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Media Access Schemes for Indirect Diffused Free-Space Optical Networks

Nicolò Macaluso, Roberto Rojas-Cessa, and Michela Meo

***Abstract*—In this paper, we propose a set of three media access control (MAC) schemes for an indirect diffused light free-space optical communications (ID-FSOCs). ID-FSOC has been recently proposed to establish wireless high-speed (i.e., $\geq$ 1 Gbps) network access using FSO from stations that have no line-of-sight (LOS) with the access point. ID-FSOC employs a diffuse reflector (DR) to uniformly reflect diffused light from an incident laser to all directions, except towards the DR. To establish a link, ID-FSOC requires LOS between the transmitter and the DR and between DR and the receiver. In this way, ID-FSOC relaxes the location of stations as long as they keep LOS to the DR. We analyze the performance and scalability of proposed schemes. We also consider the impact of the zoom-in time of a receiver in our evaluations. Our results show that our proposed MAC schemes achieve high channel utilization and higher throughput than carrier-sense multiple access schemes.**

***Index Terms*—free-space optical communications, optical wireless communications, indirect optical communications, diffuse reflection, Lambertian diffusion.**

I. INTRODUCTION

Free-space optical communications (FSOC) uses modulated laser light as the carrier of data, and it offers higher bandwidth than radio-frequency (RF) technologies because of the significantly higher operating frequencies of light than those of RF. FSOC is a line-of-sight (LOS) technology; the transmitter and receiver of a communicating pair must be in LOS from each other [1]. FSOC can achieve high-data rates in transmissions between two stations separated by a distance of a few centimeters or tens of kilometers on the ground and even hundreds of thousands in space. FSOCs have multiple additional advantages, such as license-free band use, long operational range, spatial diversity, security, and immunity to electromagnetic interference [1].

However, the LOS requirement between a pair of communicating stations in FSOC and the frequent adoption of narrow beams limit the size of the covered area, and in turn, it reduces the adoption of FSOC for a wide variety of communication scenarios. Establishing an optical link between stations and maintaining the LOS between them require pointing their transceivers towards each other by using acquisition, tracking, and pointing (ATP) mechanisms [1]. Maintaining LOS in places with a prevalence of obstacles, such as in a city with many high buildings and other infrastructure, may be challenging.

The LOS problem inherent to FSOC can be solved by a recently proposed indirect diffused light FSOC (ID-FSOC) system, which establishes high-speed optical links between a pair of stations that have no direct LOS in between [2]. An ID-FSOC system consists of a transmitter, a receiver, and a diffuse reflector (DR) that uniformly diffuses the incident light beam in all directions except towards the DR itself. Here, the transmitter and receiver must use a DR in LOS by both transmitter and receiver to establish a diffused-light optical path between them. The use of such a DR allows the receiver to detect the diffusely reflected light through a broad angle of view. Moreover, ID-FSOC simplifies the complexity of the system by easing the motion resolution of an ATP mechanism. It is then easy to establish full-duplex communications links with ID-FSOC. Figure 1 shows an example of ID-FSOC used by a large number of stations. In this figure, there is a screen used as a DR and stations on different locations, presented here as Internet access towers and transceivers at building windows and roof tops. This figure shows how ID-FSOC may provide communication links between multiple stations. In the figure, the laser beam is the uplink, and the detection of the signal is the downlink.

Several indoor wireless data communications systems that use diffuse infrared radiation have been proposed [3]–[5]. These systems are based on LED light rather than on laser light. However, the wide divergence angle of LED light hampers its application on communications of stations separated by a few meters and longer distances. Moreover, a diffuse reflection carries a small portion of the incident power so that laser light is more suitable for distances that apply in many practical cases, including those outdoor. Here we consider the application of ID-FSOC for communications between stations in a local area network although the original application of this paradigm is on vehicular communications [2].

The transmitter of the ID-FSOC system uses a laser diode (LD) to emit a narrow laser beam (i.e., with a maximum divergence angle of 1 mrad) as the light source. The transmitter points the laser beam towards a DR, where the beam creates a projection. The receiver points its aperture towards the DR to receive the diffusely reflected light. That establishes a high-speed optical link between the transmitter and the receiver.

