Directional Virtual Carrier Sensing for Directional Antennas in Mobile Ad Hoc Networks

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ABSTRACT

This paper presents a new carrier sensing mechanism called DVCS (Directional Virtual Carrier Sensing) for wireless communication using directional antennas. DVCS does not require specific antenna configurations or external devices. Instead it only needs information on AOA (Angle of Arrival) and antenna gain for each signal from the underlying physical device, both of which are commonly used for the adaptation of antenna pattern. DVCS also supports interoperability of directional and omni-directional antennas. In this study, the performance of DVCS for mobile ad hoc networks is evaluated using simulation with a realistic directional antenna model and the full IP protocol stack. The experimental results showed that compared with omni-directional communication, DVCS improved network capacity by a factor of 3 to 4 for a 100 node ad hoc network.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design – *Wireless Communication, Directional Antenna Systems*; C.2.5 [**Computer-Communication Networks**]: Local and Wide-Area Network – *Access Schemes.*

General Terms

Performance, Design, Experimentation, Verification.

Keywords

Mobile Ad Hoc Networks, Directional Antenna Systems, Medium Access Control, Carrier Sensing, IEEE 802.11.

1. INTRODUCTION

Directional antenna technology offers a variety of potential benefits for wireless communication systems. In particular, it can improve spatial reuse of the system, which often results in substantially increased system capacity and wider coverage area. The utility of directional antennas has already been demonstrated in cellular networks via its deployment at base stations [10][18]; continuing reductions in the cost and size of antennas will soon make it feasible to use this technology in mobile stations and other types of wireless network systems.

This paper addresses the use of directional antennas in mobile ad hoc networks, or MANETs, which configure the network autonomously without reliance on any underlying infrastructures such as base stations. The deployment of directional antennas in MANETs is more challenging than in cellular networks; first, a MANET node has no prior knowledge as to which other nodes it can communicate directly with, making it harder for directional antennas to beamform towards specific network nodes under dynamically changing network conditions. Second, while reducing interference, the directional communication may also reduce the number of neighbors recognized by each node, which can potentially affect the performance of MAC (Medium Access Control) protocols and destination discovery process performed by ad hoc routing protocols. Therefore, link-level optimizations used in the cellular networks with directional antennas [18] do not necessarily lead to better overall networking performance in MANETs.

This study focuses on the design and evaluation of contention based MAC protocols for MANETs using directional antennas. This class of MAC protocols is most commonly used in MANETs [2][4][5][6][7][8], and utilizes carrier sensing (CS) mechanisms to identify the channel availability for transmission. The physical CS is performed at the physical layer, which senses the carrier and determines the channel availability based on the level of interference and noise around the node. The virtual CS is an alternative mechanism to the physical CS and is performed at the MAC sublayer. It often uses RTS (Request To Send) and CTS (Clear To Send) control frames, and predicts the channel use by other nodes based on the sequence of received frames. Contention based MAC protocols use either physical or virtual CS, or both to avoid collisions of multiple frames at receivers. The IEEE 802.11 DCF (Distributed Coordination Function) is CSMA/CA (Collision Avoidance) with an optional use of RTS and CTS frames, and its back-off scheme provides good fairness by resuming the previously used back-off timer for the next contention period [6][13]. This IEEE 802.11 DCF MAC protocol has been most commonly used and referenced in MANET studies, and this study also uses it as the baseline MAC protocol.

The preceding MAC protocols have been designed for omni-directional transmissions, and may not fully exploit the potentials of

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directional antennas. The physical CS may suffer from directional transmission because the carrier is no longer a good indication of neighboring nodes competing to acquire the shared channel access. The virtual CS may also have problems as directionally transmitted RTS and CTS cannot be heard by neighbors other than those between the transmitter and the receiver. A good overview of these problems can be found in [16]. New MAC protocols that alleviate these problems have been proposed and are discussed briefly in the next section. However, these protocols use only directional transmission (no directional reception) and assume that all nodes in the network are equipped with directional antennas.

This study proposes a solution that can be used with many contention based MAC protocols to make effective use of directional antennas, while also providing interoperability with omni-directional antennas. Our solution introduces a new CS mechanism called DVCS (Directional Virtual Carrier Sensing), which can exploit the capabilities of various directional antenna systems. DVCS does not require specific antenna configurations or external devices to be operational. It requires minimal information from the underlying physical device, e.g., AOA and antenna gain for each signal, both of which are commonly used for the adaptation of antenna pattern at the physical layer. DVCS can work with omni-directional antennas, and more importantly, it can allow nodes with directional antennas to be interoperable with nodes with omni-directional antennas. The paper demonstrates the implementation of DVCS in the IEEE 802.11 MAC protocol and presents the results from a simulation study on the effectiveness of this protocol using a realistic directional antenna model and a detailed model of the full IP protocol stack. The experimental results showed 3 to 4 times network capacity increases with DVCS compared with omni-directional communication. The paper also investigates the effects of physical CS mechanism on accumulated interference created by many concurrent transmissions.

The rest of this paper is organized as follows; the next section describes previous studies on MAC protocols for MANETs using directional antennas. Section 3 shows how DVCS can be implemented in the IEEE 802.11 MAC protocol with key ideas, and Section 4 demonstrates the impact of DVCS on the MANET performance using typical simulation scenarios used in MANET studies with a realistic directional antenna model. Section 5 concludes this paper with a summary of this study.

2. RELATED WORK

In the past, there have been several studies regarding the MAC protocols for MANETs using directional antennas [9][11][16][19][23][24], and many of them attempt to solve problems with the virtual CS discussed in this paper. Ko, Shankarkumar and Vaidya [9] proposed a MAC protocol for MANETs using directional antennas in which CTS frames are always transmitted omni-directionally, while RTS control frames are transmitted directionally (scheme 1) or omni-directionally if the channel is clear for all directions (scheme 2). It is assumed that each node knows exact locations of other network nodes by means of additional hardware such as GPS, and each node transmits signals based on the direction derived from such physical location information. Nasipuri, Ye et al. [11] proposed another MAC protocol that does not require additional hardware to identify the directions to specific nodes by comparing the received power from each (sectorized) antenna upon each signal reception. Both RTS and CTS frames are transmitted omni-directionally in this study. These MAC protocols are similar to the IEEE 802.11 DCF with the RTS / CTS option and assume sectorized directional antennas as the underlying antenna configuration. Sanchez, Giles and Zander [19] studied effects of RTS frames transmitted directionally and omni-directionally along with three different beamwidth patterns, and reported that the directional RTS transmission always outperformed the omni-directional RTS transmission. Ramanathan [16] studied the effects of directional antennas with omni-directional transmission of RTS and CTS, but also studied several other aspects of directional communication including power control and neighbor discovery in MANETs.

