An Opportunistic Medium Access Control Protocol for Visible Light Ad Hoc Networks

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***Abstract*—Visible Light Ad Hoc Networks (LANETs) have the potential to offer capabilities to satisfy growing industrial and military requirements, including low-latency, high bandwidth communication under high network density and jamming conditions. The challenges imposed by hidden nodes, deafness and blockage are unique to LANET and influence the network differently from traditional Mobile Ad Hoc Networks (MANETs) due to directionality and Line of Sight (LOS) requirements. Therefore, networking protocols have to be redesigned with careful consideration of these challenges. As an initial step in this direction, this paper proposes a utility based opportunistic three-way handshake mechanism to negotiate medium access. First, a node chooses the optimal transmission sector, i.e., the "direction" that maximizes the probability of establishing a link even when some of the neighbors are affected by blockage or deafness. The utility function is designed to favor the establishment of full-duplex communication links. The full-duplex transmission or busy tone along with power control employed by the proposed Medium Access Control (MAC) protocol is aimed at mitigating the hidden node problem. All these factors contribute towards maximizing the throughput of LANET. Performance evaluation studies through extensive simulations show up to 61% increase in throughput and significant improvement in the number of full-duplex links established with respect to Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA).**

I. Introduction

Visible Light Communication (VLC) has come to the forefront with the advent of modern Light Emitting Diode (LED) technology that consumes low power and has a short response time. The unexploited, unregulated spectrum (400 to 800 THz) is a promising candidate to alleviate the Radio Frequency (RF) spectrum crunch. The exploration of VLC has been limited to various point-to-point applications including setting up Light Fidelity (Li-Fi) [1] networks using smart lights, among others. In this context, several topologies such as peer-to-peer, star and broadcast have been considered to design MAC protocols. In this paper, we concentrate on exploiting VLC for ad hoc networking in military and civilian applications. We foresee LANETs contributing considerably to the upcoming Internet of Things (IoT) revolution in both indoor and outdoor spaces. Some indoor applications of LANETs include Device-to-Device (D2D) communication to support IoT technology, enabling indoor positioning system, and aiding the traditional RF based networks [2], [3]. A simple example is the devices (TV, thermostat among others) in a smart home forming a LANET. In outdoor scenarios, one of the most promising applications for LANET is related to the vehicular communications. LANETs can also be used for air, ground and underwater tactical missions such as ISR (intelligence, surveillance, and reconnaissance) missions entailing deployment of ships, soldiers, and unmanned surface vehicles. LANETs can also be used in high security military areas where RF communication is prone to eavesdropping or is extremely congested.

A key distinguishing feature of VLC is **directionality**. While it enables better spatial re-use, directionality is the direct reason for some of the major challenges experienced in LANETs. The classical challenges like **hidden node problem** are amplified by transmission directionality, since the control packets such as Clear-to-send (CTS) transmitted by a receiver may not be received by nodes because of limited Field Of View (FOV). When a receiver is oriented towards a certain spatial sector and is therefore unable to receive from all the remaining sectors, it is referred to as **deafness**. Thus, a node may try to initiate communication with its neighbor who is experiencing deafness with respect to the node, leading to additional delays during the contention phase. Another unique challenge of LANET is the sudden communication discontinuity which may happen during the contention phase; thus, trying to access one particular neighbor may not be the most efficient way to forward packets. This problem is referred to as **blockage**. Some challenges of LANET are similar to the ones experienced by directional RF networks. The list of instantaneous neighboring nodes may change depending on the FOV. Unlike typical RF transceiver systems equipped with a single antenna to transmit or receive, VLC devices are usually equipped with a LED for transmission and Photon Detector (PD) for reception making these devices inherently capable of **full-duplex** communication. Therefore, network protocols designed for LANETs should be able to take advantage of full-duplex links to improve the network throughput.