The DRs do not have any electrical nor mechanical parts, and they are passive materials, such as Teflon, ceramic, or paint. DRs are inexpensive and easy to deploy [6]. Moreover, DRs may be easily attached to buildings, bridges, towers, walls of tunnels, traffic signs, and traffic or street lights. Therefore, it is easy to build an ID-FSOC infrastructure. Also, the geometric loss of the proposed communications system is

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minimal because the beam is narrow and collimated, and this feature considerably extends the range between the transmitter and the DR. However, this is not the case for the receiver because diffused light beams have lower intensity and larger divergence angles than direct light, but they remain coherent. The use of narrow beam(s) of a transmitting station may also extend the range of ID-FSOC up to thousands of meters [7]–[9]. Therefore, the communication range may be longer than that of RF communication technologies [1].

Herein, we adopt ID-FSOC for local area networks and propose three different schemes for media access control (MAC). The schemes are named Single Point, Random, and Selective. In all three schemes, a transmitter projects its communicating laser on a DR to request network access, and a receiver selects a beam to grant the request. Each of the ID-FSOC MAC schemes establishes a link by using a different operation of the receiver. An ID-FSOC network may achieve higher throughput than RF-based stations in crowded conditions (e.g., a large number of WiFi networks), and it may be easy to deploy in crowded areas or for emergency communications. We analyze the performance of the proposed schemes and show that each scheme has advantages over the others on different scenarios. We compare the performance of the proposed ID-FSOC MAC schemes with well-known MAC schemes; namely CSMA/CD and CSMA/CA, as our schemes are the first proposed for ID FSOC networks, to the best of our knowledge.

The remainder of this paper is organized as follows. Section II introduces the proposed ID-FSOC MAC schemes. Section III. Section IV present our conclusions.

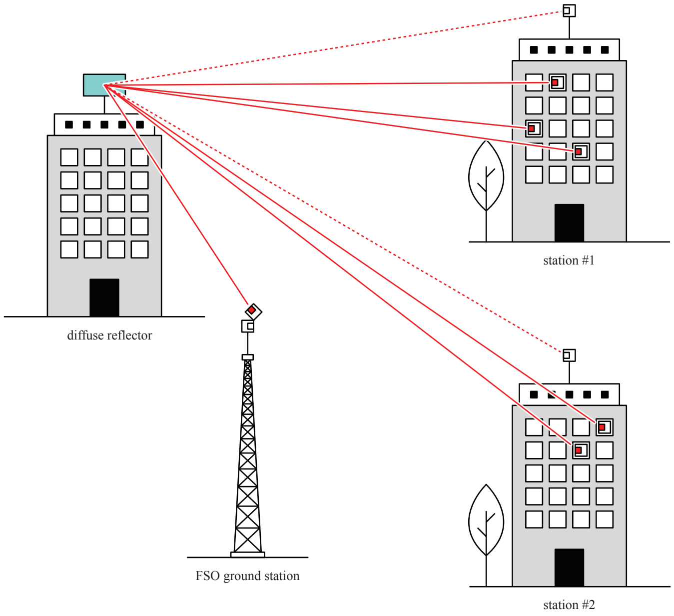

Fig. 1: Example of ID-FSOC network with multiple and varied stations.

II. Medium Access Control Scheme for ID-FSO

The three proposed MAC schemes for ID-FSOC differ from each other on the used beam selection method. Random randomly selects a projected beam from all those on the DR. The communicating pair establishes a link if the reflected beam is collision free; this is, if two or more projected beams are far enough (e.g., 10-cm or more from each other) or at the same location on the DR. The ability of the receiver to zoom-in on a projection area defines the collision distance. Selective selects a collision-free beam by following a random search for a collision-free projection, and Single Point uses a single location on the DR for the projection of beams, so that a collision occurs when there are two or more simultaneous transmissions.

Figure 2 shows an example of the occurrence of multiple and simultaneous beam projections on a DR. Here, the receiver zooms-in on the area marked by the dashed lines, where transmitters project beams A, B, and C. Here, r is the minimum collision distance between two beam projections (10 cm in this paper). As the figure shows, beams A and B collide, but beam C is collision-free. A receiver may then establish a link only with beam C. The selection of a beam is defined by the adopted MAC scheme, as described in the remainder of this section.

