POLITECNICO DI TORINO

Department of Electronics and Telecommunications

Master's Degree program in

ICT for Smart Societies

Master Thesis

Development of a new MAC protocol for Indirect Diffused Free Space Optical Communications.

Supervisors:

Michela Meo

Roberto Rojas-Cessa (NJIT)

Candidate:

Nicolò Macaluso

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Dedico questo lavoro ai miei genitori, Elisa e Aldo, per avermi sempre sostenuto, spronato e per avermi dato la possibilità di intraprendere e portare a compimento questo traguardo nel migliore dei modi.
A mia sorella Alice che mi è stata vicina nei momenti più difficili.
Ai miei fantastici nonni.
Ai miei più cari amici e a tutti quelli che mi hanno accompagnato durante questi cinque anni.

Abstract

In this thesis, a set of three media access control (MAC) schemes for an indirect diffused light free-space optical communications (ID-FSOCs) are proposed. ID-FSOC has been recently proposed to establish wireless high-speed (i.e., greater or equal to 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. Obviously if we want to use a technology that relies on optical communication and laser light we need to investigate new protocols, never standardized before, to deal with this physical characteristics. The performance and scalability of proposed schemes are analyzed; and also the impact of the zoom-in time of a receiver is considered in the evaluation. Results show that the proposed MAC schemes achieve high channel utilization and higher throughput than carrier-sense multiple access schemes.

POLITECNICO DI TORINO

1859 1906

NJIT

New Jersey Institute of Technology

Contents

1 Introduction

1.1 Overview

With the introduction of technology in everyday life, communication protocols are becoming increasingly important. Even though oral communication is still preferred among people, nowadays, in the 21st century the majority of ways people communicate involve: technology, sensors and smartphones independently from age, race and gender of the users. This is why in every field of communication the goal is to achieve higher speed and higher reliability, in order to make the telecommunication easier and accessible from everywhere and by everyone.

The Internet is undoubtedly the most effective and far-reaching communication tool we have at present. Communication on the Internet is free and fast. We all are connected with each other on various computers and IP. Indeed we are also using standardized communication protocols but the Internet evolves constantly by using artificial intelligence and search engines to find out how we communicate, how this can be made simpler for us to use and have a better experience in the shortest possible time. Wireless technology applied to the ICT has changed our lives drastically during last years, as shown in Fig. 1.1 and has a great potential to improve our life quality.

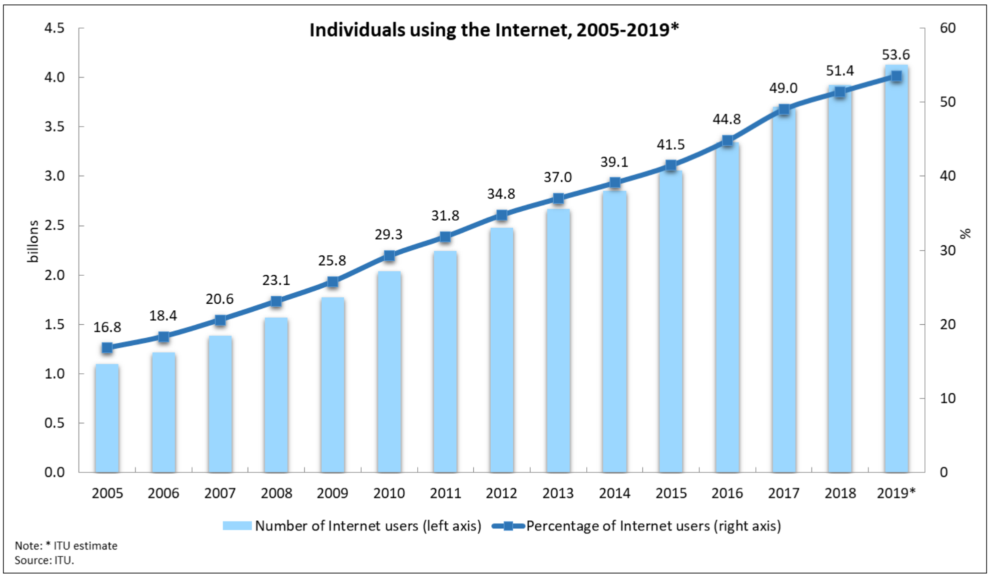

***Fig. 1.1**: Individuals using the Internet [1].*

The ever changing mix and growth of wireless devices that are accessing mobile networks worldwide is one of the primary contributors to global mobile traffic growth. Each year several new devices in different form factors and with increased capabilities and intelligence are introduced in the market. In the last couple of years, we have seen a rise of phablets and more recently we have seen many new M2M connections coming into the mix. More than 600 million mobile devices and connections were added in 2017. In 2017, global mobile devices and connections grew to 8.6 billion, up from 7.9 billion in 2016. Globally, mobile devices and connections will grow to 12.3 billion by 2022 at a compound annual growth rate (CAGR) of 7.5 percent (Fig. 1.2). By 2022, there will be 8.4 billion handheld or personal mobile-ready devices and 3.9 billion M2M connections. [2]

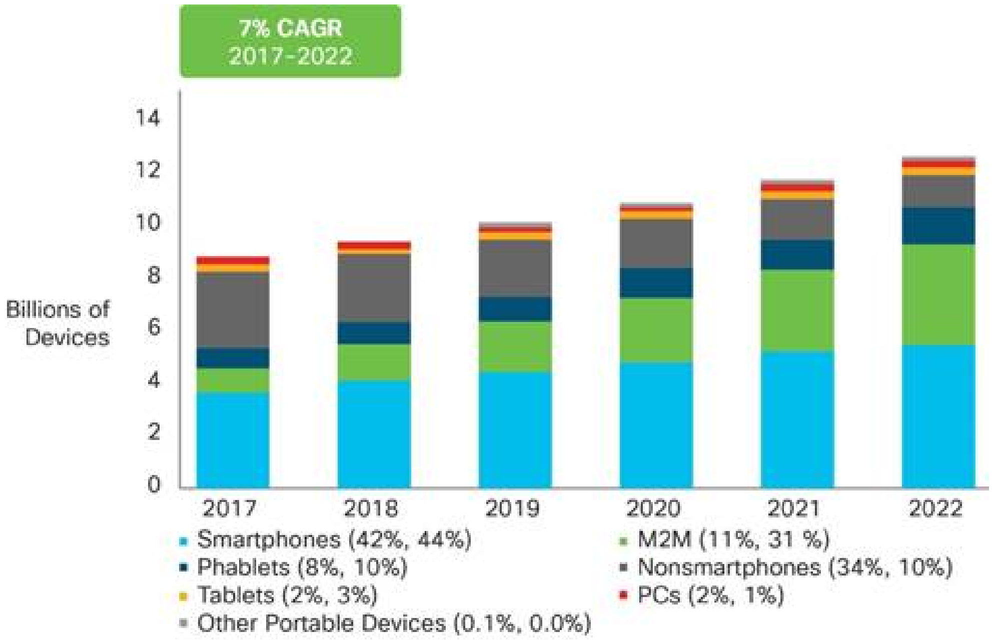

***Fig. 1.2**: Global mobile devices and connections growth[2].*

Mobile devices and connections are not only getting smarter in their computing capabilities but are also evolving from lower-generation network connectivity (2G) to higher-generation network connectivity (3G, 3.5G, 4G or LTE and now also 5G). This is the second year, that we are projecting the growth of devices and connections with 5G connectivity based on some initial trial deployments (limited in scope) and larger-scale commercial efforts that are planned in the future for various locations around the world. Combining device capabilities with faster, higher bandwidth and more intelligent networks will facilitate broad experimentation and adoption of advanced multimedia applications that contribute to increased mobile and Wi-Fi traffic (Fig. 1.3). The explosion of mobile applications and the expanded reach of mobile connectivity to a growing number of end users has prompted the need for optimized bandwidth management and new network monetization models to sustain a maturing mobile industry. In a highly competitive mobile market, we have seen the growth of global 4G deployments as well as earlystage 5G implementations. Service providers globally are busy rolling out 4G networks to help them meet the growing end-user demand for more bandwidth, higher security, and faster connectivity on the move. Many providers have also started field trials for 5G and are gearing towards rolling out 5G deployments towards the middle of the forecast period to capture new market opportunities.