The unique characteristics of VLC impose the need for cross-layer design as shown in Fig. 1 to address these challenges [3]. Here, we start the process by designing a novel opportunistic MAC protocol that optimizes the

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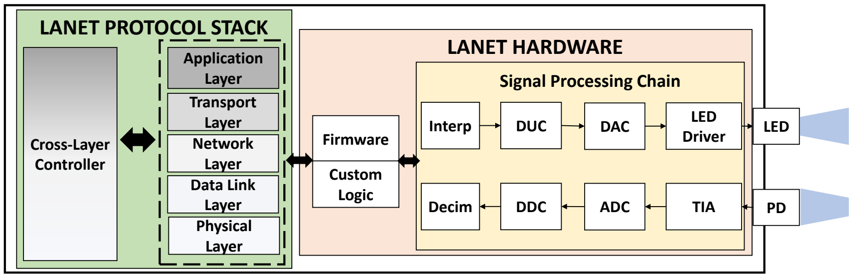

Fig. 1: Architecture of a LANET Node

throughput of LANETs using a divide-and-conquer approach aimed at achieving the following objectives:

- maximize the probability of establishing a link in a given direction while overcoming challenges caused by the hidden node problem, deafness and blockage;
- improve the probability of full-duplex communication;
- maximize the amount of spatial re-use.

The rest of the paper is organized as follows. In Section II, we discuss MAC protocols proposed in the literature. The system model is described in Section III. The detailed design of the proposed MAC protocol is discussed in Section IV along with simulation results in Section V. Finally, conclusions are presented in Section VI.

II. Related Work

The study of MAC solutions for VLC is still in its infancy and even more limited is the attention given to MAC in the context of ad hoc networks. Unfortunately, the few existing MAC schemes designed for point-to-point VLC are not easily extendable to LANETs as they do not consider some unique challenges and opportunities related to VLC. Some of the existing MAC protocols are discussed below.

In [4], the authors propose a full-duplex MAC protocol with Self-Adaptive minimum Contention Window (SACW) that delivers higher throughput from the central node to the terminal nodes by increasing probability of full-duplex operation. The proposed algorithm still uses the basic slotted CSMA/CA mechanism as in IEEE 802.15.7 [5] with adaptive contention window. The authors of [6] also propose a high speed full-duplex MAC protocol based on Carrier Sense Multiple Access/Collision Detection (CSMA/CD). The Access Point (AP) receives the data and repeats it to all the terminal nodes. When one terminal node wants to upload to an AP, it first ensures no carrier is being transmitted. If the data received by the transmitting terminal node coincides with its own data, communication continues, otherwise the signal is discarded assuming collision at AP. Optical wireless MAC (OWMAC) [7] is a Time Division Multiple Access (TDMA) based approach aimed to avoid collision, retransmission and overhead due to control packets. In OWMAC, each node reserves time slot and advertises the reservation using a beacon packet. All three [4], [6] and [7] are designed for a star topology and not extendable to LANETs. For example, the beacon packets transmitted to reserve the time slot may not be received by a neighbor due to deafness and may try to communicate with the node later during its transmission leading to collisions. While the MAC proposed in [4] increases the probability of full-duplex link, it has a centralized structure where the central node monitors the data flow and controls the channel access accordingly. This centralized nature is not suitable for ad hoc networks. The repetition of data in [6] eliminates the ability to exploit full-duplex communication hence significantly degrading the achievable throughput.

A cooperative MAC protocol is proposed in [8] to reduce latency and for on-demand error correction. Though the cooperative operation provides on-demand error correction, it does not help to overcome the challenges like deafness or hidden node problem. Therefore, the cooperative operation can be used to bolster the operation of LANETs but cannot be the primary MAC protocol used to establish the link initially. Another popular method of multiple access used in RF based systems is Code Division Multiple Access (CDMA), which employs orthogonal codes to enable multiple users to transmit on the same frequency simultaneously. There has been several works aimed to employ this form of multiple access to VLC. A system using CDMA along with Orthogonal Frequency Division Multiplexing (OFDM) platform is proposed by authors in [9]. The proposed design uses Polarity Reversed Optical OFDM (PRO-OFDM) to overcome the inherent light-dimming problem associated with using CDMA with visible light. In this work, Hadamard sequences is chosen to accomplish Multi-carrier CDMA (MC-CDMA). The traditional bipolar codes such as Gold and Walsh-Hadamard sequences are not directly applicable to intensity modulation. In [10], authors discuss how Gold sequences and Walsh-Hadamard sequences can be adapted to make them suitable for VLC. CDMA based schemes can be utilized to separate Control Channel (CC) and Data Channel (DC) and ensure simultaneous operation of both without interference. It may be complex to negotiate different codes for each link in LANET in a distributed manner.

