning node and a listening node detect each other through a three-way neighbour-discovery hand-shake, they negotiate with each other in search for a commonly free future slot in the so-called "make reservation" sub-frame. If such a slot is available, the two nodes reserve it, i.e., associate a snapshot of their current configuration, including especially the direction of antenna and power, with this slot. In other words, a link (between these two nodes) is reserved. As the time of this slot arrives, the two nodes will adjust their power, steer their antennas accordingly and initiate another three-way make-reservation (for data transmission slot) handshake. During the make- reservation hand-shake, they will negotiate with each other in search for a number of commonly free future slots in the so- called "data-transmission" sub-frame for actual data transmission. If a set of free slots is available, the two nodes reserve them, i.e., associate a snapshot of their current configuration. When there is mobility and/or packet loss because of collision, error in power/direction estimation, etc., the configuration information (established during the neighbour discovery sub- frame or previous re-visit/make reservation sub-frames) may be inaccurate or invalidated. In such case, two nodes may not be able to actually utilize the slots they reserved earlier. In order to mitigate the impact of mobility, "spiral search" combined with "best-effort direction estimation with rough location information" will be applied during the re-visit and make- reservation sub-frames. If the current power level either has unnecessary coverage or fails to deliver packets to intended nodes, power adjustment will be applied. Therefore, sufficiently accurate power estimation methodologies are desirable.

3. SIMULATION RESULTS

To evaluate the performance of LiSL/d and compare its performance with IEEE 802.11 MAC (omni) and DVCS, we carry out extensive simulations. We study their performance under two network (topologies and mobility) scenarios.

3.1 RANDOMLY SELECTED NETWORK TOPOLOGY WITH RANDOM WAYPOINT MOBILITY

In this set of simulations, we assume that there are 25 nodes in the network, randomly located in the range of 2000 x2000 m2. We simulated two cases: no mobility and mobility with a maximum speed of 10 miles/hour. When there is mobility, we assume that the mobility pattern is random waypoints. The link capacity is 5.5Mbps. Since the transmission is half- duplex, the capacity in one direction is about 2. 7Mbps.The traffic demand is assumed to be among 6 node-pairs, each node pair requires a constant bit rate (CBR) flow. The band- width required for each flow varies from 0 to 65% of the link capacity. The power used in both IEEE802.11 (using omni- directional antenna) and LiSL/d is assumed to be the same. We assume that the number of mini-slots in one slot is 3, and the duration of a slot is 3 ms. The duration of a frame is 100 slots. The number of slots allocated for neighbour discovery is 5, and the number of slots for reservation is 4 and the remaining 91 slots are allocated for data transmission. For each set of the simulation, we take the average of 10 runs, using different seeds to generate the random numbers.

Two existing routing protocols: AODV (Perkins *et al*., 2015) and OLSR (Clausen *et al*., 2016) are considered. AODV is an on-demand routing protocol and OLSR is a proactive routing protocol. In the routing protocols considered, broadcast is used to find or update route information. In the directional transmit and receive algorithm, this broadcast feature is realized by sending the same packet sequentially (by changing different directions of the antenna). In Figure 2, the throughputs of four different combinations of the MAC and routing algorithms: IEEE 802.11-AODV, IEEE 802.11-OLSR, LiSL/d-AODV and LiSL/d-OLSR, are plotted assuming there is no mobility. From the figure, we notice that the throughput under LiSL/d-AODV is about 4 times of that under IEEE 802.11-AODV. The improvement under LiSL/d over the IEEE 802.11 omni-directional is therefore obvious. The throughput under LiSL/d-AODV is also higher than that under LiSL/d-OLSR, one of the reasons is that when there is no mobility, the route does not change, and since AODV is on-demand routing, the overhead for route search and maintenance is therefore lower under AODV compared with OLSR.

InFigure3,thethroughputsofthesamefour combinations of the MAC and routing algorithms are plotted assuming that the nodes move according to the random-waypoint mobility model. In this case ,the through put under LiSL/d-OLSR is higher than that of LiSL/d-AODVandisabout3 times of the throughput under IEEE802.11-AODV(OLSR),which indi- cates that our LiSL/d handles mobility very well. When there is mobility, routes change constantly, the advantage of the proactive routing protocol, OLSR, becomes clear. Note that when the traffic is light (less than about 15% of the link capacity), the throughput under LiSL/d-AODV (OLSR) is slightly lower than that under IEEE802.11.There as on for this is that there is an overhead of broadcasting those updating packets for the routing protocol to establish routes under the directional antenna case as these broadcasting packets must be transmit done by one sequentially. Also, packets have to wait till its reserved data slot for transmission. When the traffic load is light, under IEEE 802.11, which uses omni-directional antenna for broadcasting and doesnot require reservation, packets can be transmitted sooner. However, as the traffic load become sheavier, the benefits of directional antenna and scheduling offset the overhead and hence yield higher throughput.