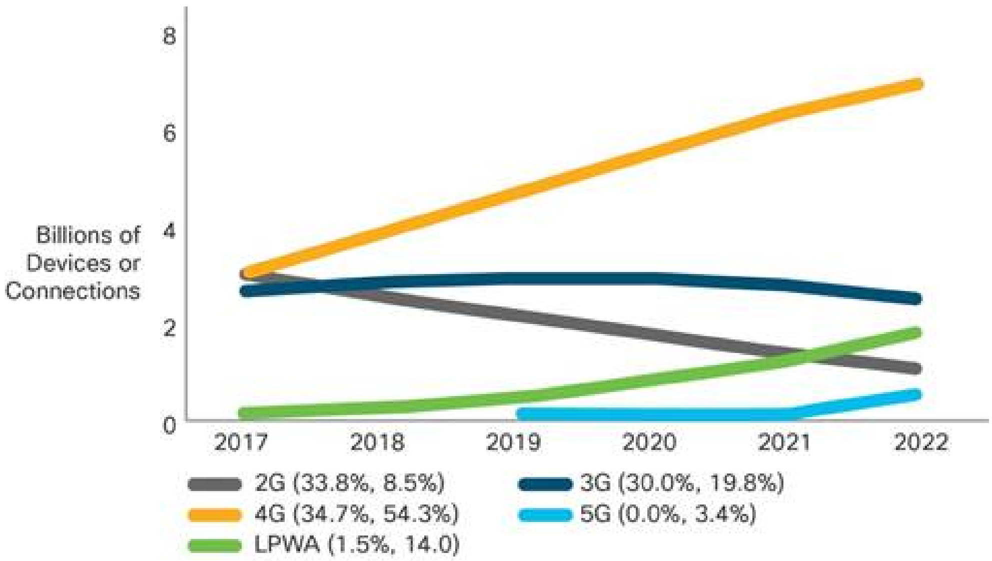

Fig. 1.3*: Global mobile devices and connections by network type[2].*

The speed at which data can travel to and from a mobile device can be affected in two places: the infrastructure speed capability outside the device and the connectivity speed from the network capability inside the device (Fig. 1.4).

These speeds are actual and modeled end-user speeds and not theoretical speeds that the devices, connection, or technology is capable of providing. Several variables affect the performance of a mobile connection: rollout of 2G, 3G, and 4G, and now 5G in various countries and regions, technology used by the cell towers, spectrum availability, terrain, signal strength, standard ratifications and number of devices sharing a cell tower. The type of application the end user uses is also an important factor. Increase in speeds by 2022 is due to the expected rollout and commercial deployment of 5G.

Download speed, upload speed, and latency characteristics vary widely depending on the type of application, be it video, radio, or instant messaging.

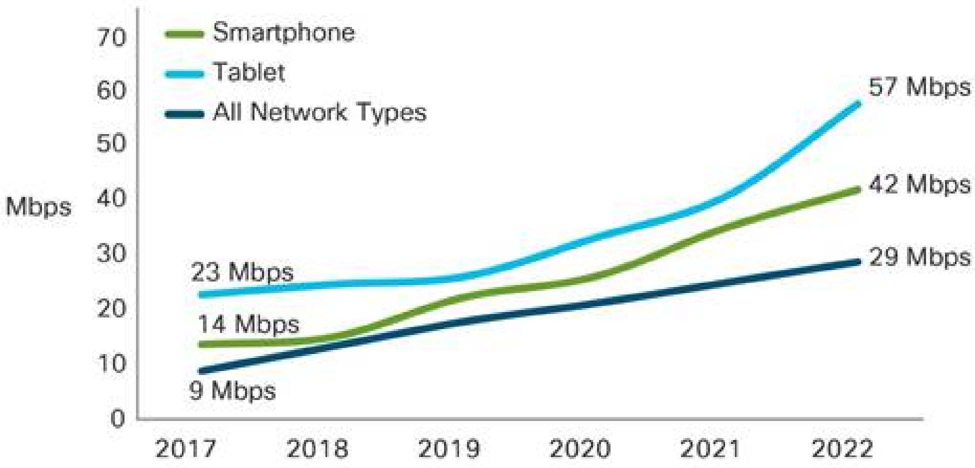

Fig. 1.4*: Mobile speed by device [2].*

Mobile connectivity has become essential for many network users. Most people already consider mobile voice service a necessity, and mobile voice, data, and video services are fast becoming an integral part of consumers and business users' lives. Used extensively by consumer as well as enterprise segments, with impressive uptakes in both developed and emerging markets, mobility has proved to be transformational. The number of mobile subscribers has grown rapidly, and bandwidth demand for data and video content continues to increase. Mobile M2M connections represent the fastest growing device/connection category in our forecast. The next 5 years are projected to provide unabated mobile video adoption. Backhaul capacity and efficiency must increase so mobile broadband, data access, and video services can effectively support consumer usage trends and keep mobile infrastructure costs in check. We continue to see evolution of mobile networks. While 4G or LTE connectivity is forecasted to have the primary share of the market, there are field trials currently underway for 5G in some countries. Deploying next-generation mobile networks requires greater service portability and interoperability. With the proliferation of mobile and portable devices, there is an imminent need for networks to allow all these devices to be connected transparently, with the network providing high-performance computing and delivering enhanced real-time video and multimedia. New network capabilities have generated uptake of newer advanced mobile services such as augmented reality and virtual reality. We find that this continuous evolution towards enhanced bandwidth, latency, security and openness of mobile networks will broaden the range of applications and services that can be deployed, creating a highly enhanced mobile broadband experience. The expansion of wireless access (both cellular and Wi-Fi) will increase the number of consumers who can access and subsequently rely on mobile networks, creating a need for greater economies of scale and lower cost per bit [2].

As many business models emerge with new forms of advertising; media and content partnerships; and mobile services including M2M, live gaming, and augmented and virtual reality, a mutually beneficial situation needs to be developed for service providers and over-the-top providers. New partnerships, ecosystems, and strategic consolidations are expected to further transform the wireless networking landscape as mobile operators, content providers, application developers, and others seek to monetize the content, services, and communications that traverse mobile networks. Operators must solve the challenge of effectively monetizing video traffic while developing profitable business cases that support capital infrastructure expenditures needed for 5G. They must become more agile and able to change course quickly and provide innovative services to engage and retain a wide range of customers from technology savvy to technology agnostic. While the net neutrality regulatory process and business models of operators evolve, there is an unmet demand from consumers for the highest quality and speeds. There is a definite move towards wireless technologies becoming seamless with wired networks for ubiquitous connectivity and experiences. The next few years will be critical for operators and service providers to plan future network deployments that will create an adaptable environment in which the multitude of mobile-enabled devices and applications of the future can be deployed.

1.2 Communication protocols

What is a communication protocol? communication protocols are formal descriptions of digital message formats and rules. Protocols are required for exchanging messages in or between computing systems and are necessary in telecommunications. Communication protocols may include authentication, error detection/correction, and signaling functions, among others. They can also describe the syntax, semantics, and synchronization of analog and digital communications. Communication protocols are implemented in hardware and software, and computer networks cannot exist without them. Communications devices have to agree on many physical aspects of the data to be exchanged before successful transmission can take place. Rules defining transmissions are called protocols. There are many properties of a transmission that a protocol can define. Common ones include: packet size, transmission speed, error correction types, handshaking and synchronization techniques, address mapping, acknowledgement processes, flow control, packet sequence controls, routing and address formatting [3].

In modern designs, protocols are layered. This means that layers (of protocols) handle the transfer of data from one computer/device to another computer/device. Each layer performs a particular function. TCP/IP and OSI are the most widely used communication networking protocols. The main difference is that OSI is a conceptual model that's not practically used for communication. Rather, it defines how applications can communicate over a network. TCP/IP, on the other hand, is widely used to establish links and network interaction. The TCP/IP protocols lay out standards on which the internet was created, while the OSI model provides guidelines on how communication has to be done [4]. Therefore, TCP/IP is a more practical model. These are the seven layers of the OSI model:

Layer 7, the application layer, lets the user (software or human) interact with the application or network when the user wants to read messages, transfer files or engage in other network-related activities.

Layer 6, the presentation layer, translates or formats data for the application layer based on the semantics or syntax that the app accepts.

Layer 5, the session layer, sets up, coordinates and terminates conversations between apps.

Layer 4, the transport layer, handles transferring data across a network and providing error-checking mechanisms and data flow controls.

Layer 3, the network layer, moves data into and through other networks.

Layer 2, the data-link layer, handles problems that occur as a result of bit transmission errors.

Layer 1, the physical layer, transports data using electrical, mechanical or procedural interfaces. TCP/IP specifies how data is exchanged over the internet by providing end-to-end communications that identify how it should be broken into packets, addressed, transmitted, routed and received at the destination. TCP/IP requires little central management, and it is designed to make networks reliable, with the ability to recover automatically from the failure of any device on the network. These are the four layers of the TCP/IP model:

The application layer provides applications with standardized data exchange. Its protocols include the HTTP, FTP, Post Office Protocol 3 (POP3), Simple Mail Transfer Protocol (SMTP) and Simple Network Management Protocol (SNMP). At the application layer, the payload is the actual application data.

The transport layer is responsible for maintaining end-to-end communications across the network. TCP handles communications between hosts and provides flow control, multiplexing and reliability. The transport protocols include TCP and User Datagram Protocol (UDP), which is sometimes used instead of TCP for special purposes [4].

The network layer, also called the internet layer, deals with packets and connects independent networks to transport the packets across network boundaries. The network layer protocols are the IP and the Internet Control Message Protocol (ICMP), which is used for error reporting.

The physical layer, also known as the network interface layer or data link layer, consists of protocols that operate only on a link -- the network component that interconnects nodes or hosts in the network. The protocols in this lowest layer include Ethernet for local area networks (LANs) and the Address Resolution Protocol (ARP).

TCP/IP is nonproprietary and, as a result, is not controlled by any single company. Therefore, the Internet Protocol suite can be modified easily. It is compatible with all operating systems, so it can communicate with any other system. The Internet Protocol suite is also compatible with all types of computer hardware and networks; TCP/IP is highly scalable and, as a routable protocol, can determine the most efficient path through the network. It is widely used in current internet architecture.