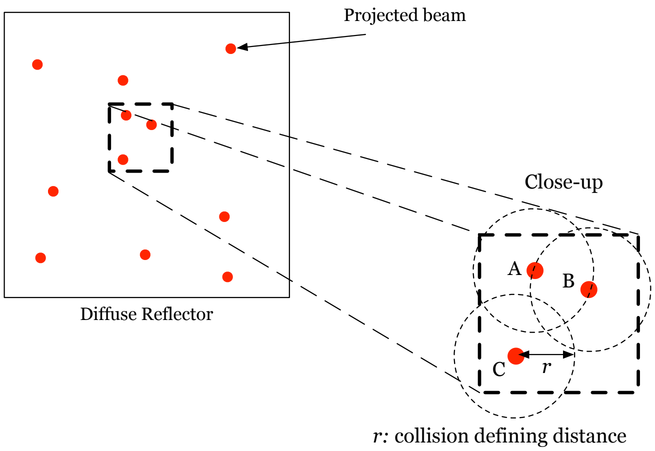

Fig. 2: Example of multiple beam projections in ID-FSOC and colliding and not-colliding beams. Here, beam C is collision-free.

One may expect Selective to achieve a higher rate of successful transmissions than Random because it searches for a collision-free beam. This search, however, makes Selective more complex than Random.

Single Point is a scheme with the lowest complexity of the three. Also, it mimics the operation CSMA/CD and CSMA/CA (where one station transmits, all the other stations detect the transmission). Here, for simplicity and fairness, we neglect the hidden station problem of CSMA/CA. At the same time, the use of a single access point in this network removes the exposed station problem of that scheme.

In general, FSO presents similar features to both wired and wireless links (e.g., Ethernet and WiFi) and therefore, the MAC schemes for ID-FSOC show a combination of functions from those two. For example, a transmitter must *follow* its transmitted beam on the DR to detect a collision, as wired transmissions do. Also, the network must use collision avoidance to keep additional transmissions from occurring while a transmission takes place, as CSMA/CA does. Therefore, the ID-FSOC MAC schemes adopt the use of Request for Send (RTS) and Clear to Send (CTS) frames. We, therefore, focus on the Distributed Inter-Frame Spacing (DIFS) of IEEE 802.11 and the ID-FSOC MAC schemes mimic its operation.

For simplicity, we consider that there is one access point (AP) in the network, in this paper. Therefore, stations in the network, except for the AP, transmit packets (as frames) to other stations or toward the Internet through the AP. In general, a transmitter performs the following operations in a ID-FSOC scheme:

1. Points towards a precise location on the DR.
2. Observes (because it is an optical transmission) the channel.
   - If the channel is busy, the transmitter starts a random back-off process.
   - Otherwise, it transmits with probability P_t. This probability aims to emulate the random wait of the mini-slots used by CSMA.
3. Transmits an RTS packet.
4. Receives a CTS from the AP within a time window (DIFS interval).
5. Transmits the data packet during the time interval indicated by the network allocation vector (NAV).
6. Receives acknowlegdment from AP.

The AP performs such operations as well, but as a transmitter. The following sections describe the receiver operation according to the MAC scheme used.

A. Ramdom

Figure 3 shows the flow chart of the operation of Random. If the selected beam collides with at least another beam, no CTS is issued. Otherwise, the AP issues a CTS. The figure shows the unique operations to this scheme in the lower part of the chart. After the successful transmission of data, the receiving station goes to the start of the operation, waiting for another transmission.

Random has low complexity and uses the whole area of the DR, or spatial diversity, to minimize the number of collisions. This scheme lets a transmitter select randomly any point on the DR where to project its beam. However, the scheme does not guarantee the selection of a collision-free beam as only one bean is selected.

B. Selective

Selective is a more complex scheme than Random. It also uses spatial diversity and may be more effective than Random. However, Selective requires a more complex receiver; one that can scan the DR in the search for a collision-free beam. Therefore, the receiver may require both a mechanical/software-based ATP mechanism but also a longer response time.