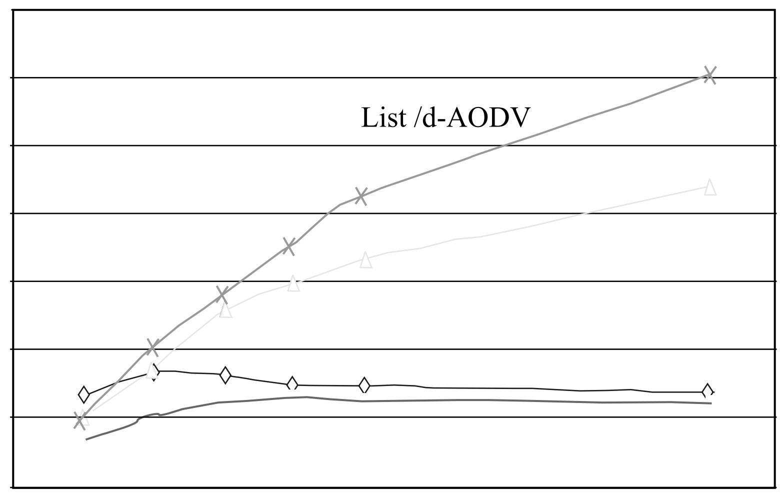

Figure 2. Aggregatethroughput versus traffic load, without mobility, no jamming

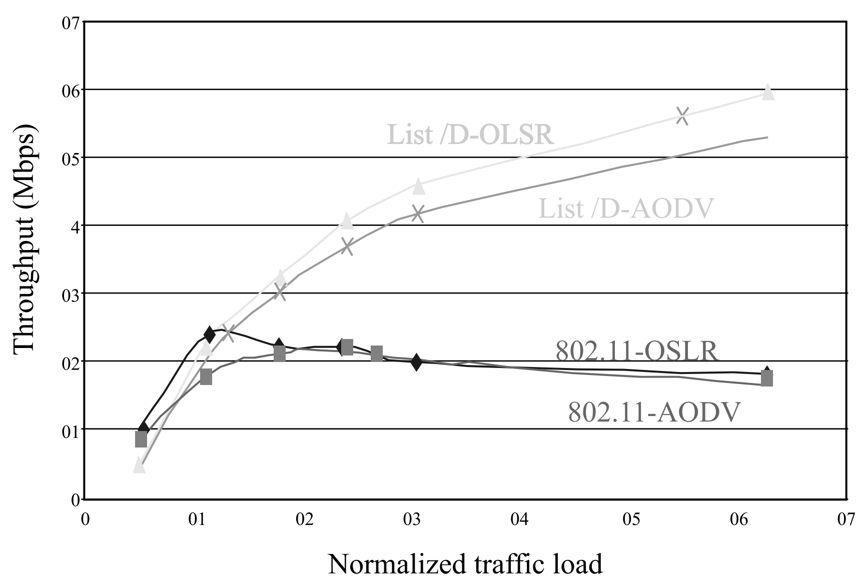

Figure 3. Aggregate throughput versus traffic load, with mobility, no jamming

3.2 LAKEHURST SCENARIO:

The Lakehurst Scenario (Hsu *et al*., 2013), located at Lakehurst Naval Air Station(NAS) in NewJersey, consists of 20 nodes (1base station and 19 mobile nodes) in dual counter rotating rings with 5 inner and 14 outer loop nodes. The duration of the simulation is about 4 hours with a channel band width of 2Mbps. The traffic modelling is done by using the Qual Net MGEN traffic generation scripts. The Multi-Generator (MGEN) is an open source software specially used by the Naval Research Laboratory (NRL) Protocol Engineering Advanced Net- working(PROTEAN) Research Group. The network game can be different ways to set the direction device generates traffic patterns. The four ships of one the species in the different data traffic to be weighed dispassionately.