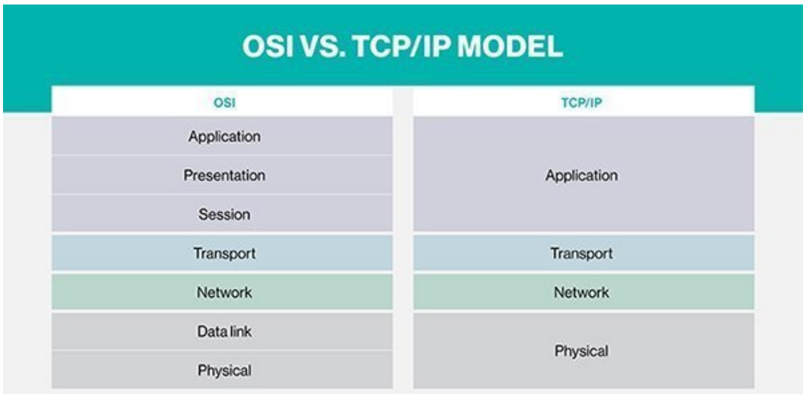

Fig. 1.5: *OSI vs. TCP/IP model [4].*

We will focuses only on the data link layer in the OSI architecture model, especially on the MAC sublayer that handles the moving of data into and out of a physical link in a network. Data bits are encoded, decoded and organized in the data link layer, before they are transported as frames between two adjacent nodes on the same LAN or WAN. The data link layer also determines how devices recover from collisions that may occur when nodes attempt to send frames at the same time.

1.3 Spectrum management

Spectrum management, what is it?

Spectrum management is the process of regulating the use of radio frequencies to promote efficient use and gain a net social benefit. The term radio spectrum typically refers to the full frequency range from 3 kHz to 300 GHz that may be used for wireless communication, as shown in Fig. 1.4. Increasing demand for services such as mobile telephones and many others has required changes in the philosophy of spectrum management. Demand for wireless broadband has soared due to technological innovation, such as 4G and 5G mobile services, and the rapid expansion of wireless internet services [5].

Since the 1930s, spectrum was assigned through administrative licensing. Limited by technology, signal interference was once considered as a major problem of spectrum use. Therefore, exclusive licensing was established to protect licensees' signals. This former practice of discrete bands licensed to groups of similar services is giving way, in many countries, to a "spectrum auction" model that is intended to speed technological innovation and improve the efficiency of spectrum use. During the experimental process of spectrum assignment, other approaches have also been carried out, namely-lotteries, unlicensed access, and privatization of spectrum.

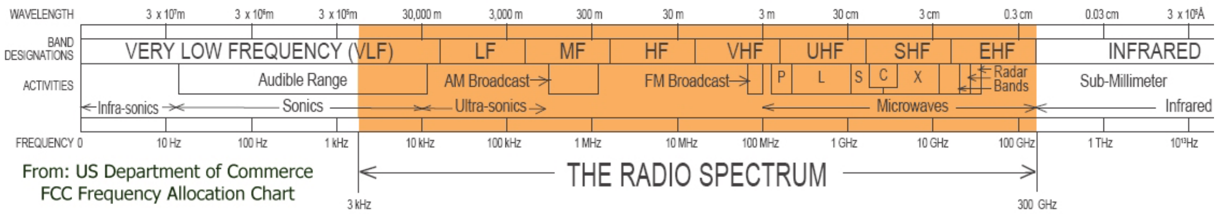

***Fig. 1.6**: Radio spectrum [6].*

Effective use of spectrum can make a big difference to a country's prosperity, especially where communications are heavily reliant upon wireless technologies such as mobile phones. Spectrum scarcity whether it is real or artificial can have an adverse impact upon prosperity. This is why nowadays when the spectrum is going to be saturated, we need to find new resources and new way to communicate. Introduction and expansion of new services is seriously impeded in the absence of effective spectrum management structures. The major objective of BDT (Telecommunication Development Bureau) work in this area is to strengthen national regulatory bodies in frequency planning and assignment, management and monitoring, setting fees for spectrum utilization. BDT provides assistance in various aspects of spectrum management including efficient tools for managing the spectrum [7].

Obviously, the ways machines can communicate are various: radio frequencies, wired cable and optical fiber, all relying on communication schemes already standardized since many years. Another way communication is possible is by using the space we live in, without any kind of complex and expensive infrastructure: free-space optical communication system based on laser light, but for the time being the theme has not been properly addressed.

1.4 Goals of the thesis

This thesis focuses on the formulation of new MAC protocol schemes for a novel indirect diffused light free-space optical communications (ID-FSOC) system based on laser light. The considered system aiming to extend the FSOC reach to locations that have no Line-Of-Sight from the transmitter. The first step is to explain that the proposed MAC schemes inherit features from wired and wireless multiple access schemes based on the properties of ID-FSO, and after that we show that these schemes will reach high channel utilization and achieve higher throughput than Wi-Fi access schemes. In order to support these claims we show the performance of ID-FSO under different scenarios.

This field of study really interested me because of its novelty and possible outbreak in the following years. Obviously another factor drives me through this direction is the moving on of the technology, all other ways in which machines are communicating right now will become out of date, or at least will become slower. Therefore in my opinion it is a good idea try to find other way to communicate, faster and that covers higher distances. Another critical factor is the saturation of the spectrum of RF and the linked difficulties in finding always new band in which transmit, a possible solution of the problems could be ID-FSOC, anyhow this is what I want to demonstrate with my thesis.

Obviously if we want to use a technology that relies on optical communication and laser light we need to find new protocols, never standardized before, to deal with this physical characteristics. Most of the work consists in the implementation of a MAC protocol simulator, used to run five different simulation scenarios, in order to evaluate the performances of using different communication protocols and architectures. Initially, the simulated protocols were the well-known Wi-Fi and Ethernet (IEEE 802.11 and 802.3), then the developed protocols are Random, Selective and Single Point. In summary, the three main goals of this thesis are the following:

- We propose three MAC ID-FSO schemes based on laser light, ID-FSO communications do not require a direct LOS between transmitter and receiver. We believe that this is the first proposal of such ID-FSOC MAC schemes.
- We propose the use of diffuse reflectors to extend the LOS of FSOC, which enables communications within a wide coverage area, since a receiver with LOS to the reflector may access it with any angle of view (up to 90◦) so that the receiver's location is widely relaxed.
- We show that ID-FSOC is able to achieve high-data rates using an existing sensitive photodiode as receiver and for different distances between the diffuse reflector and the receiver.

The whole work leads to a publication, presented during Sarnoff 2019 conference, in partnership with NJIT University and especially with professor Roberto Rojas-Cessa. The paper entitled "Media Access Schemes for Indirect Diffused Free-Space Optical Networks " has been accepted by Sarnoff and it has been proposed as one of the three which later will be published

1.5 Organization of the thesis

The entire project is structured in six chapters. Chapter 1 is the introduction, in which the thesis is described at a glance. Chapter 2 is about the State of The Art of the communication protocols at level MAC. More precisely, it describes the communication schemes that inspire the new ones; and the current state of the FSO communication is contextualized. Chapter 3 introduces the MAC protocols formulated and it is the core of the thesis. Chapter 4 explains in detail the implementation of the algorithm (Python code) that has been developed to run all the simulations. Chapter 5 is the presentation and the explanation of the results. Chapter 6 draws conclusions for the overall work and suggests future developments, focusing on the possible application of the protocols to other fields of study.

2 State of the art

2.1 Medium Access Control protocols

In order to explain the protocols that has been developed, this chapter introduces the concept of medium access control (MAC) protocol in the most used communication system i.e. the ones applied to radio frequencies and wired system. Medium Access Control protocols are mechanisms that allow users to access a common medium or channel. Their variants, Aloha, slotted Aloha, Carrier Sense Multiple Access with Collision Detection and Collision Avoidance are used a great deal in communication networks [8].
MAC is the protocol layer that transfers data between adjacent network nodes in a wide area network or between nodes on the same local area network. The data link layer provides the functional and procedural means to transfer data between network entities and might provide the means to detect and possibly correct errors that may occur in the physical layer. When devices attempt to use a medium simultaneously, frame collisions occur. Data-link protocols specify how devices detect and recover from such collisions, and in some cases provide mechanisms to reduce or prevent them.