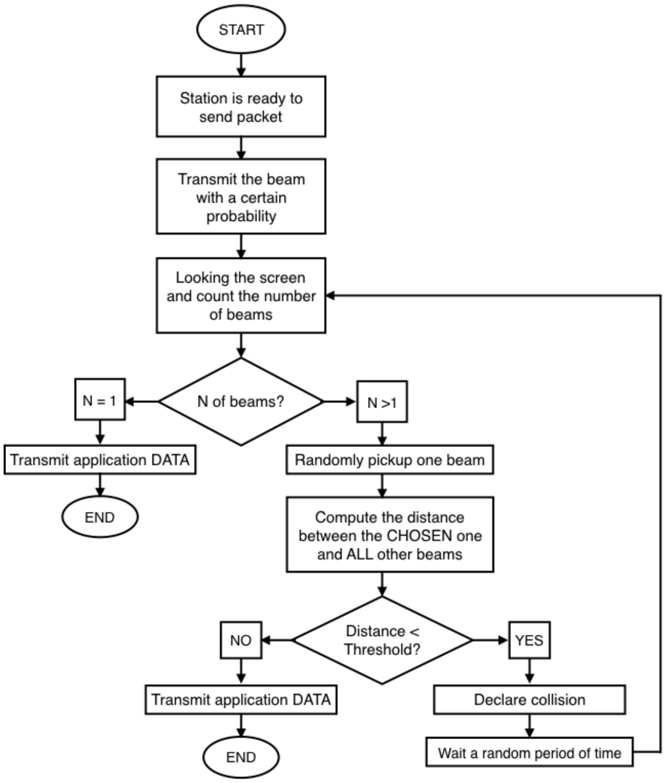

Fig. 3: Flow chart of Random.

III. PERFORMANCE STUDY

We modeled the proposed ID-FSOC MAC schemes in Python for evaluating their throughput, network channel utilization, and flow success rate as functions of the input load and the number of stations, N, in the network. We also modeled CSMA/CD and CSMA/CA for performance comparison with the proposed schemes as there are no other ID-FSOC MAC schemes at the time of writing this paper, to the best of our knowledge. We comment on the differences and similarities among these schemes. We call transmission probability, P_t, to the probability of a station to transmit a packet after finding an idle slot and when it has a packet to send (upper layers of the protocol stack on the station generate the packets). In the presented simulations, $P_t = 0.87$, such that a station is prone to transmit the packet in the next time slot. Each simulation lasts for 100,000 time slots.

A. Throughput

We define throughput as the number of frames transmitted to the AP over the number of frames generated at the stations. We first consider a network with 20 stations (i.e., $N = 20$). We present the throughput as a function of the packet generation probability, P_g, or input load. With this number of stations, the admissible input load for the network is equal to or less than 0.05 per station. Therefore, we consider an input load from 0.005 to 0.05. Figure 5 shows the throughput of the studied schemes. The figure shows that Random and Selective outperform the other schemes as these two schemes allow multiple stations to transmit RTS frames and yet, a receiver

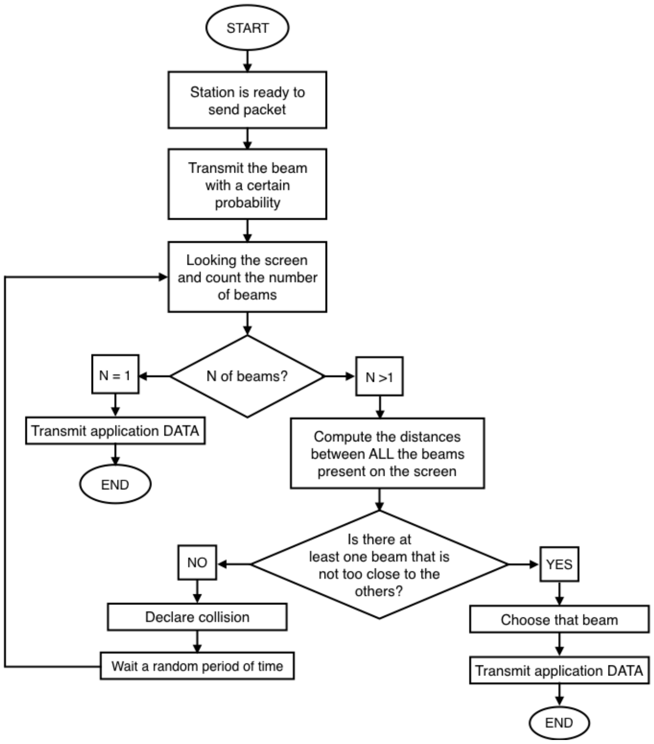

Fig. 4: Flow chart of Selective.

can establish a link with one projected beam. Therefore, a receiver may not consider projections on different places on the DR if it finds one collision-free beam. ID-FSOC may allow a larger number of requests for establishing a link as the DR area increases.