All these previous studies discuss only the transmitter side beamforming, while directional antennas can be used for both transmitting and receiving. In many situations, the receiver beamforming can yield better performance as the receiver can maximize the gain for the signal of interest with the channel response, whereas the transmitter needs to guess the best direction to beamform for the intended receiver without knowing the channel conditions. DVCS introduced in this paper supports both directional transmission and reception based on the radio reciprocity, which allows directional transmissions of all frames without incurring unnecessary collisions.

Further, these studies design the proposed MAC protocol only for directional antennas, and there is no discussion as to whether these MAC protocols can be operational in nodes with omni-directional antennas, or can be interoperable with nodes equipped with omni-directional antennas. The implementation of DVCS in a MAC protocol does not lose compatibility with the original protocol as demonstrated with the IEEE 802.11 DCF MAC in this paper.

Our paper also extends previous studies in the area of performance analysis of MAC protocols. The MAC protocols in the previous studies are evaluated using simulation with ideally sectorized [9][11] or flat-topped [16][19] antenna patterns. Antenna patterns have a great impact on the level of interference, which can significantly change the overall network performance predicted by simulation as revealed in [21]. Therefore, it is critical to use realistic physical layer models including the antenna pattern even in the evaluation of MAC protocols. While DVCS is generic and does not depend on a specific antenna configuration, this study uses a highly detailed directional antenna model together with the full IP protocol stack in order to analyze the impact of the proposed mechanism on the MANET performance under realistic conditions.

3. DIRECTIONAL VIRTUAL CARRIER SENSING

As described in Section 1, CS mechanisms are used by contention based MAC protocols to determine channel availability for transmissions. DVCS allows the MAC protocol to determine *direction-specific* channel availability. The next subsection demonstrates how DVCS can be implemented as an enhancement to the IEEE 802.11 MAC protocol. In our implementation of DVCS, the use of additional resources is minimized as much as possible in order to make the protocol practical and realistic. Such resources include multiple orthogonal channels for transmission of control frames, or external devices such as compass, ultrasound, or GPS (Global Positioning System) for location information. GPS can give several other pieces of information such as a synchronized clock and distances to other network nodes if their locations are already known, but DVCS does not require any of these capabilities.

3.1 IEEE 802.11 MAC with DVCS

The IEEE 802.11 DCF is a contention based MAC protocol that supports various physical devices such as infrared, FHSS (Frequency Hopping Spread Spectrum) and DSSS (Direct Sequence Spread Spectrum) radios. The protocol is operational in MANETs with its independent configuration, which does not rely on channel control by access points unlike the infrastructure configuration. In the standard, the use of RTS and CTS control frames is optional, but these control frames can reduce data frame collisions due to the hidden terminal problem [22], which often happens in MANETs. While DVCS itself works with or without those control frames, for simplicity, this paper assumes that the protocol uses this option.

Three primary capabilities are added to the original IEEE 802.11 MAC protocol for directional communication with DVCS: caching the Angle of Arrival (AOA), beam locking and unlocking, and use of DNAVs. The following paragraphs briefly describe each of these features.

- **AOA Caching**

Each node caches estimated AOAs (Angle of Arrivals) from neighboring nodes when it hears any signal, regardless of whether the signal is sent to the node. When the node has data for transmission to one of its neighbors, if AOA information for the neighbor has been cached, it beamforms the underlying directional antenna in that direction to transmit the RTS frame; otherwise the frame is transmitted omni-directionally. The node updates the cached AOA every time it receives a newer signal from the same neighbor, and invalidates the cache if it fails to get the CTS response back from the neighbor after 4 directional transmissions of the RTS frame; subsequent RTS frames are sent omni-directionally. This assumes that the failure to get the response from the neighbor is not due to collisions with other signals, but because the direction of transmission is inaccurate. As the maximum number of RTS retransmissions is defined to be 7 in the IEEE 802.11 standard, each node will still transmit 3 omni-directional RTS frames before notifying the higher layer of a link failure.

- **Beam Locking and Unlocking**

When the node receives an RTS frame from a neighbor, it adapts its beam pattern to maximize the received power and locks the pattern for the CTS transmission. If the node transmitted an RTS frame to a neighbor, it locks the beam pattern after it receives the CTS frame from the neighbor. The beam patterns at both sides are used for both transmission and reception, and are unlocked after the ACK frame transmission is completed. These locked patterns maximize the signal power at the receiver as long as the channel condition remains the same. Note that the pattern locking that occurs during the sequence of frame transmissions (CTS through ACK) is for only a short period of time and is reasonable for the 2.4 GHz ISM band at which the IEEE 802.11 operates. The channel response is generally assumed to be stable until the node moves half a wavelength of the channel frequency, and this corresponds to a maximum speed of around 40 m/s for the whole sequence of a 512 byte data transmission with RTS / CTS control frames (12.5 cm / 3.2 ms). This pattern lock also prevents the nodes from being distracted by signals from other directions.

- **DNAV Setting**

With DVCS on, the protocol uses DNAV[1] (Directional Network Allocation Vector) instead of the NAV (Network Allocation Vector) used in the original IEEE 802.11 MAC. Unlike NAV, each DNAV is associated with a direction and a width, and multiple DNAVs can be set for a node. A node maintains a unique timer for each DNAV, and also updates the direction, width and expiration time of each DNAV every time the physical layer gives newer information on the corresponding ongoing transmission. For directional transmission, DVCS determines that the channel is available for a specific direction when no DNAV covers that direction. For omni-directional transmission, it determines that the channel is available when no DNAV is set for the node.

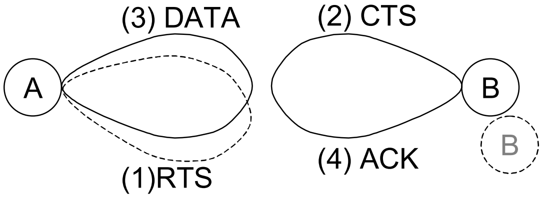

Figure 1: Negotiation between the source and the destination.