Fig. 2.1 represents the subdivision of the Medium Access Control protocols:

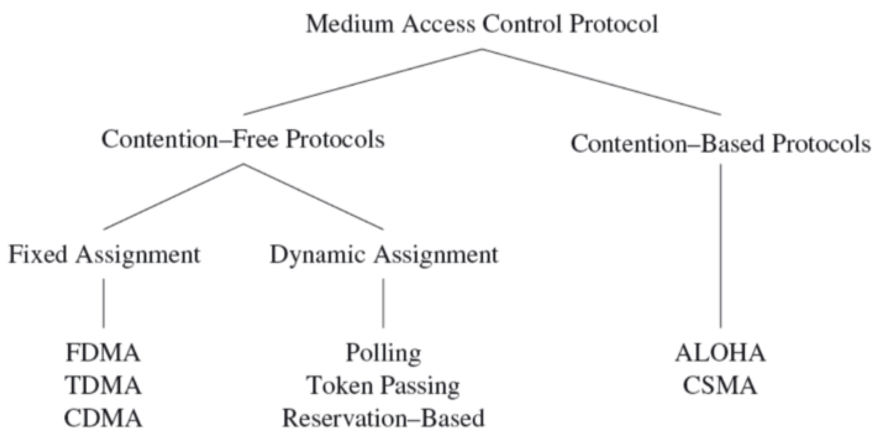

***Fig. 2.1**: Medium Access Control schemes [8].*

Contention-free protocol will be briefly discussed, they are subdivided in two different types, identified by the kind of assignment:

- Fixed assignment:
    - Frequency Division Multiple Access (FDMA) in which frequency band is divided into several smaller frequency bands; the data transfer between a pair of nodes uses one frequency band, instead all the other nodes use a different frequency band.
    - Time Division Multiple Access (TDMA) in which multiple devices are allowed to use the same frequency bands; it relies on periodic time windows (frames). Frames consists of a fixed number of transmission slots to separate the medium accesses of different devices. A time schedule indicates which node may transmit data during a certain slot.
    - Code Division Multiple Access (CDMA) in which simultaneous accesses of the wireless medium are supported using different codes; if these codes are orthogonal, it is possible for multiple communications to share the same frequency band. At the receiver it is exploited Forward Error Correction to recover from interreferences among these simultaneous communications.

But since fixed assignment are inefficient for the following reasons:

- Impossible to re-allocate slots belonging to one device to other devices if not needed in every frame
- Generating schedules for an entire network can be a taunting task
- These schedules may require modification every time the network topology or traffic characteristics in the network change.

We need to use dynamic assignment, that allow nodes to access the medium on demand.

- Dynamic assignment:
    - Polling-based protocols: a contention device issues a small polling frames in a round-robin fashion, asking each station if it has data to send , if no data to be sent, the controller polls another station.
    - Token passing: stations pass a polling request to each other using a special frame called token, a station is allowed to transmit only when it holds the token
    - Reservation-based protocols: static time slots are used to reserve future access to the medium , each node can indicate its desire to transmit data toggling a reservation bit in a fixed location

Contention-based protocol are used because nodes may initiate transmissions at the same time, so it is required a technique useful to reduce the number of collisions and to recover from them. Since these protocol do not rely on transmission schedules, they require other mechanism to resolve contention when it occurs. The main advantage of contention-based is their simplicity compared to the most scheduled-based. We will focus on these protocols also because they are more similar to the ones proposed in this thesis.

2.1.1 Aloha

Following a chronological order of development, the first protocol to be described is Aloha, which is the earliest random access method developed, it was designed for a radio (wireless) LAN, but it can be used in any kind of shared medium. The scenario is the following: many transmitter, one single receiver as shown in Fig. 2.2. It is obvious that there are potential collisions in this arrangement; the medium is shared between the stations. When a station sends data, another station may attempt to do so at the same time, data from the two stations collide and become garbled.

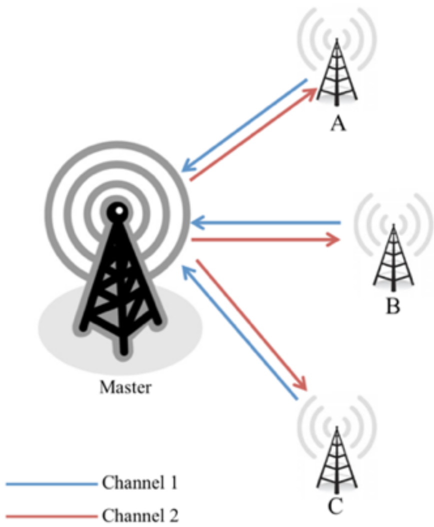

***Fig. 2.2**: Aloha scenario.*

Aloha is the first protocol developed obviously because it has an easy implementation, it does not require any kind of synchronization and it can start the transmission whenever a station wants. The acknowledgment of the correct receipt is on another channel so there is no collision at all. The only negative aspect is that the probability to have a collision is very high, especially with an elevated number of transmitting stations.

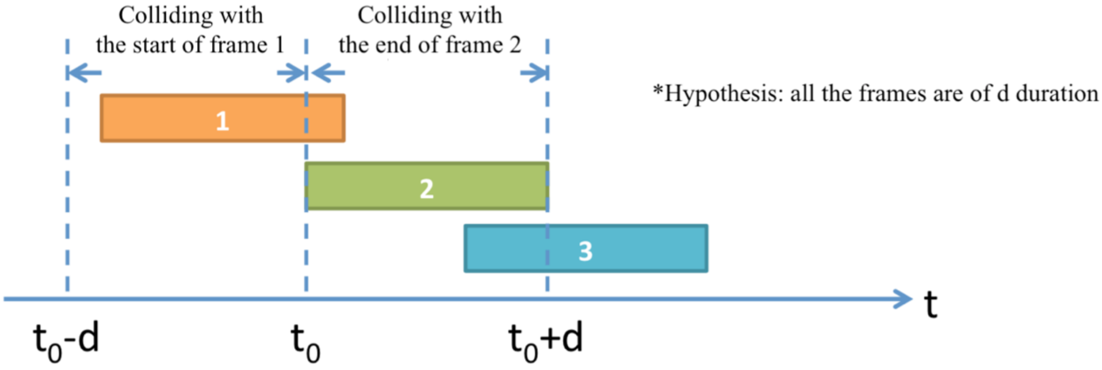

Fig. 2.3*: Aloha timeline, with collision.*

As shown in Fig. 2.3 there is the possibility that the final part of one frame collide with the first part of the next one and vice-versa. The way in which collisions are tried to be resolved is the back-off strategy: the colliding station decides to wait a random period of time before transmitting again the frame. The time is random for interrupting the determinism in the transmission, another collision between the same two stations will occur with probability 1 only if the random extracted back-off value is the same; but if this happens, the back-off is doubled (exponential back-off).

2.1.2 Slotted Aloha

We have an enhancement of the Aloha protocol with its successor: Slotted Aloha. The main difference here is that the time is divided in slots of one packet duration, when a node have a packet to send , it waits until the start of the next time slot to send it; obviously this procedure requires synchronization between stations. If no other nodes attempt transmission during that time slot, the transmission is successful, otherwise there is a collision. Colliding packets are re-transmitted after a random back-off.

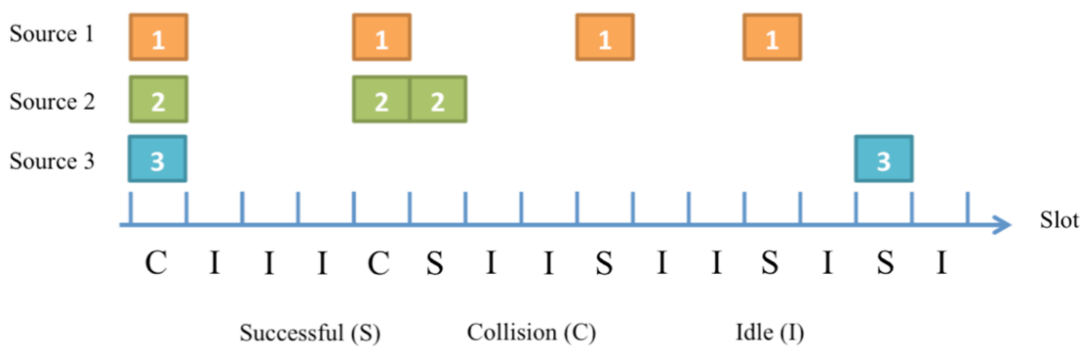

Fig. 2.4*: Slotted Aloha timeline.*

The collision probability is a lower than the one of Aloha but also slotted Aloha is a simple protocol and so not so effective, that's why they are unsteady and they cannot reach high throughput value.

2.1.3 CSMA

In order to solve the problems present in Aloha and slotted Aloha, another scheme is introduced: Carrier Sense Multiple Access. CSMA technique relies on the sender sensing the state of the transmission channel and basing its actions on this. It can therefore only be effectively used in channels which have short propagation delays, since for channels with long delays (e.g. satellite) the sensed data is considerably out of date. In a perfect channel (zero transmission delay) the sender could listen to the state of the channel when it was ready to transmit, and only send when the channel was free, so avoiding any collision and increasing the possible reachable throughput.