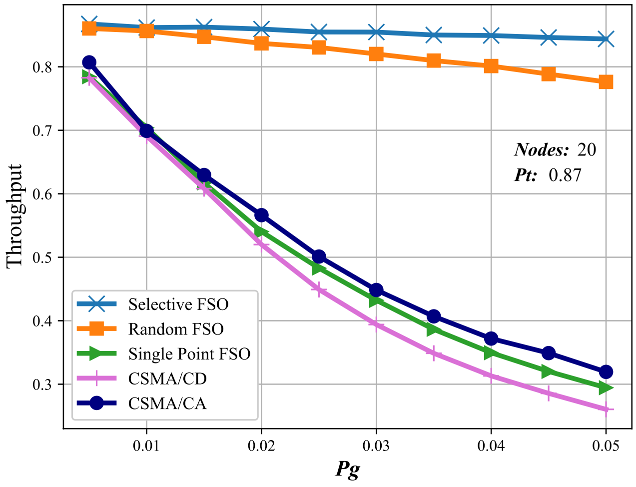

Fig. 5: Throughput of the proposed MAC schemes and compared schemes as a function of the packet generation probability.

We analyze the scalability of the ID-FSOC MAC schemes by evaluating the throughput as a function of the number of stations in the network when they access the AP. Figure 6 shows the throughput of the compared schemes with 2 to 40 stations, where each station generates traffic at $\frac{1}{20}$, as normalized load. As the figure shows, Random and Selective show more scalability as their throughput remains high as the number of stations increases. They achieve this performance because they use spatial diversity, and that reduces frequency of collisions. Yet, Selective shows the highest performance of all as it largely minimizes the number of collisions by searching for a collision-free beam on the DR. The throughput of Random slightly deteriorates as N increases. Single Point, as expected, achieves a performance similar to that of the CSMA schemes. The figure also shows that the deterioration of the throughput of the CSMA schemes is significant, especially after the stations reach the capacity of the network (i.e., 20 stations). As before, the admissible region is $1 \leq N \leq 20$ and the inadmissible one is $N > 20$.

On the other hand, Selective is unable to reach 1.0 throughput in the admissible region as there are unused time slots due to the RTS-CTS exchange and the few experienced collisions. However, the throughput of Selective remains high for inadmissible traffic. That property shows that Selective keeps finding collision-free projections despite the growth of the network.

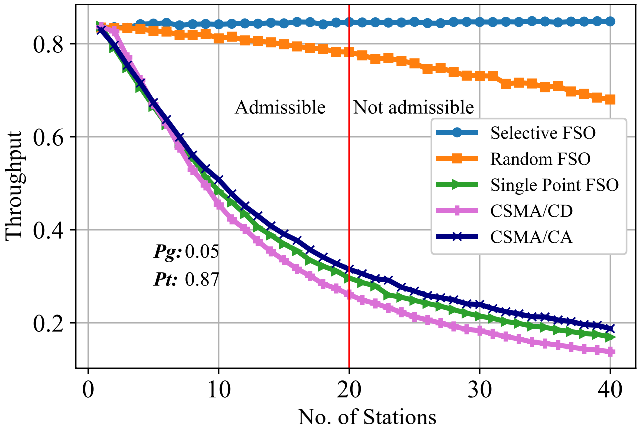

Fig. 6: Throughput of the ID-FSOC MAC and CSMA schemes as a function of the number of stations in the network.

B. Utilization

We define the utilization of the network channel as the number of transmissions achieved by all the stations in the network over the maximum number of possible transmissions. Figure 7 shows the network utilization of the compared schemes for the 20 stations. The figure shows that the network utilization of Random and Selective increase linearly as the input load increases. However, when the input load is high, Random experiences more collisions than Selective. The utilization saturates at about 0.8 for Random and at about 0.9 for Selective.