To the best of our knowledge, this is the first MAC protocol designed specifically for LANETs. The major contributions of this paper can be summarized as follows,

- We discuss the vision of using LANET for military and civilian applications requiring short range, low-latency, high-data rate links and establish the role of cross-layer technology in realizing it.
- We design a novel multi-utility based opportunistic MAC protocol aimed to maximize the throughput of LANET improving the probability of establishing links and promoting the percentage of full-duplex communication in the network. The proposed MAC protocol overcomes deafness, blockage and hidden node problem.
- Extensive simulations are performed to demonstrate improvements achieved by the proposed MAC protocol.

III. System Model

Consider a multi-hop LANET with N static Visible Light Nodes (VLNs) modeled as a directed connectivity graph $\mathcal{G}(\mathcal{U},\mathcal{E})$, where $\mathcal{U} = \{u_0, u_1, ..., u_N\}$ is a finite set of VLN of the graph, and $(i, j) \in \mathcal{E}$ represents a feasible unidirectional wireless link from node u_i to node u_j (for simplicity, we also refer to them as node i and node j) representing neighboring relationships, i.e., there is a feasible link if the nodes are close enough. In LANET, each node consists of LED luminaires and PDs adopted as transmitters and receivers, respectively. Since the transmissions are directional, the directions to which the FOV of each node can be set to are represented by N_s equal sectors $s \in \mathcal{S}$. The FOVs of typical LEDs and PDs can vary from $\pm 10°$ to $\pm 60°$ [11], [12], e.g. Vishay TSHG8200, OSRAM LCW W5SM Golden Dragon and Vishay PD TESP5700. Here, for the sake of simplicity, but without loss of generality, we choose FOV for both LED and PD to be $\pm 22.5°$, leading to eight sectors. This can be easily extended according to the FOV of the hardware available on specific VLN. We also assume that a VLN is capable of directing its FOV to all the N_s sectors when required for transmission and reception. This is possible with multiple LEDs and PDs, that can be used depending on which sector the nodes want to access (only one sector of a node is activated at any given time). In non-ideal scenarios, interference mitigation techniques [13] can be employed to reduce the interference between sectors. The neighbors are grouped into sectors based on their location which can be provided when the network is deployed or learned by exchanging of control packets. Thus, the superset of neighbors for node i consists of the set of neighbors in each sector represented as $\mathcal{NB}^i \in \{\mathcal{NB}_1^i, \mathcal{NB}_2^i, ..., \mathcal{NB}_{N_s}^i\}$, where $\mathcal{NB}_s^i \triangleq \{j : (i, j) \in \mathcal{E}\}$ is the neighbor of node i in sector s.