Other than the addition of the three preceding functions, the protocol logic of the IEEE 802.11 is unchanged with DVCS. Figure 1 illustrates the sequence of steps used to establish communication between two nodes A and B using RTS / CTS frames with these functions. Assume that Node A has data to be sent to Node B, and finds an estimated AOA (shown via a dashed line) from Node B in its cache. It transmits the RTS frame in the direction of the cached AOA, which is a little off the exact direction due to the time lapse from the previous communication with Node B (1). Node B senses the RTS frame from Node A, and adapts the antenna pattern to maximize the gain for the frame from Node A. Upon successful reception, Node B locks the pattern and transmits the CTS frame back to Node A (2). The CTS frame from Node B can give Node A a better and updated AOA for Node B, and Node A adjusts its antenna pattern and locks it until the completion of the ACK frame transmission. Node A then transmits the data frame with the updated pattern, which is highly likely to be received by Node B as the pattern of Node B has also been adapted for the frame reception from Node A (3). The ACK frame transmission is made in the opposite direction from Node B to Node A, but needs little adjustment on the patterns used by both nodes unless the channel conditions dramatically change (4).

The following subsections describe key ideas behind DVCS and its implementation in the IEEE 802.11.

3.2 DNAV

In the IEEE 802.11 standard [6], a NAV (Network Allocation Vector) is set in a node when it hears any non-ACK unicast frames that are to be received by other nodes. The node holds it until the entire data transmission completes. Until the NAV expires, the node cannot transmit any frames to the channel, reserving the channel for

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[1] DNAV was also proposed independently in [3].

other nodes. NAV is effective even without RTS / CTS control frames as its duration includes the time for the ACK transmission to be completed. DNAV (Directional Network Allocation Vector) is a directional version of NAV, which reserves the channel for others only in a range of directions. Figure 2 depicts how DNAVs can be set; three DNAVs are set up towards 30°, 75° and 300° with the 60° width. Until the expiration of these DNAVs, this node cannot transmit any signals whose direction is between 0° and 105° or between 270° and 330°, but is allowed to transmit signals towards 105° to 270° and 330° to 360° (0°).

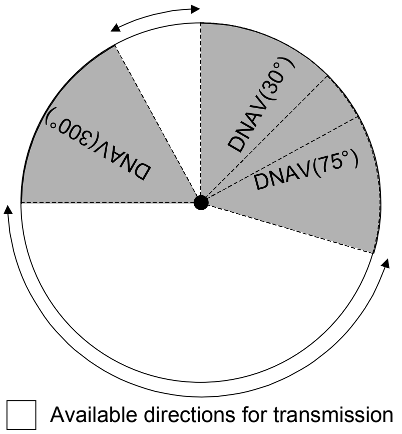

Figure 2: Three DNAVs set for different directions.

DVCS selectively excludes directions included in DNAVs for transmission, in which the node may cause interference to other ongoing transmissions, but it allows the node to transmit frames along other directions. Figure 3 illustrates a network situation where DVCS can improve the network capacity with DNAVs. Nodes A, C and E have data to be transmitted to Nodes B, D and F respectively, and all nodes are within direct communication range of all other nodes. If all nodes have omni-directional antennas, these three data communications are clearly sequentialized because each omni-directional transmission occupies the whole space. Suppose all the nodes have directional antennas that can beamform narrowly towards a specific node, and use the virtual CS of the original IEEE 802.11 to determine the channel availability. In this case, both Nodes A and C can start the data transmission simultaneously because the RTS and CTS communication made between Nodes A and B cannot be heard by Nodes C and D, and vice versa. This can significantly increase the capacity of the network, but Node E cannot start transmission towards Node F due to the NAV for the two preceding communication pairs. However, this Node E being blocked may not be necessary if Node E can receive signals from Node F despite the other ongoing transmissions. With DVCS, Node E sets four DNAVs towards Nodes A, B, C and D, but can transmit the RTS frame towards Node F because the direction to Node F is not included in any of the preceding DNAVs.

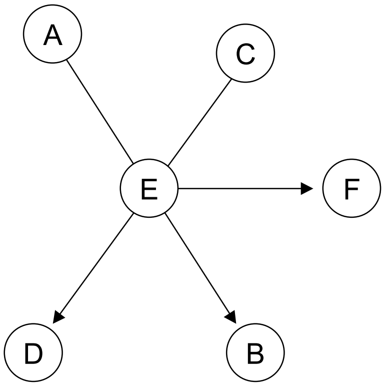

Figure 3: Three data communications among six nodes.

Precise setting of directions and widths for the DNAVs is crucial in DVCS as it directly affects the determination of channel availability for transmissions. The direction for DNAV is set based on an estimated AOA (Angle of Arrival) for each signal, rather than in the direction in which the transmitter is physically located. While the estimated AOA and the physical direction appear to yield the same angle, there are several fundamental differences between the two. First, the AOA is an essential piece of information for the digital beamforming, and it is reasonable to assume that the underlying directional antenna is capable of estimating AOAs of signals[2]. Thus the AOA of each signal can be obtained from the antenna itself and needs no external device such as GPS. This also allows protocols relying on signal AOAs to work even in environments where such external devices do not work properly. Second, although the direction of transmitter could be used as an estimation of AOA, those angles for the same transmitter can be quite different when scattering, reflection and diffraction occur on a path between the transmitter and the receiver. The AOA is always the most effective direction to reach the transmitter with the minimum path loss. This also implies that the transmission towards the AOA of the transmitter can cause the most interference, and setting DNAVs towards AOAs is the most effective way of avoiding possible collisions even under harsh environments where the signal AOA does not match the physical direction to the transmitter. Lastly, as the antenna system becomes smarter, it can identify multiple AOAs for a single signal due to its multipath components, and depending on the received signal power from each multipath component, the radio can set up multiple DNAVs for a single signal to reduce interference through those paths. Therefore, the AOA is preferred if it is available, even when external devices can provide the physical locations of neighboring nodes.