C. Flow Success Rate

We call flow success rate of a MAC scheme to the ratio of the number of successful transmissions over the number of

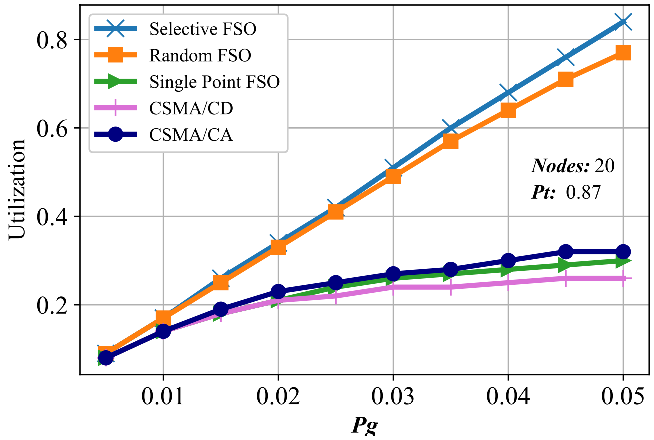

Fig. 7: Utilization of the proposed MAC schemes and compared schemes.

attempts made by the network stations. This metric indicates the efficiency of a station to avoid collisions in transmissions. Figure 8 shows the flow success rate of the proposed and compared schemes. The results show that the spatial diversity on Random and Selective dramatically improves the success of transmission attempts. Single Point shows a similar performance to that of the CSMA schemes as their channel is unique so that they are prone to collisions.

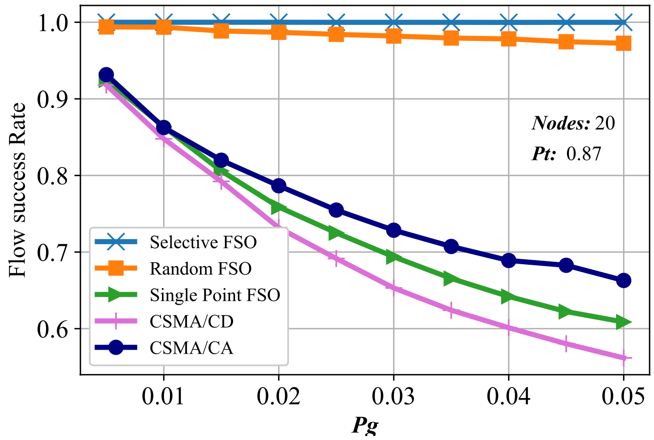

Fig. 8: Flow success rate of the proposed MAC schemes and compared schemes.

To support these observations, we counted the number of collisions experienced by the considered schemes during simulation time. Figure 9 shows the number of experienced collisions. The number of experienced collisions greatly affects the performance of the scheme. As expected, the figure shows that the schemes with spatial diversity outperform the schemes without it. Here, Selective experiences the fewest collisions, followed by Random.

D. Response Time on Beam Detection

The ID-FSOC MAC schemes proposed in this paper, specifically Random and Selective, zoom-in on the receiver to search for colliding beams, which we recall here as having multiple beams projected onto the DR within a distance of 10 cm from each other. Zooming-in the receiver may not be instantaneous; it may take some time depending on how the focusing mechanism (e.g., signal processing or mechanical [1]) works. The receiver may not be able to establish a link or transmit data during this zoom-in time. Therefore, Random and Selective may experience a reduced effective communication time as compared to Single Point and the CSMA schemes. Figure 10 shows the throughput of the proposed and comparison schemes for different zoom-in times, which are expressed as a number of time slots, for the ID-FSOC schemes. As the figure shows, the performance of Random and Selective is outstanding when the zoom-in time is negligible (or near zero time slots) but it worsens as the zoom-in time increases. We observe that the normalized throughput of Random and Selective is equivalent to that of the CSMA schemes when the zoom-in time of the receiver is about 60 time slots. For longer zoom-in times, the CSMA schemes outperform the ID-FSOC MAC schemes, in terms of normalized throughput. A very interesting observation here is that Single Point, while attaining a similar performance to that of the CSMA schemes, needs not to zoom-in as all transmissions are projected on the same point on the DR. Therefore, this scheme performs better than Random and Selective for zoom-in times longer than 60 time slots, just as is the case for the CSMA schemes.