Let the traffic in the network consist of multiple sessions $q = 1, 2, ..., Q$, characterized by the source-destination pairs. In this work, we define feasible next hop for a session as any neighbor that is closer to the destination and is termed as forward progress. In this context, each session q in node i belongs to one or more sector queue sets $q \in Q_i^s$ (q can be a component of more than one sector queue sets) such that the sector contains neighbors that ensure forward progress for packets in a queue. This information will be used by the VLN while choosing an optimal sector to forward packets. The arrival rate of each session $q \in Q_i^s$ at node i is given by $\lambda_q^i(t)$, and characterized through the vector of arrival rates Λ. The VLNs in the network are assumed to be synchronized with each other using techniques like Global Positioning System (GPS) based clock synchronization. The time spent listening to each sector is called sector duration (t_{sec}) and this forms a sector slot as shown in Fig. 2. The sector slot is further divided into multiple control micro-slots (CMS). Control packets are transmitted only at the beginning of a CMS. The duration of a CMS is set such that transmission of a control packet can be completed in one CMS. A set of N_s sector slots forms a super-slot. VLNs have two operational states; Synchronous Idle State (S-IDLE) and Transceiving State (TR). In S-IDLE, nodes sequentially listen in each sector following a fixed pattern. In this way, a VLN that has to transmit in a given sector knows the appropriate sector slot when the idle neighbors (in the given sector) will be listening, thus mitigating the effect of deafness. The channels used by the LANET are divided into CC and DC using for example, orthogonal CDMA codes as discussed in Section II.

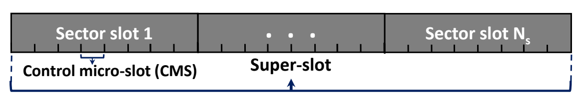

Fig. 2: Super-slot structure

IV. Design of MAC protocol for LANET (VL-MAC)

The objective of this paper is to design a MAC protocol for LANETs to overcome challenges like deafness, blockage and problems due to hidden nodes. Unlike RF based MANETs, the accessibility of neighbors changes drastically with time due to deafness and blockage and therefore the traditional approach of choosing a neighbor to forward a packet before negotiating medium access may not be the most efficient approach. *We introduce the concept of opportunistic link establishment wherein a VLN uses a utility function to identify the optimal sector that maximizes the probability of establishing a link.* The VLN then broadcasts a control packet in the chosen sector for two purposes; to negotiate the access of the medium and find the optimal next hop. The neighboring VLNs that receive the broadcast respond based on a second utility function and provide parameters for efficient transmission. *This step further contributes to maximizing the network throughput by favoring the establishment of full-duplex links.* Thereafter, the channel is reserved to complete the data transmission.

The timing diagram of the mechanism followed by VL-MAC is depicted in Fig. 3 and an example of the three way handshake exchange of control packets is illustrated in Fig . 4. Since VL-MAC is designed to encourage full-duplex communication, the use of terms transmitter and receiver becomes confusing. Therefore, hereafter, we replace the terms transmitter and receiver by initiator and acceptor depending on which node initiates communication. Consider four nodes A, B, C and D, among which B and C are the initiators with packets to be transmitted and A and D are prospective acceptors in S-IDLE. Once a node has packets to transmit, it has to choose a sector to transmit such that it maximizes the initiator's utility function ($U^i_{ini}(s)$). This is a joint function of backlog and the achievable forward progress through the chosen sector. To better understand $U^i_{ini}(s)$, consider a node i with intended destination k, and let j be the possible next hop. The $U_{ini}(s)$ for node i is given by,

$$U^i_{ini}(s) = \sum_{q \in Q^i_s} \sum_{j \in \mathcal{NB}^i_s} b^i_q \, \overline{d}_{ij}, \;\; \forall j : d_{ik} - d_{jk} > 0 \qquad (1)$$

where,

$$\overline{d}_{ij} = \frac{d_{ik} - d_{jk}}{d_{ij}}, \qquad (2)$$

b^i_q is the backlog length of session $q \in Q^s_i$ at node i, Q^i_s is set of all sessions with packets that can be forwarded through sector s. This term ensures that heavily backlogged sessions result in higher utility function. The distance between nodes i and k is denoted as d_{ik} (each node stores the last known location of the neighbors acquired from control packets). In (2), $d_{ik} - d_{jk}$ represents the function that evaluates the forward progress achieved by choosing j as the next hop. The denominator (d_{ij}) can be considered as the cost of achieving the forward progress. Greater transmission distance implies more resources (power) may have to be utilized to reach the neighbor. This also implies that a larger area will be under the interference range of the transmitter. Therefore, this parameter helps to be more conservative by providing nodes at a smaller angular distance preference over the others that have same $d_{ik} - d_{jk}$ values. The summation over all feasible neighbors (that provide forward progress) ensures that the utility function increases proportionally to the number of feasible neighbors in the given sector, which in turn increases the probability of finding an available next hop. This is a critical differentiating feature of the proposed MAC protocol since it introduces the *concept of opportunistic link establishment in contrast to traditional methods where a forwarding node is chosen before the negotiation for channel access begins.* This mitigates the inaccessibility caused due to deafness or blockage. Accordingly, the sector that maximizes the utility function for i is chosen as the optimal sector s^* and can be represented as,