The width of DNAV is based on the beamwidth made by the underlying directional antenna, and can be dynamic if the antenna can adaptively change the beam shape. The width can also be used to control aggressiveness of the transmitter as a narrower DNAV width makes more directions available for transmission. Also, the width does not depend on the beamwidth of the intended receiver, and there is no need to make it global for all the nodes in the network. *This implies that DVCS can be provided as an optional*

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[2] Even if the antenna cannot estimate AOAs, the boresight of the antenna that maximizes the gain for the signal can be roughly used as the signal AOA.

enhancement to an existing MAC protocol without altering the protocol behaviors in the standard configuration. In fact, if the beamwidth of the antenna is 360° (omni-directional), DNAV becomes identical to the NAV as used in the IEEE 802.11 MAC, and such omni-directional nodes can be interoperable with nodes with directional antennas. In Figure 3 for instance, suppose that Node E does not have a directional antenna and it can transmit signals only omni-directionally. When Node E sends an RTS to Node F, all the other nodes hear its transmission, thus Nodes A and C do not transmit anything to Nodes B and D because the DNAV directions set at Nodes A and B match the directions to Nodes B and D respectively. When either Node A or C transmits an RTS, Node E sets a NAV (360°-width DNAV) and does not start transmitting an RTS to Node F until the NAV expires. In this case, the four nodes with directional antennas (Nodes A, B, C and D) can communicate with each other directionally and concurrently without a collision. Therefore, different widths of DNAVs in different nodes do not introduce any channel inefficiency or incur unnecessary collisions.

The support of heterogeneous network configuration with DNAVs faciliates incremental deployment of directional antennas as in cellular networks, where omni-directional antennas at some base stations can be replaced with directional antennas without having to change the configuration of mobile stations or other base stations. Without this ability for incremental deployment, it is doubtful that directional antennas could have been successfully exploited in cellular network systems, in spite of their proven performance benefits. However, much of the current research in directional antennas for MANETs ignores the issue of interoperability with omni-directional antennas. As described in the previous subsection, DVCS requires a few enhancements to the IEEE 802.11 MAC protocol to allow suitably equipped nodes to exploit directional communication, without affecting its interoperability with nodes using omni-directional antennas.

3.3 Transmitter and Receiver Beamforming

As described in Section 2, several studies have tried omni-directional transmissions of RTS or CTS control frames, as all neighbors around the communication link may not overhear the control frames transmitted directionally. However, omni-directional transmission of control frames is unnecessary if each node uses the same beam pattern for both transmitting and receiving because of their reciprocal relationship. Suppose that Node X transmits a control frame directionally to Node Y using a beam pattern. If one of its neighbors, Node Z, does not sense the control frame, Node Z is not sensitive to the direction in which Node X is located. This also means that Node X is not sensitive to signals from Node Z if the same transmission beam pattern is used for receiving. Thus, having this neighbor set a DNAV for the node by transmitting omni-directional control frames could reserve unnecessarily large channel space, which results in reduced network capacity. The DVCS implementation described in Section 3.1 transmits and receives all frames directionally, and avoids substantial pattern changes during each data communication.

There are several options when beamforming and controlling transmission power for the intended receiver. In this study, the node chooses the antenna pattern that maximizes the power from the receiving signal, rather than the one that yields the highest SIR (Signal to Interference Ratio) as usually performed in the cellular networks. Unlike cellular networks where mobile stations keep connections to the nearest base stations, the SIR value at a receiver can fluctuate even without fading due to a contention based MAC protocol which generates many short control frames to acquire the channel access. This makes the antenna difficult to optimize the pattern to maximize SIR, which also requires frequent pattern updates. Therefore, this study uses the beamforming strategy that maximizes the gain and avoids frequent pattern updates during each data communication.

With directional transmissions, the antenna creates higher radiated power towards the antenna boresight than omni-directional transmission. Thus, in addition to reduced interference, directional antennas can also provide communication range extension. However, as shown in [16], there are inherent conflicts between these two characteristics of directional antennas and this paper focuses only on interference reduction; as such we explicitly use power control at the transmitter to minimize the range extension effect of directional antennas. Ideally, the transmission power should be reduced to compensate for the total gain yielded by the directional antennas: if the gain of the antenna is G dBi, the communication link can benefit $2G$ dBi by beamforming at both transmitter and receiver sides, and the transmission power should be reduced by $2G$ dB. However, it is almost impossible for the transmitter to predict the gain at the receiver, which depends on the receiver capabilities and may even be 0 dBi (isotropic antenna). In this study, the transmitter reduces the transmission power by up to G dB, and the antenna gain at the receiver is used to make the link more robust compared to omni-directional reception. This also preserves the communication with network nodes using omni-directional antennas whose gain is typically close to 0 dBi.

4. PERFORMANCE ANALYSIS

4.1 Directional Antenna Model

Most studies on MANETs using directional antennas have used either ideally sectorized or flat-topped antenna patterns as mentioned in Section 2. An ideally sectorized antenna pattern has a constant gain for all directions within the sector, and has no radiated power towards the other sectors. A flat-topped antenna pattern also has a constant gain for all directions within the specified angle (sector), and has a lower constant gain for all other directions, representing lobes on the sides and the back of the pattern. Although both types of patterns have been used for the network capacity analysis [10], no physical antenna can provide such constant gain for a given angle. The shape of the pattern including side-lobes and back-lobes has non-negligible effects on the interference among network nodes. As demonstrated in [21], even for omni-directional antennas, the interference can causes collisions of MAC control frame, which, in turn has a substantial impact on network performance. To adequately account for such effects, this study uses a realistic antenna pattern together with detailed physical layer models to evaluate the performance of DVCS.

In this study, each network node is assumed to have an electrically steerable antenna system, which can variably change the antenna boresight by means of a beamforming network. The cost and complexity of antenna system implementation depends on many factors including the number of antenna elements and the beamforming algorithm. This study assumes a relatively simple configuration that consists of a circular antenna array with six isotropic elements, each of which is spaced with 0.4 wavelength of the channel frequency. The 2.4 GHz ISM band is chosen in this study as the original IEEE 802.11 standard operates in this band. It is also reasonable to assume that the antenna system can transmit signals omni-directionally if necessary at this frequency. The antenna system uses only a phase shifter per element to control the input phase, and does not change the input weight with an amplifier. The beamforming criterion is simply to maximize the gain of boresight, and has no nulling capability which requires an advanced beamforming algorithm. The antenna system is assumed to have an AOA and an antenna gain estimation modules, which can report the estimated values to the MAC protocol. Although errors in AOA and gain estimations can affect the network performance with DVCS, this study uses the AOA and gain information obtained from the propagation model with no error. The antenna system can steer the boresight at one-degree step based on the estimated AOA of the signal of interest.