If the channel is busy, three way to proceed are possible (Fig. 2.5):

1. CSMA 1-persistent: waiting for the channel to be idle and then immediately transmit
2. CSMA non-persistent: sense the channel after a random period of time and then transmit
3. CSMA p-persistent: waiting for the channel to be idle and then transmit with probability p

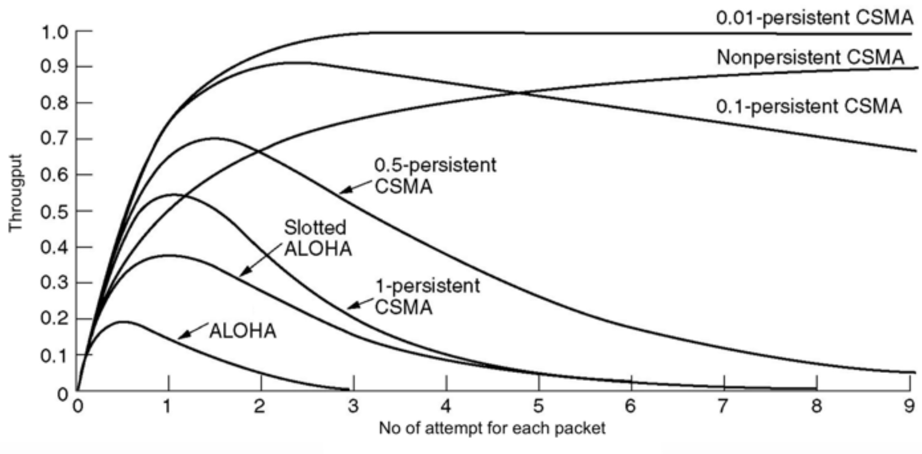

Fig. 2.5: Different performance depending on persistence [9].

2.1.3.1 CSMA/CD

Carrier Sense Multiple Access with Collision Detection (CSMA/CD) is mainly used in half-duplex ethernet networks. This algorithm helps devices on the same network segment to decide when to send packets and what to do in case of collisions. CSMA/CD is commonly used in networks with repeaters and hubs because these devices run in the half-duplex mode and all of their ports are in the same collision domain [10].

Consider a scenario where there are *n* stations on a link (Fig. 2.6) and all are waiting to transfer data through that channel. In this case all *n* stations would access the link to transfer their own data. Problem arises when more than one station transmits the data at the same instant. In this case, there will be collisions in the data from different stations. CSMA/CD is one such technique where different stations that follow this protocol agree on some terms and collision detection measures for effective transmission. This protocol decides which station will transmit, doing that data reaches the destination without corruption.

The algorithm works following these steps:

- Check if the sender is ready for transmitting data packets.
- Sender has to keep on checking if the transmission link/medium is idle. In order to do this, it continuously senses transmissions from other nodes. Sender sends dummy data on the link, if it does not receive any collision signal, this means the link is idle at the moment; if it senses that the carrier is free and there are no collisions, it sends the data. Otherwise it refrains from sending data.
- Transmit the data and check for collisions. Sender transmits its data on the link. CSMA/CD does not use acknowledgement system. It checks for the successful and unsuccessful transmissions through collision signals. During transmission, if collision signal is received by the node, transmission is stopped. The station then transmits a jamming signal that causes all the participants on the network to stop sending data and waits for random time interval before it resends the frame. After some random time, it again attempts to transfer the data and repeats above process.
- If no collision was detected in propagation, the sender completes its frame transmission and resets the counters.

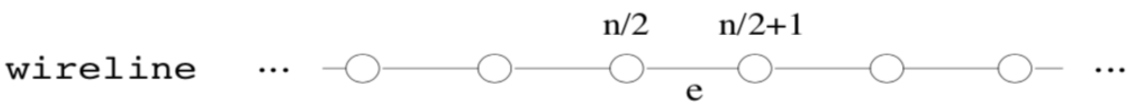

Fig. 2.6: Example of possible wired LAN.

CSMA/CD is specified in the IEEE 802.3 standard and the block diagram is shown in Fig.2.7.

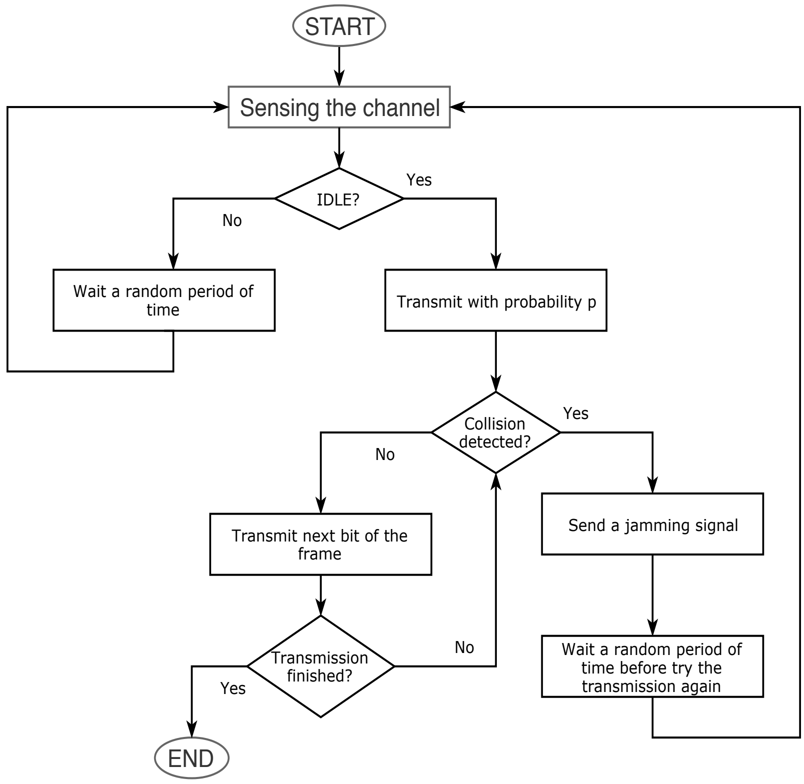

Fig. 2.7: CSMA/CD block diagram.

2.1.3.2 CSMA/CA

CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) is a protocol for carrier transmission in 802.11 networks, the ones used in Wi-Fi protocol (Fig 2.8). Unlike CSMA/CD which deals with transmissions after a collision has occurred, CSMA/CA aims to prevent collisions before they happen [10].

In CSMA/CA, as soon as a node receives a packet that has to be sent, it checks whether the channel is clear (i.e., no other node is transmitting at the time). If the channel is clear, then the packet is sent. If the channel is not clear, the node waits for a randomly chosen period of time, and then checks again to see if the channel is clear. This period of time is called the back-off factor, and is counted down by a counter. If the channel is clear when the back-off counter reaches zero, the node transmits the packet, if the channel is not clear when it reaches zero, the back-off factor is set again, and the process is repeated. Collision avoidance is used to improve the performance of the CSMA method by attempting to divide the channel somewhat equally among all transmitting nodes within the collision domain.

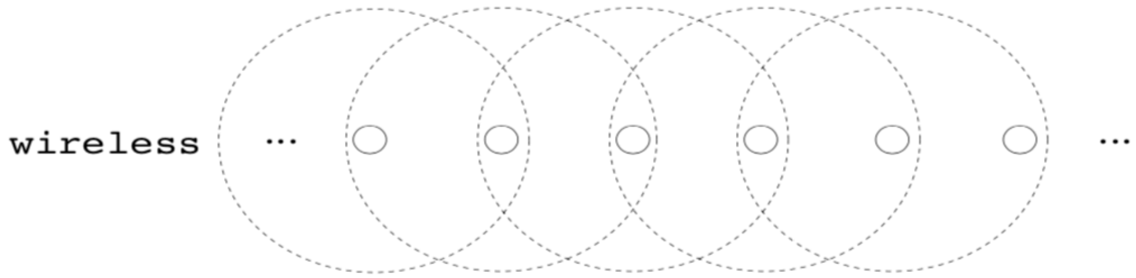

***Fig. 2.8**: Example of possible wireless LAN.*

The algorithm works following these steps:

- Check if the sender is ready for transmitting data packets.
- Carrier Sense: before transmitting a node listens to the shared medium (such as listening for wireless signals in a wireless network) to determine whether another node is transmitting or not.
- Collision Avoidance: if another node was heard, we wait for a period of time (usually random) for the node to stop transmitting before listening again for a free communications channel.
- Request to Send/Clear to Send (RTS/CTS) (Fig.2.10) may optionally be used at this point to mediate access to the shared medium. This goes some way to alleviating the problem of hidden nodes because, for instance, in a wireless network, the Access Point only issues a Clear to Send to one node at a time. However, wireless 802.11 implementations do not typically implement RTS/CTS for all transmissions; they may turn it off completely (Fig.2.9), or at least not use it for small packets since the overhead of RTS, CTS and transmission is too great for small data transfers.
- Transmission: if the medium was identified as being clear or the node received a CTS to explicitly indicate it can send, it sends the frame in its entirety. Continuing the wireless example, the node awaits receipt of an acknowledgement packet from the Access Point (AP) to indicate the packet was received and check summed correctly. If such acknowledgement does not arrive in a timely manner, it assumes the packet

collided with some other transmission, causing the node to enter a period of binary exponential back-off before attempting to re-transmit.