$$s^*_i = arg\ max_{s \in S}(U^i_{ini}(s)) \qquad (3)$$

Accordingly, B and C choose the sector corresponding to their maximum $U_{ini}(s)$. In this example, assume that both choose the same sector. Nodes B and C choose a random backoff depending on their U_{ini} and broadcast an *Availability Request (ART)* packet if the channel is idle within the *ART* transmission period of the sector duration. The *ART* consists of the information regarding the source node (initiator) such as node ID, location, backlog length of all sessions considered for the given sector and channel state. As shown in Fig. 3, both A and D listen to control packet during the corresponding sector duration. On reception of *ARTs*, A and D will switch to TR and calculate their respective acceptor's utility function, $U^j_{acp}(i)$, using information from all the *ARTs* received during the sector duration. The $U^j_{acp}(i)$ for any initiator-acceptor pair i and j can be computed as follows,

$$U^j_{acp}(i) = \delta_{ij}(q^*_i)C_{ij}\overline{d}_{ij} + \delta_{ji}(q^*_j)C_{ji}\overline{d}_{ji} \qquad (4)$$

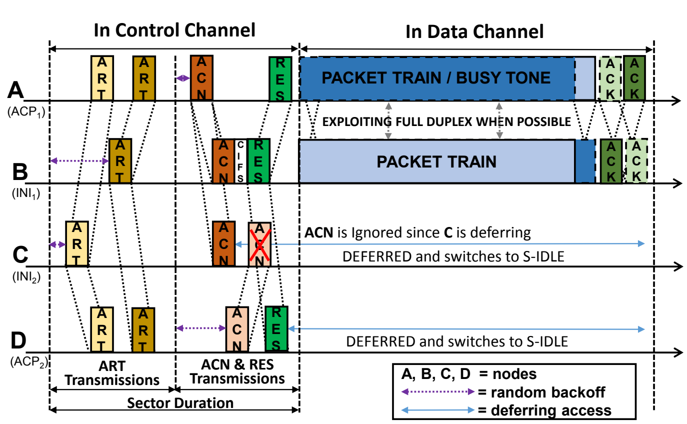

Fig. 3: Timing diagram of VL-MAC

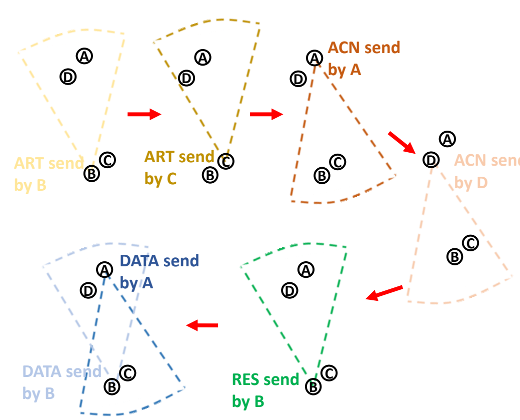

Fig. 4: Handshake procedure of VL-MAC

where q_i^* is the session selected for transmission from i to j such that it maximizes the differential backlog. The maximum differential backlog between nodes i and j is given by,