The antenna patterns that the antenna system can generate with these assumptions have been created using MATLAB [12], a common tool to model wireless communication devices. Figure 4 shows two of the resulting patterns whose boresights are directed towards 0° and 30° on a polar plane. As shown in this figure, although the antenna configuration is symmetric, the shapes of side-lobes and back-lobe change substantially as the boresight is steered from 0° to 30°. The pattern for the 0° boresight has two small side-lobes and a back-lobe, while the other has two large side-lobes but no back-lobe. For a more detailed view, Figure 5 shows the pattern changes as the boresight moves from 0° to 54° at 6° steps. Regardless of the direction of the boresight, the shape of main-lobe remains the same with 15.5 dBi gain and 45° beamwidth, but the graph shows creation of the back-lobe and its inclusion into side-lobes as the beam is steered. In order to account for these lobe changes, all ten patterns shown in Figure 5 are included in the simulation, and depending on the boresight of the antenna system, one of these patterns is chosen for the calculation of interference.

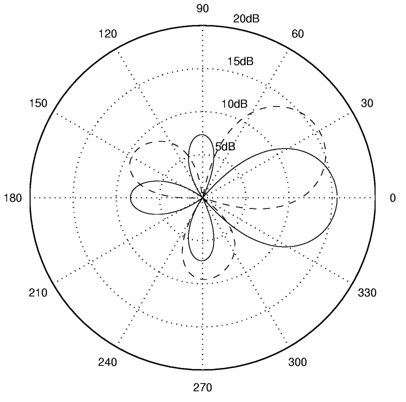


Figure 4: Two antenna patterns bearing 0° and 30°.

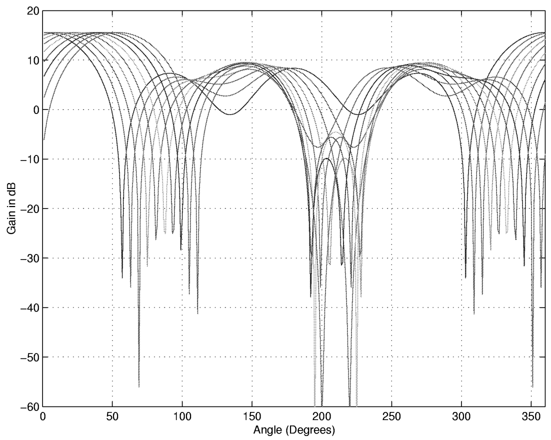


Figure 5: Ten antenna patterns between 0° and 60° at 6° steps.

In the simulation study in this section, the width of DNAV for this antenna pattern is set to 74° while the beamwidth of the main-lobe is 45°. This is because the beamwidth is calculated as the angle within which the antenna gives 0 to 3 dB less than the maximum gain, and setting the DNAV width equal to the beamwidth may still cause strong interference to the ongoing communication. The DNAV width of 74° includes all directions in which the antenna yields 0 to 9 dB less than the maximum gain. This setting may be somewhat conservative but still allows the node to transmit signals in the other 286° directions.

There are several other factors that determine the behaviors of a physical device. This study uses a set of parameters typically used in an implementation of the IEEE 802.11 DSSS (Direct Sequence Spread Spectrum) standard, which is listed in Table 1. The transmission (TX) power is set to 15 dBm and 0 dBm for omni-directional and directional transmissions respectively. The TX power for omni-directional transmission is taken from the Lucent WaveLAN card specification. The 15 dB reduction in the transmission power for directional transmission consists of the 15.5 dBi antenna gain minus 0.5 dB as a margin. The receiving threshold (RXT) is used in signal reception to decide whether to lock on to an incoming signal. The CS threshold (CST) determines the channel availability indicated by the physical CS, and its value of -91 dBm is also taken from the WaveLAN card specification. RXT is raised by 15 dB for the directional reception not to extend the communication range, and CST is also raised by 15 dB if the next frame is to be transmitted directionally as the physical CS uses the directional antenna pattern in that case.

The BER (Bit Error Rate) signal reception model looks up the BER for a given SINR (Signal to Interference and Noise Ratio), and probabilistically determines whether or not each node receives a frame without errors. It evaluates each frame segment, in which the interference from other transmissions is constant, with a BER value derived from the modem performance. DBPSK (Differential Binary Phase Shift Keying) is used as the modulation scheme in this study. The direct communication range resulting from these parameters together with the two-ray path loss model is 376 m (no interference).

Table 1: Set of parameters used in the simulation.

Channel frequency	2.4 [GHz]
Signal reception	BER based (with DBPSK modulation)
Data rate	2 [Mbps]
Noise figure	10.0 [dB]
TX power	15.0 [dBm]
TX power (directional)	0.0 [dBm]
RX threshold (RXT)	-81.0 [dBm]
CS threshold (CST)	-91.0 [dBm]
AOA cache expiration time	2 [s]

4.2 Simulation Scenarios

The following scenarios are configured for the performance evaluation of DVCS; one hundred nodes are randomly placed over a 1500 x 1500 m flat terrain. The two-ray model, also known as the plane earth loss model is used as the path loss model because of environmental similarities of the MANET to the micro-cell environment where antenna heights of the base stations are relatively low [17]. Each node is equipped with the electrically steerable directional antenna described in Section 4.1, whose height is set to 1.5 m. Forty nodes are randomly chosen to be CBR (Constant Bit Rate) sources, each of which generates 512 byte data packets to a randomly chosen destination at the rate of 1 to 40 pps (packets per second). The network uses AODV (Ad Hoc On-Demand Distance Vector Routing) [14] for each CBR source to discover a route to the destination. In the mobility scenario, the random waypoint model is used as the mobility model in which each node chooses a random destination within the terrain and moves straight towards the destination. After the node reaches the destination, it chooses another point on the terrain and moves towards the new destination. In this study, the speed at which the node moves is always 10 m/s and the pause time for which the node stays at each destination is 0 (constantly moving). In the no-mobility scenario, each node stays at the initial location and does not move at all.