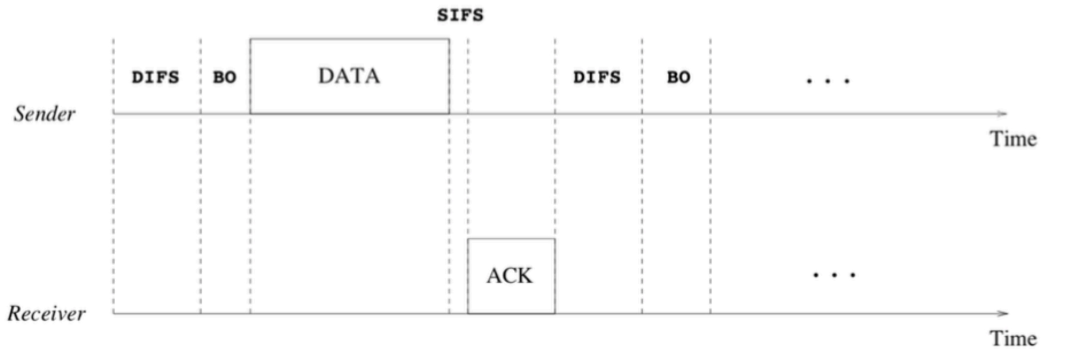

Fig. 2.9*: CSMA/CA example without handshaking and without collision.*

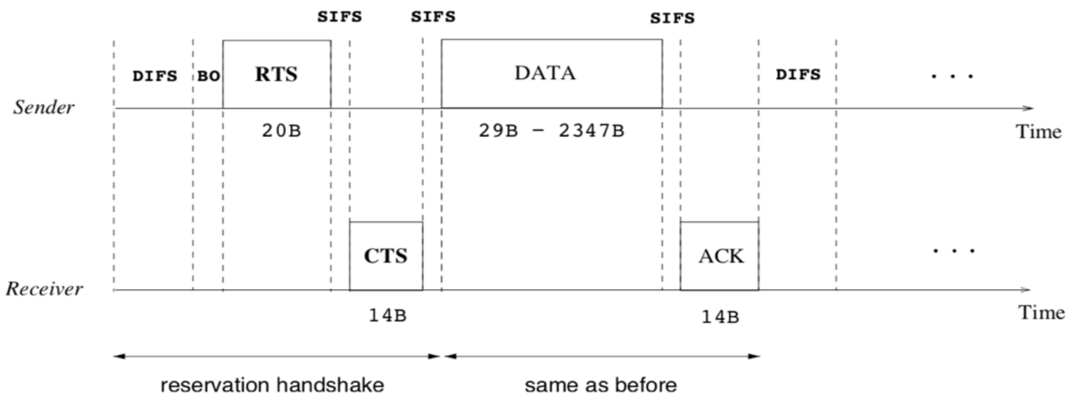

Fig. 2.10*: CSMA/CA example with handshaking.*

Although CSMA/CA has been used in a variety of wired communication systems, it is particularly beneficial in a wireless LAN (Fig 2.8) due to a common problem of multiple stations being able to see the Access Point, but not each other. This is due to differences in transmit power, and receiver sensitivity, as well as distance, and location with respect to the AP. This will cause a station to not be able to "hear" another station's broadcast. This is the so called "hidden station" problem. Devices utilizing 802.11 based standards (Fig. 2.11) can enjoy the benefits of collision avoidance (RTS / CTS handshake), although they do not do it by default. By default they use a Carrier sensing mechanism called Distributed Coordination

Function (DCF) that relies upon a station attempting to wait for another station's broadcast before sending. CA relies upon the AP granting a station the exclusive right to transmit for a given period of time after requesting it. Two problems arises with the use of CMSA/CA used in 802.11.

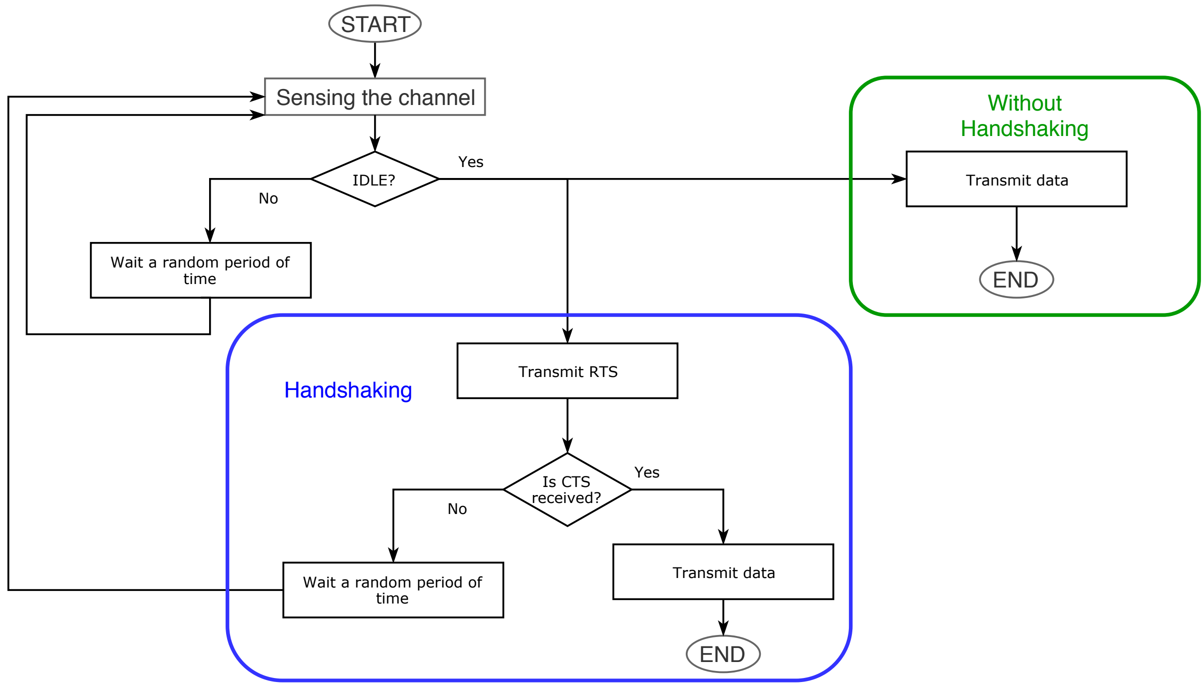

Fig. 2.11: CSMA/CA block diagram.

1) Hidden station problem:

In wireless networking, the hidden node problem or hidden terminal problem (Fig. 2.12) occurs when a node can communicate with a wireless AP, but cannot directly communicate with other nodes that are communicating with that AP. If a node (A) does not see in its radio range another node (C) it thinks that the channel is easy, but instead it is used by the other node (C) to transmit. This leads to difficulties in medium access control sublayer since multiple nodes can send data packets to the AP simultaneously, which creates interference at the AP resulting in neither packet getting through.

Although some loss of packets is normal in wireless networks, and the higher layers will resend the lost packets, if one of the nodes is transferring a lot of large packets over a long period, the other node may get very little goodput.

There is a practical protocol solutions to the hidden node problem. For example, Request To Send/Clear To Send (RTS/CTS) mechanisms where nodes send short packets to request permission of the access point to send longer data packets. Because responses from the AP are seen by all the nodes, the nodes can synchronize their transmissions to not interfere. However, the mechanism introduces latency, and the overhead can often be greater than the cost, particularly for short data packets [11].

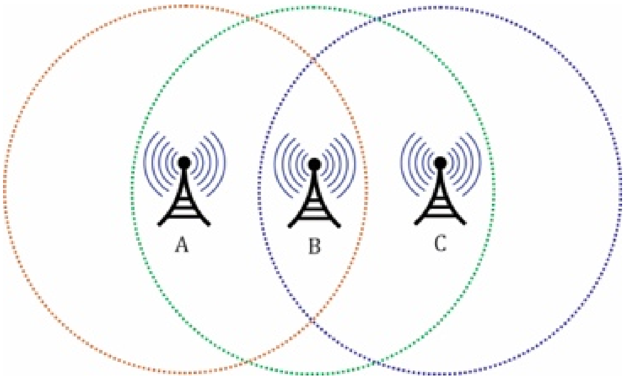

Fig. 2.12: Hidden node problem [11].

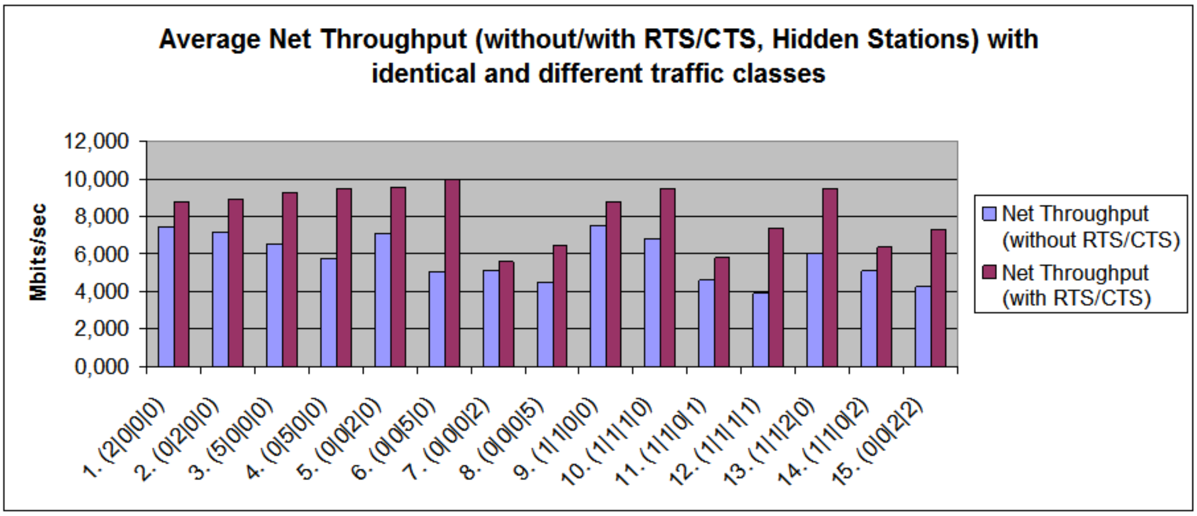

Fig. 2.13: Throughput with and without RTC/CTS procedure [12].