$$\delta_{ij}(q_i^*) = arg\ max_{q \in Q_s^i}[b_q^i - b_q^j] \quad (5)$$

It can be seen that (4) includes the product of maximum differential backlog, channel capacity and forward progress from both directions. This is because a VLN uses hardware that inherently supports full-duplex communication. Therefore, the initiator-acceptor pair that can achieve higher combined throughput using duplex communication gets access to the channel thereby improving the overall throughput of the network. Assuming LOS transmission, the Shannon capacity can be computed as,

$$C_{ij} = B \log_2 \left(1 + \frac{(P_t L_P)^2}{\sigma_{shot}^2 + \sigma_{thermal}^2} \right) \quad (6)$$

where σ_{sho} and $\sigma_{thermal}$ are the standard deviations of shot noise and thermal noise respectively, P_t is the transmit power and L_P is the path loss value for a Lambertian LED source and is given as [14],

$$L_P = \frac{(m+1)A_r}{2\pi d^2} \cos(\alpha) \cos^m(\beta) \quad (7)$$

where m is the order of Lambertian emission, A_r is the receiver's aperture area, α is the incident angle and β is the irradiation angle and d is the distance between the initiator and acceptor. Using (6) and (7), the acceptor can calculate the transmit powers required to satisfy the Signal-to-Noise Ratio (SNR) threshold for the full-duplex communication.

According to the above discussion, A and D choose the initiator (B or C) that they want to provide access to. The acceptors also select the initiator's session and acceptor's session for full-duplex communication such that it maximizes their respective $U_{acp}^j(i)$ and the transmission power to be used by the initiator-acceptor pair to ensure the required Bit Error Rate (BER) is achieved as shown below,

$$(i^*, p_i^*, p_j^*, q_i^*, q_j^*) = \arg\ \max(U_{acp}^j(i)). \quad (8)$$

This is the second critical step taken by the MAC protocol *to maximize the network throughput by choosing initiator-acceptor pairs favoring opportunities for establishing full-duplex communication.* These chosen parameters are encapsulated in a *Availability Confirmation (ACN)* packet and transmitted by the acceptors to the chosen initiators. In this case, A transmits a *ACN* to B after a random backoff which is dependent on U_{acp}. The *ACN* contains information that is used by the initiator to set the transmission parameters (modulation, power and channel if applicable). In this example, the *ACN* from A is received by intended node B and overheard by C. Accordingly, B transmits *Reserve Sectors (RES)* packet to reserve time required to complete the transmission. Node C learns that it was not chosen for transmission by overhearing the *ACN*, and hence defers access and returns to the S-IDLE. Similarly, D overhears the *RES* packet and returns to S-IDLE.

After the three-way handshake, nodes A and B perform full-duplex data transmission as shown in Fig. 3. Each data packet is followed by an *Acknowledgment (ACK)* packet from the respective receiver. After the completion of the full-duplex transmission, both the nodes return to the S-IDLE. In cases where there is no opportunity for full-duplex communication (acceptor does not have any session to be transmitted to the initiator), a busy tone is transmitted by the acceptor. This ensures that other nodes sense the channel to be busy from both directions of the initiator-acceptor pair and reduces the hidden node problem. All these factors collectively mitigate the effects of deafness, blockage and hidden node problem while favoring the establishment of full-duplex links thereby maximizing the throughput of the network.

V. Performance Evaluation

To evaluate the performance of the proposed MAC protocol, we implement a packet level simulator that operates at the data-link layer. To abstract the evaluation from the effects of physical layer, the simulator only considers packet loss caused due to collisions. This can be easily extended to include any modulation and coding scheme at the physical layer and will show similar trend in performance at the data-link layer. The simulator is used to compare the performance of VL-MAC and a CSMA/CA based MAC. To ensure a fair comparison, VLNs are synchronized in both cases. The network consists of 50 VLNs with transmit range of 5 m deployed at random locations within a 25 m x 25 m area on the same plane. The size of control and data packets were 20 $Bytes$ and 2500 $Bytes$ respectively and the data rate was set to 10 $Mbps$. Each session in the network is characterized by the source node and a random point on the topology indicating the destination. The destination is used to determine the direction of forward progress in case of VL-MAC and to choose next hop for the session in case of the CSMA/CA scheme. To this end, the neighbor that provides the most forward progress is chosen as the next hop for a given session. The CSMA/CA based MAC protocol can also establish full-duplex links if the intended acceptor has a session to be forwarded to the initiator. This is a single hop simulation so a packet being successfully forwarded to a suitable next hop in the specified direction contributes towards the overall network throughput.