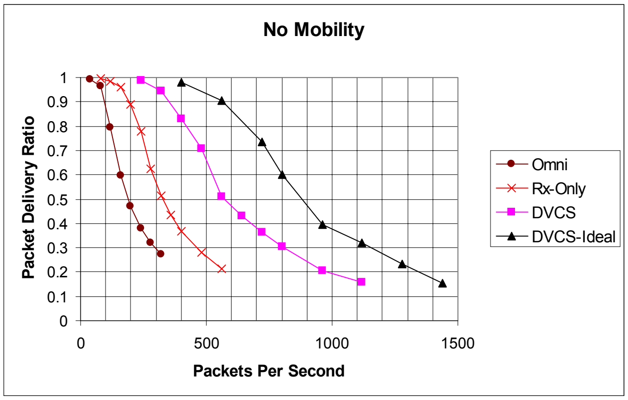
4.3 Simulation Results

These scenarios are simulated using QualNet [15], a discrete-event network simulator that includes a rich set of detailed models for wireless networking. QualNet is the next generation of the GloMoSim simulator [1][20]; its model library includes all the protocol models necessary for the scenarios: CBR traffic, UDP, IP, AODV, IEEE 802.11 DCF MAC, IEEE 802.11 DSSS PHY, steerable antenna, two-ray path loss and random waypoint models. The three functions described in 3.1 are implemented in its IEEE 802.11 DCF MAC and DSSS PHY models.

The following three subsections show different aspects of directional communication with DVCS: network performance improvement with directional antennas, effects of physical CS, and interoperability with nodes running the original MAC protocol with omni-directional antennas. The primary metric collected to measure the network performance is PDR (Packet Delivery Ratio), which is calculated as the number of data packets received by the CBR destinations over the number of data packets originated from the CBR sources in the network. The PDR indicates how many packets the data source can deliver to the destination over multiple hops without packet drops due to queue overflow or transmission failure. The throughput, which is the product of the PDR and the number of packets originated, is also shown in the first subsection to show the peak performance of the network. Each data point shown in these experiments represents the averaged value from 8 simulation runs with different random number seeds; more than 1200 simulation runs were executed to obtain all the results shown in this paper.

4.3.1 Network Performance with Directional Antennas

In order to clarify the effects of DVCS, the physical CS of the IEEE 802.11 is disabled in this subsection. Also note that AODV is slightly modified in the no mobility scenario to suppress the number of broadcast packets in the network. The charts in Figure 6 respectively show the PDR and the throughput as a function of network traffic in the no mobility scenario. Each chart includes four different configurations of network nodes: Omni, Rx-Only, DVCS and DVCS-Ideal. In the Omni configuration, each node transmits and receives frames omni-directionally with the original IEEE 802.11 DCF. The Rx-Only configuration is the same as Omni except that each node is assumed to have a directional antenna and to be able to receive frames directionally. As each node still transmits frames omni-directionally, the original virtual CS in the IEEE 802.11 MAC is used in this configuration. In the other two configurations, each node transmits and receives frames directionally with DVCS for unicast communications. The DVCS



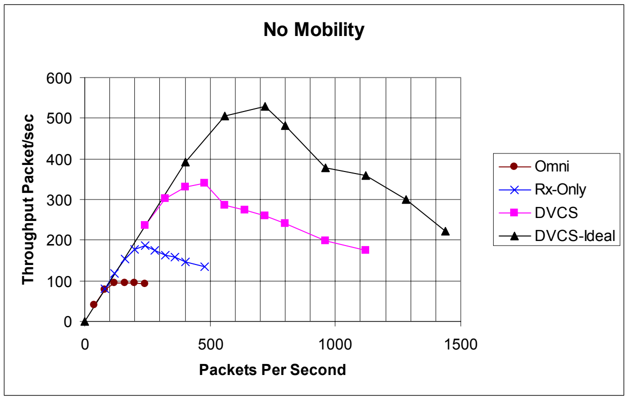


Figure 6: PDR and throughput of the network in the no mobility scenario (without the physical CS in the IEEE 802.11).

configuration uses the antenna pattern described in Section 4.1, and DVCS-Ideal uses an idealized antenna pattern with no side-lobes or back-lobe; the pattern is created from the original pattern by setting a low gain (-34 dBi) for directions not included in the main-lobe.

Please note that DVCS-Ideal is used only to show the impact of side and back lobes on the overall network performance; it is not representative of the performance that is likely to be obtained from physical antennas. Also note that this study did not examine cases where directional antennas were only used for transmission and not reception because such systems are unlikely due to the hardware complexity for directional transmission that can always accommodate directional reception at no additional cost.

As clearly shown from these charts, the network capacity increases dramatically with directional antennas; at the peak throughput, Omni yields around 95 pps while Rx-Only gives 187 pps, or about 2 times the maximum throughput with Omni. DVCS gives 339 pps, or more than 3.5 times better throughput compared to Omni. These results clearly show that directional communication significantly increases the network capacity, allowing more concurrent data flows in the network. In all cases, the throughput increases linearly with sustainable amount of traffic, and then degrades when overloaded due to the nature of contention based MAC protocols.

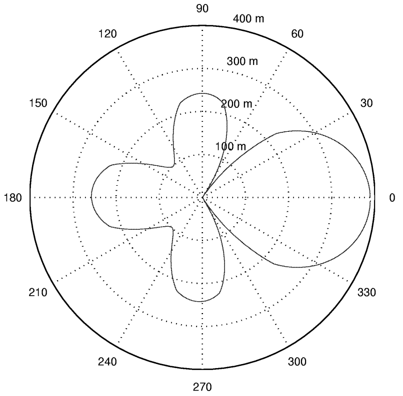


Figure 7: Directional communication range that gives signal power of more than -81 dBm with the two-ray path loss model.

In these charts, DVCS-Ideal gives 528 pps or more than 1.5 times better throughput than DVCS with the realistic antenna pattern. In order to explain this substantial gain with no side and back lobes, Figure 7 shows the communication area that gives at least -81 dBm signal power with the two-ray path loss model using the directional antenna pattern for the 0° boresight. As the RXT of all receivers is set to -81 dBm in the study, this picture gives the area in which neighbors can receive frames with enough power from the node. Compared to the gain pattern shown in Figure 4, the shape of the main-lobe is truncated due to high path loss exponent of 4.0 for far sight in the two-ray path loss model, making the relative sizes of side and back lobes larger. Although neighbors around the node can still avoid collisions and transmit frames to other directions with DVCS, radio power leaked towards the sides and back of the node undoubtedly causes substantial interference with other communications, which reduces network capacity. Therefore, the effects of side and back lobes cannot be ignored in the evaluation of network performance with directional antennas. In fact, the increased interference from the back lobes counteracted expected performance benefits with many of the more aggressively concurrent transmission schemes attempted in our study.