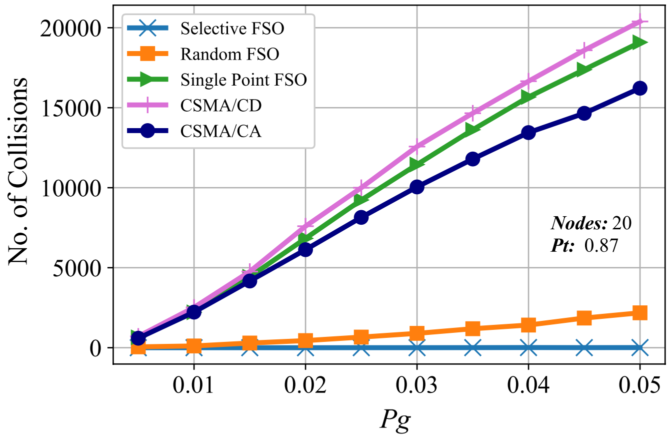

Fig. 9: Number of collisions experienced by the proposed MAC schemes and compared schemes.

Note that the number of collisions alone may not reflect the achievable data rate of the proposed schemes. For that, we consider that a beam may achieve very high data rates, of about 1 Gb/s, and RF signals (or CSMA schemes) considered here may achieve up to 54 Mb/s. Figure 11 shows an example of the achieved data rates for a zoom-in time of about 100 time slots. As the figure shows, Single Point has the advantage of requiring no zoom-in time, and therefore, it is not affected by that parameter. However, the performance of Random and Selective is lower than that of Single Point, but still significantly higher than that of the CSMA schemes.

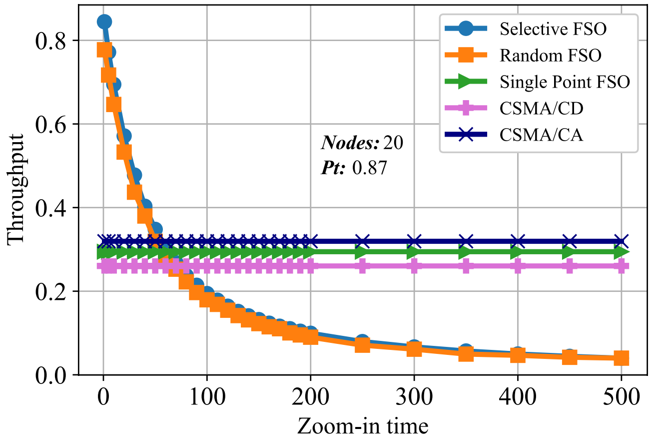

Fig. 10: Throughput of the proposed MAC schemes under different zoom-in times.

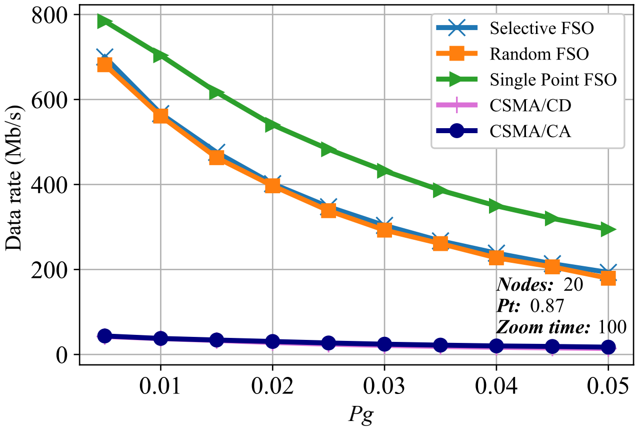

Fig. 11: Data rates according to both the active cycles used by a MAC scheme and the feasible data rates.

IV. CONCLUSIONS

We proposed three medium access schemes for indirect diffused free-space optics (ID-FSO) communication networks: Random, Selective, and Single Point, in this paper. Each of the ID-FSOC MAC schemes determines which of the transmitters communicates with the access point. In Random, the receiver randomly selects a projected beam for establishing a communication link. In Selective, the receiver searches for the diffuse reflector for a collision-free projection. In Single Point, the receiver checks a single and predetermined point on the diffuse reflector for a collision-free reflected beam. Random and Selection may use spatial diversity, which is inherent to ID FSOC, and that improves network access. We showed the performance of the proposed scheme in terms of throughput and compared them to those of CSMA/CD and CSMA/CA. We showed that the ID FSOC MAC schemes achieve higher throughput than the RF counterparts, not only because they can transmit at higher data rates but also because they use spatial diversity. Despite Selective being more complex than Random, it may not achieve much higher throughput than Random because the search process may require additional time cost that lowers utilization. On the other hand, Random seems to be simple and scalable.

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