2)Exposed station problem:

In wireless networks, the exposed node problem (Fig. 2.14) occurs when a node is prevented from sending packets to other nodes because of co-channel interference with a neighboring transmitter. Consider an example of four nodes labeled R1, S1, S2, and R2, where the two receivers (R1, R2) are out of range of each other, yet the two transmitters (S1, S2) in the middle are in range of each other. Here, if a transmission between S1 and R1 is taking place, node S2 is prevented from transmitting to R2 as it concludes after carrier sense that it will interfere with the transmission by its neighbor S1. However note that R2 could still receive the transmission of S2 without interference because it is out of range of S1.

IEEE 802.11 RTS/CTS mechanism helps to solve this problem only if the nodes are synchronized and packet sizes and data rates are the same for both the transmitting nodes. When a node hears an RTS from a neighboring node, but not the corresponding CTS, that node can deduce that it is an exposed node and is permitted to transmit to other neighboring nodes.

If the nodes are not synchronized (or if the packet sizes are different or the data rates are different) the problem may occur that the sender will not hear the CTS or the ACK during the transmission of data of the second sender [13].

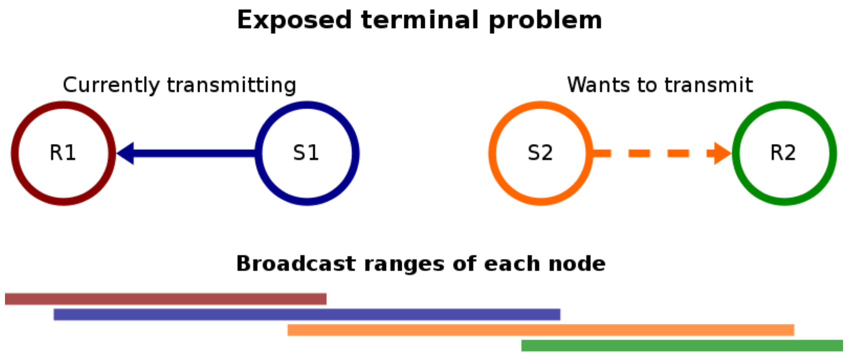

Fig. 2.14: *Exposed node problem [13].*

2.2 FSOC introduction

Free-space optical communication (FSO) is an optical communication technology that uses light propagating in free space to wirelessly transmit data for telecommunications or computer networking. "Free space" means air, outer space, vacuum, or something similar [14]. This contrasts with using solids such as optical fiber cable. The technology is useful where the physical connections are impractical due to high costs or other considerations. Free-space optical communications (FSOC) uses modulated light as carrier of data. Recently, FSO communications technology has attracted considerable attention because it has the potential to provide transmissions at very-high data rates between two terminals separated over a distance that varies from a few meters to thousands of kilometers; FSOC can also deliver a higher bandwidth than RF technologies because of the significantly higher operating frequencies of light than those of RF, thus FSO communications can provide proportionally much higher data rates than RF communications while using antennas that occupy smaller real estate. Moreover, the coherence of laser light in FSO links may reduce geometrical loss and enable the transmission of high data rates at long distances.

FSOC is a line-of-sight (LOS) technology; the transmitter and receiver of a communicating pair must be in LOS from each other. FSO finds its applicability to many use cases, such as in high-speed trains, UAVs, building-to-building, satellites, indoor and outdoor local/wide-area networks, and deep-space communications. Fig. 2.15 shows some FSO applications with their communication ranges.

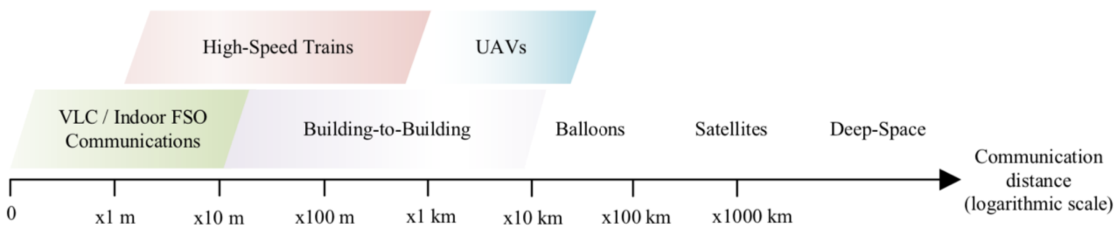

***Fig. 2.15**: Communication ranges of different applications.*

FSO communication system offers several advantages over RF system. The major difference between FSO and RF communication arises from the large difference in the wavelength. For FSO system, under clear weather conditions (visibility>10 miles), the atmospheric transmission window lies in the near infrared wavelength range between 700 nm to 1600 nm. The transmission window for RF system lies between 30 mm to 3 m. Therefore, RF wavelength is thousands of times larger than optical wavelength [15]. This high ratio of wavelength leads to some interesting differences between the two systems as given below:

- Huge modulation bandwidth: It is a well-known fact that increase in carrier frequency increases the information carrying capacity of a communication system. In RF and microwave communication systems, the allowable bandwidth can be up to 20% of the carrier frequency. In optical communication, even if the bandwidth is taken to be 1% of carrier frequency (≈1016 Hz), the allowable bandwidth will be 100 THz. This makes the usable bandwidth at an optical frequency in the order of THz, which is almost 105 times that of a typical RF carrier.

- Narrow beam divergence: The beam divergence is proportional to λ/D_R, where λ is the carrier wavelength and D_R the aperture diameter. Thus, the beam spread offered by the optical carrier is narrower than that of RF carrier. This leads to increase in the intensity of signal at the receiver for a given transmitted power.

- Less power and mass requirement: For a given transmitter power level, the optical intensity is more at the receiver due to its narrow beam divergence. Thus, a smaller wavelength of optical carrier permits the FSO designer to come up with a system that has smaller antenna than RF system to achieve the same gain (as antenna gain scales inversely proportional to the square of operating wavelength). The typical size for the optical system is 0.3 m vs 1.5 m for the spacecraft antenna

- High directivity: Since the optical wavelength is very small, a very high directivity is obtained with small sized antenna. The directivity of antenna is closely related to its gain. The advantage of optical carrier over RF carrier can be seen from the ratio of antenna directivity as given below:

$$\frac{Gain_{(optical)}}{Gain_{(RF)}} = \frac{\frac{4\pi}{\theta^2_{div(optical)}}}{\frac{4\pi}{\theta^2_{div(RF)}}}$$

  where $\theta_{div(optical)}$ and $\theta_{div(RF)}$ are the optical and RF beam divergence, respectively and are proportional to λ/D_R .

- Unlicensed spectrum: In RF system, interference from adjacent carrier is the major problem due to spectrum congestion. This requires the need of spectrum licensing by regulatory authorities. But on the other hand, optical system is free from spectrum licensing till now. This reduces the initial set up cost and development time.

- High Security: FSO communication cannot be detected by spectrum analyzers or RF meters as FSO laser beam is highly directional with very narrow beam divergence. Any kind of interception is therefore very difficult. Unlike RF signal, FSO signal cannot penetrate walls, which can therefore prevent eavesdropping.

In addition to the above advantages, FSO communication offers secondary benefits as: it is easily expandable and reduces the size of network segments, light weight and compact, easy and quick to deploy, and it can be used where fiber optic cables cannot be used. However, despite of many advantages, FSO communication system has its own drawbacks over RF system. A disadvantage is the requirement of tight acquisition, tracking and pointing (ATP) system due to narrow beam divergence. Also, FSO communication is dependent upon unpredictable atmospheric conditions that can degrade the performance of the system.

Terrestrial links include communication between building-to-building, mountain-to-mountain or any other kind of horizontal link between two ground stations. These FSO network can be deployed with point-to-point or point-to-multipoint. Laser beam propagates through atmosphere, it experiences power loss due to various factors and a role of system design engineer is to carefully examine the system design requirements in order to combat with the random changes in the atmosphere. For reliable FSO communication, the system design engineer need to have thorough understanding of beam propagation through random atmosphere and its associated losses. The various losses encountered by the optical beam when propagating through the atmospheric optical channel are:

1. Atmospheric turbulence: Atmospheric turbulence is a random phenomenon which is caused by variation of temperature and pressure of the atmosphere along the propagation path. It will result in the formation of turbulent cells, also called eddies of different sizes and of different refractive indices. These eddies will act like a prism or lenses and will eventually cause constructive or destructive interference of the propagating beam. It will lead to redistribution of signal energy resulting in random fluctuations in the intensity and phase of the received signal. Furthermore fog may interfere with laser beams, because its molecules are very small and they interfere with laser light wavelength.
2. Absorption and scattering loss: The atmospheric absorption is a wavelength dependent phenomenon. The wavelength range of FSO communication system is chosen to have minimal absorption. Scattering of light is also responsible for degrading the performance of FSO system. Like absorption, scattering is also strongly wavelength dependent. If the atmospheric particles are small in comparison with the optical wavelength, then Rayleigh scattering is produced.