The two charts in Figure 8 show the PDR and the throughput of the network in the mobility scenario. As shown, the peak throughput yielded by each configuration is significantly lower than the corresponding throughput in the no mobility scenario. However, the relative ranking of these configurations remains the same, and the relative performance improvements achieved by the directional antenna are even higher in the mobility scenario: 2.7 and 4.1 times better peak throughputs with Rx-Only and DVCS respectively compared to the Omni configuration (36 pps). This demonstrates that the directional communication with DVCS can reduce the performance degradation due to mobility in the network.

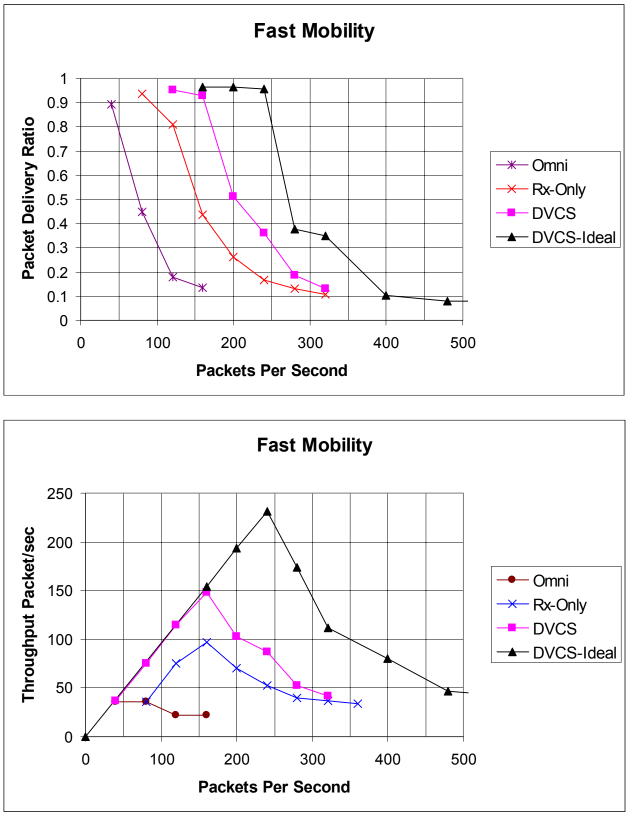


Figure 8: PDR and throughput of the network in the mobility scenario (without the physical CS in the IEEE 802.11).

4.3.2 Effects of the Physical CS

This subsection examines the effects of the physical CS on directional communication. The physical CS can be effective as network nodes around active communication links can still sense transmissions even if they fail to receive RTS / CTS control frames. Figure 9 shows the impact of physical CS on the PDR metric presented in Figure 6 and Figure 8. The data for the cases without physical CS are taken from the experiments in the previous subsection, and the corresponding cases with physical CS are added to the charts. As shown in the first chart, the physical CS in the no mobility scenario seems to have modest effects on the network performance with Omni or DVCS, yielding up to 16% more packets delivered, and small differences for cases with highly congested traffic. However, in the mobility scenario, the physical CS increases the PDR dramatically with DVCS, from 18% to 81% for the cases with given traffic at 280 pps for instance. This PDR improvement is even higher than the differences between DVCS and DVCS-Ideal shown in Figure 6 and Figure 8.

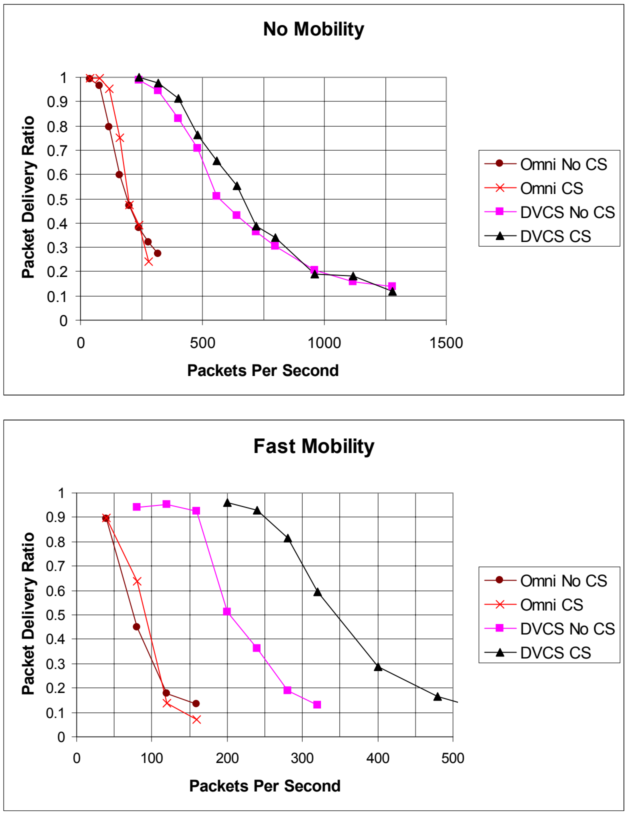


Figure 9: PDRs with and without the physical CS.

This dramatic improvement with the physical CS, in the presence of mobility, can be explained as follows; the directional communication allows many nodes to transmit frames concurrently, which results in significantly increased network capacity. At the same time, many nodes experience highly accumulated interference due to numerous concurrent transmissions even if each transmission contributes little interference to other receivers. With the physical CS off, nodes transmit frames regardless of the level of accumulated interference, making it harder for other nodes to receive directionally transmitted RTS / CTS control frames. This reduces the number of neighbors who can receive these control frames without errors, thus accelerating failure of setting DNAVs by the neighbors. The physical CS can effectively alleviate this situation by indicating channel unavailability for transmission under high interference conditions. The effects of the physical CS are not significant in all Omni cases, as there are never sufficient concurrent transmissions to create highly accumulated interference in the network.

Please note, however, that the beneficial effects of physical CS are not observed for DVCS under the no mobility scenario. Recall that the AODV implementation in the no mobility scenario was modified to reduce unnecessary broadcasts. The original AODV floods the network with route requests by broadcasting, which is implemented via omni-directional transmissions. Broadcast packets are transmitted omni-directionally with 15 dB higher transmission power than unicast packets, and they cause much higher interference in all directions. As the location of each node is unchanged in the no mobility case, route breakage occurs only due to link failures caused by interference from other communications. Therefore, simply ignoring link breakage can reduce the number of broadcast packets in the network. In the no mobility scenario, AODV is modified such that it does not start the route discovery process for 98% of the link failures detected by the IEEE 802.11 MAC. The smaller difference in PDRs with and without the physical CS when AODV is modified indicates that the network can avoid high interference conditions when omni-directional transmissions are suppressed.