We compute the throughput normalized to link rate, evaluate the percentage of full-duplex links established and track collisions due to hidden node as the number of session increases from 4 to 140 with each session containing 500 packets. The results were computed over 100 seeds. The comparison of normalized throughput between VL-MAC and CSMA/CA is depicted in Fig. 5.

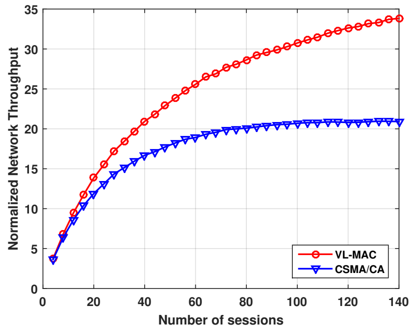

Fig. 5: Throughput comparison between VL-MAC and CSMA/CA

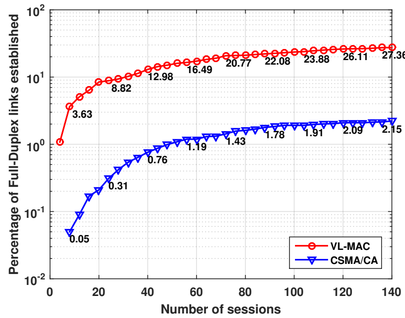

Fig. 6: Percentage of full-duplex communication established

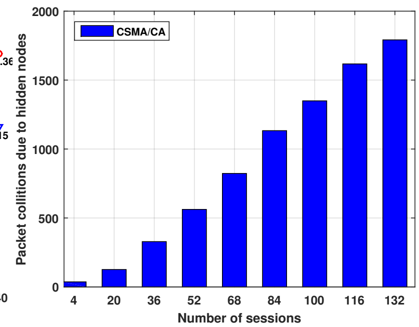

Fig. 7: Packets dropped due to hidden nodes

The difference in performance grows as the number of sessions in the network increases. As discussed earlier, the opportunistic approach of VL-MAC along with the carefully designed utility function ($U^i_{ini}(s)$) increases the probability of establishing a link to forward the packets. Similarly, the second stage of negotiation using $U^j_{acp}(i)$ favors the full-duplex links which can be further corroborated by Fig. 6. Since $U^j_{acp}(i)$ utilizes both differential backlog and capacity, it aims to maximize the throughput achieved by initiator-acceptor pair thereby maximizing the throughput of the overall network. Next, in Fig. 7, we depict the total number of packets dropped due to collision from hidden node problem. It can be seen that the number of packets dropped in CSMA/CA increases with increase in number of sessions. Throughout the evaluations, no collision due to hidden nodes were observed for the proposed VL-MAC. This is because VL-MAC employs separate CC and DC and uses either busy tone or full-duplex communication links (always keeping both directions busy). All these factors jointly provides upto 61% improvement in the throughput achieved by LANET employing proposed VL-MAC. These experiments establish how the performance of LANETs can be significantly improved by taking into consideration unique properties of VLC while designing the communication protocols.

VI. Conclusions and Future Work

The proposed protocol, VL-MAC, implements a three-way handshake procedure to negotiate access to the medium. VL-MAC optimizes the throughput of the network by dividing the complex problem into a step-by-step utility based opportunistic negotiation to establish links. Results show how VL-MAC significantly mitigate deafness, blockage and hidden node problems and drastically improve the percentage of full-duplex links established, all leading to 61% improvement in network throughput over CSMA/CA. Our next step is to implement VL-MAC on a LANET testbed to corroborate simulation results.

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