Flow Type: 0 is the low rate uni-directional traffic to the Base Station generated in every 300 Seconds. Total of 15 flows with average of 0.8kbps is generated with packet size of 100 bytes. Flow Type: 1 is the low rate 1KB Random Unidirectional traffic to the Base Station. Total of 4 flows with average of 40kbps is generated with packet size of 1024bytes Flow Type: 100 is the low rate 1KB Random Bidirectional traffic between the Mobile Nodes. Total of 69 flows with average of 40kbps is generated with packet size of 1024 bytes Flow Type: 200 is the High rate 1KB Bidirectional traffic between the Mobile Nodes generated at regular intervals. Total of 6 flows with average of 200-120kbps is generated with packet size of 1024bytes.

The performance of LiSL/d is compared with one of the previously developed directional antenna MAC protocols, directional virtual carrier sensing (DVCS) (Takai *et al*., 2014) and Omni 802.11 MAC. Two sets of simulation results are presented. One with- out jamming and the other with a white noise jammer modelled in Qual Net MAC/PHY. The jammer would continuously, within each tiny interval, broadcast radio signal with the same channel frequency to create a lot of interference to the passing signals. The effect of the jammer on the network performance is investigated by varying the power level of the Jammer. The plots show the comparison of the protocols based on the percentage of packets received (total number of packets received/total number of packets transmitted). The traffic load is 5 times of the original MGEN data traffic. The routing protocol used in the simulation is AODV. The beam width of the antenna beam is assumed to be 5 degree in all the figures In Figures 4-6,the non-jammer case is presented. From the figures, we observe that without jamming, the performance improvement of both directional protocols (LiSL/d and DVCS) over omni-directional antenna protocol is about 3 times for both high-rate and low-rate traffic types. Further- more LiSL/d also slightly out performs DVCS. Figure 4 and Figure5, show the percentage of packets received for the aggregate traffic for all nodes in the network and for high data flow between nodes 13 and 14 (packet size of 1024 bytes), respectively. In Figure 6, the percentage of the packets received for high data flow from node 19 to node 1 and low data flow from node 19 to node 20 are plotted. It can be observed that for lower data flows, all three protocols perform about the same and for high data rate flow, directional protocols outperform omni-directional protocol.

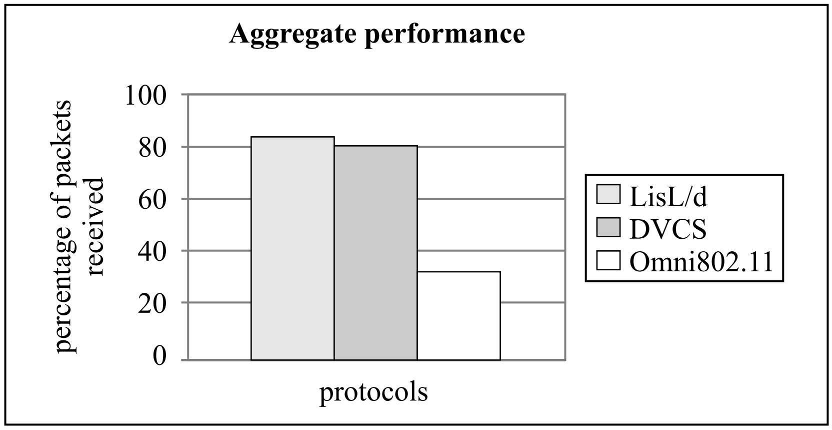

Figure 4 : Percentage of packets received for the aggregated traffic under different protocols (without jamming)

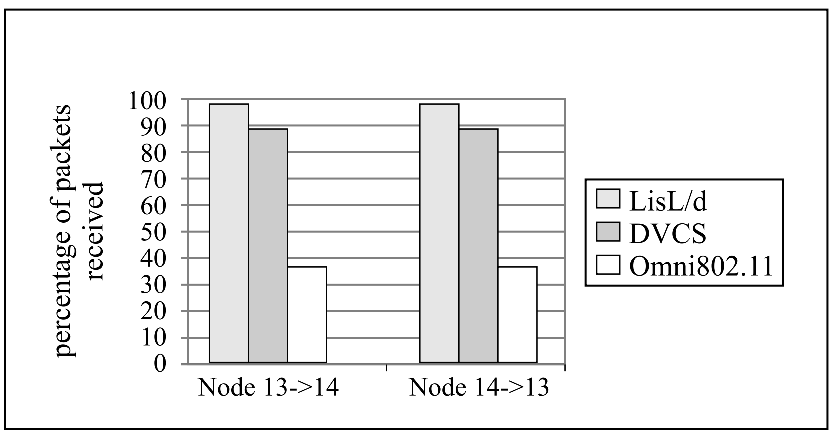

Figure 5 : Percentage of the packet received for high data flow between nodes 13 and 14 under different protocols