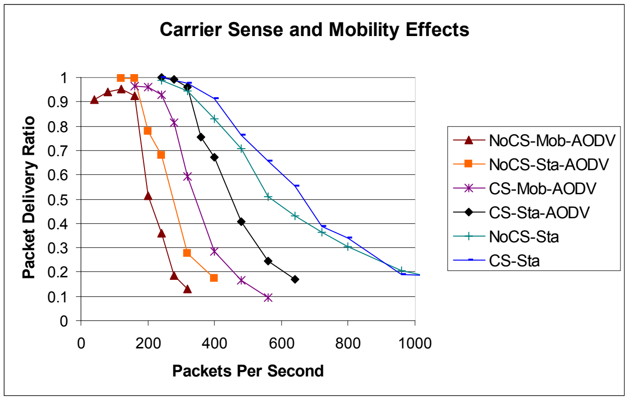


Figure 10: Effects of the physical CS in mobility scenarios.

A separate experiment was run to investigate the relative impact of mobility, physical CS and AODV modification to suppress broadcasting. The results presented in Figure 10 support the preceding observation. The graph shows the PDRs in the network under six different cases. Four cases are stationary and consist of different combinations of the physical CS and modified and unmodified AODV implementations (NoCS-Sta, CS-Sta, NoCS-Sta-AODV and CS-Sta-AODV); the first two cases use broadcast suppression in AODV. The remaining two cases use the unmodified AODV with mobility and examine the impact of physical CS being on or off (NoCS-Mob-AODV and CS-Mob-AODV). As expected, when the corresponding cases with and without mobility are compared (NoCS-Sta-AODV – NoCS-Mob-AODV or CS-Sta-AODV – CS-Mob-AODV), the stationary case yields better packet delivery than the mobility case. When the corresponding cases with and without the physical CS are compared (NoCS-Sta-AODV – CS-Sta-AODV or NoCS-Mob-AODV – CS-Mob-AODV), the case with the physical CS outperforms the other, and the performance gain by turning on the physical CS is significantly more than the difference between the mobility and the stationary cases. Note that the cases with the AODV modification have the best performance, but the difference made by the physical CS in these cases (15% between NoCS-Sta and CS-Sta at 560 pps) is smaller than the cases with the original AODV (67% between NoCS-Sta-AODV and CS-Sta-AODV at 320 pps). Given that the AODV modification suppresses most of the broadcast packets in the simulation, this implies that the impact of physical CS is correlated to the number of broadcast packets in the network. While routing protocol issues are not within the scope of this paper, this result suggests that some modifications to suppress broadcasting in ad hoc routing protocols like AODV should significantly improve the overall network performance with directional antennas.

4.3.3 Interoperability with Omni-Directional Nodes with DVCS

As discussed in Section 3.2, DVCS is interoperable with omni-directional communication, and the enhancements to IEEE 802.11 to support DVCS does not impact its ability to inter-operate with the original, unmodified protocol. This subsection illustrates this concept by configuring the network such that some nodes are given omni-directional antennas and the others use directional antennas. Three different configurations of the network are used with the mobility scenario: Omni, DVCS and Mixed. In the Omni configuration, all nodes run the original IEEE 802.11 DCF with the omni-directional antenna, while all are equipped with the directional antenna and run the IEEE 802.11 with DVCS in the DVCS configuration. In the Mixed configuration, the CBR sources (40 nodes) are assumed to have omni-directional antennas, and run the original IEEE 802.11 MAC protocol. All other nodes, including CBR destinations, have directional antennas, and run the IEEE 802.11 with DVCS. As the sources can only omni-directionally transmit data packets that are eventually to be received by the destinations running DVCS, this configuration ensures that the two types of network nodes communicate to deliver data packets. This does not preclude omni-directional nodes to be used as routers. In this subsection, the physical CS is turned on for all cases.

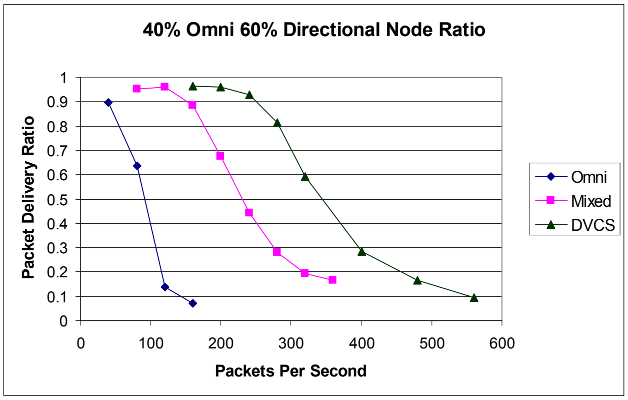


Figure 11: Mix of omni-directional and directional antennas.

Figure 11 shows the PDRs yielded by these configurations. As clearly shown in the figure, the Mixed configuration gives performance between Omni and DVCS, with Mixed closer to the performance of DVCS. This indicates that DVCS can effectively increase the network capacity even if some nodes in the network have only omni-directional antennas.

5. CONCLUSIONS

This paper has presented DVCS, a new CS mechanism designed to exploit the potential of directional antennas in MANETs. The implementation of DVCS in a contention based MAC protocol does not require any specific physical configuration of directional antennas; rather, it enhances the original MAC protocol such that it is possible to use DVCS with a subset of nodes, while the other nodes communicate using the original protocol and omni-directional antennas. This paper described an implementation of DVCS with the IEEE 802.11 DCF MAC protocol, and evaluated its performance via simulation using a highly detailed directional antenna model. The experimental results showed that directional communication with DVCS can increase the network capacity 3 to 4 times. The simulation results also indicate that the physical CS alleviates the effects of accumulated interference due to many concurrent directional transmissions in some situations. Further, the omni-directional transmission of broadcast packets showed a great impact on the network performance, suggesting a fruitful direction for future research – alternative schemes for route discovery in ad hoc routing protocols with minimal use of broadcast packets. The study also demonstrated interoperability of DVCS with nodes running the original IEEE 802.11 DCF MAC with omni-directional antennas.

6. ACKNOWLEDGEMENT

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