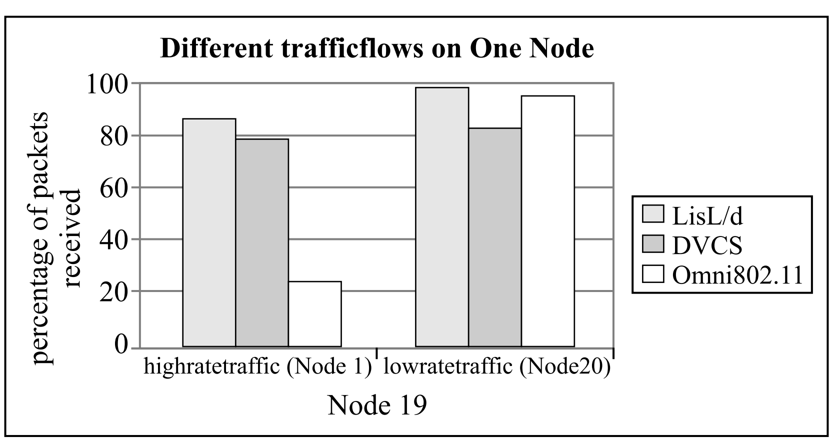

Figure 6 : Percentage of packets received for node 19, high data rate flow to node 1 and lower date rate flows to node 20

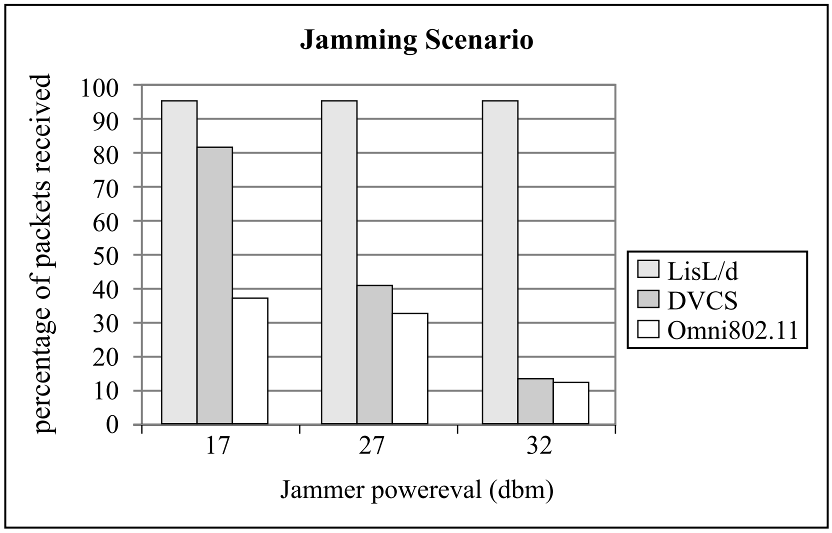

Figure 7 : Percentage of packets received with jamming under different protocol

In Figure7, the jammer case is presented. The Scenario considers one jammer located in the center with different power levels. The percentage of packets received for the aggregated traffic is plotted. As the power level of the jammer increases, the percentage of packets received under DVCS and omni-802. 11 dropped significantly, while the percentage of packets received under LiSL/d remains the same as LiSL/d doesn't depend on omni reception at any phase of the algorithm. With become more pronounced.

5. CONCLUSION

In this paper, we investigate the performance of a pure directional transmission with smart antennas. The protocol is distributed and can dynamically assign slots to links based on traffic demand. The algorithm is useful when omnidirectional antennas are not available or desirable due to anti jamming requirement. Simulation results show that the directional algorithms usually outperform 802.11 for some given network topologies such as Lakehurst real time scenario. The LiSL/d significantly outperforms DVCS and 802.11 omni when jamming is present. Performance comparison with other protocols will be conducted in the future.

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