3. Beam divergence loss: As the optical beam propagates through the atmosphere, beam divergence is caused by diffraction near the receiver aperture. Some fraction of the transmitted beam will not be collected by the receiver and it will result in beam divergence loss/geometrical loss. This loss increases with the link length unless the size of the receiver collection aperture is increased or receiver diversity is employed.
4. Ambient light: Light from luminous bodies like Sun, moon or fluorescent objects produces shot noise and it interferes with the noise present at the detector. Both the detector noise and ambient noise contribute to total receiver noise and this result in some noise flicker or disturbances. In order to minimize noise from ambient light sources, FSO system should be operated at higher wavelengths.
5. Mis-alignment or building sway: The optical beam used in FSO communication is highly directional with very narrow beam divergence. Also, receivers used in FSO links have limited FOV. Therefore, in order to have 100% availability of FSO link, it is very essential to maintain a constant LOS connection between the transmitter and receiver. However, the building over which FSO transceivers are mounted are in constant motion due to variety of factors such as thermal expansion, vibrations or high wind velocity. This will lead to failure of FSO link due to mis-alignment or building sway. It poses a great challenge for transceiver alignment and one needs to have very accurate pointing and tracking mechanisms to overcome FSO link failure.

The tasks of an ATP mechanism include pointing the transmitter in the direction of the receiver, acquiring the incoming light signal, and maintaining the FSO link by tracking the position of a remote FSO terminal. Pointing is the process of aligning the transmitter in the field-of-view (FOV) of the receiver. Signal acquisition is the alignment process of the receiver in the arrival direction of the beam. Tracking is the maintenance of both pointing and signal acquisition throughout the optical communication between communicating terminals [16]. An ATP mechanism is a crucial element of an FSO communications system as this communications technology requires LOS between transmitter and receiver. The use of coherent light as in laser beam is mostly applied for communications in moderate-to-long distances. Alignment is required in most cases of FSO communications; small displacements by the receiver or the transmitter can make them fall out of sight for short distances. As the distance between transceivers increases, the required alignment precision for FSO transmitter also increases due to the narrow divergence of the employed beams. In fact, the motion is actually restricted to both communicating stations because full-duplex communication requires the use of transmitters and receivers by both ends. Therefore, designing FSO transceivers with a suitable ATP mechanism is critical for realizing effective FSO communications.

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 the previously described ATP mechanism. Maintaining LOS in places with a prevalence of obstacles, such as in a city with many high buildings and other infrastructure, may be challenging. Here we want to address the LOS problem inherent to FSOC by proposing a novel indirect diffused light FSOC (ID-FSOC) system, which establishes high-speed optical links between a pair of stations with no direct LOS between these stations [17].

The proposed 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, which allows the receiver to detect the diffusely reflected light on any existing angle of view. The transmitter of the ID-FSCO system uses a laser diode to emit a narrow laser beam as the light source. The transmitted laser beam is pointed towards a DR, where it creates a projection of the signal (Fig. 2.18). 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. Fig. 2.16 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.

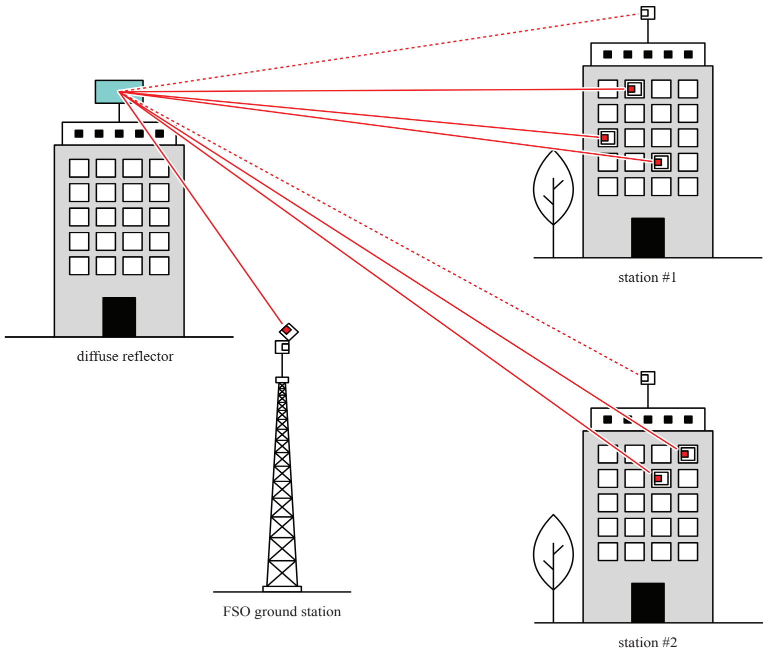

Fig. 2.16: Use case of the proposed system.

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, they are inexpensive and easy to deploy. 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 minimal because the beam is narrow and collimated, and this feature considerably extends the range between the transmitter and the DR.

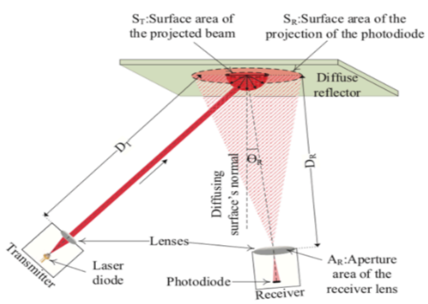

Fig. 2.17: Geometric model of the ID-FSOC system using a perfect Lambertian DR.

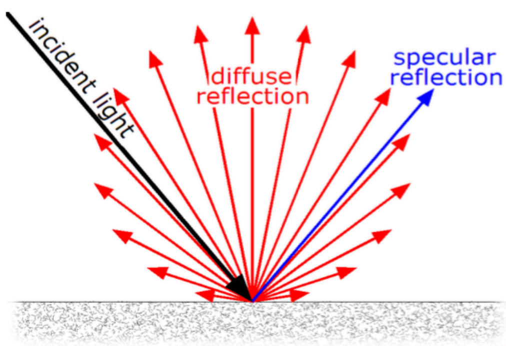

Fig. 2.18: Diffusion of the light through the DR.

Fig. 2.17 shows our geometric system model based on a perfect Lambertian DR, where the incident light is uniformly distributed over all directions except towards the DR. The receiver focuses its photodiode aperture on the area of the diffusing surface where the projection of the transmitted beam overlaps to establish an optical link. The notations used in Fig. 2.17 are as follows: D_T and D_R are the transmitter and the receiver distances, respectively, and θ_R is the reflectance angle from the receiver to the normal of the DR [18].

The received power (P_{rx}) of the proposed ID-FSOC system is calculated by integrating the reflected light over the intersection of the surface area (S_T) of the projected laser beam and the surface area of the projection of the photodiode (S_R) on a Lambertian DR as:

$$P_{rx} = \int_{S_T \cap S_R} \frac{P_{tx} R A_R \cos\theta_R}{\pi S_T D_R^2} d\sigma$$

where P_{tx} is the total transmission power of the projected laser beam, R is the reflectance of the DR, A_R is the aperture area of the receiving lens, and $d\sigma$ is the position of the intersected area of $S_T \cap S_R$ on the diffusing surface. It could be interesting to focus on the coefficient of reflectance and energy used by a precise diffuse reflectors (Fig. 2.19), as found in a website of manufacturers of DRs, so the data are reliable at all [19].

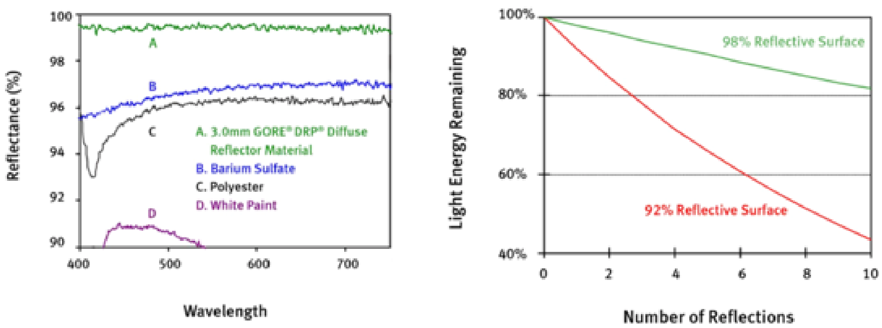

Fig. 2.19: Energy and reflectance.

3 ID-FSOC MAC protocols

3.1 Introduction

As mentioned in the previous chapter, an ID-FSOC system consists of a transmitter, a receiver, and diffuse reflector (DR) that uniformly diffuses the incident light beam in all directions except towards the DR itself, which allows the receiver to detect the diffusely reflected light on a wide angle of view. Moreover, ID-FSOC simplifies the complexity of the system by easing the motion resolution of an ATP mechanism. With ID-FSOC, it is then simple to establish full-duplex communications links.

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 transmitted laser beam is pointed towards a DR, where it creates a projection of the signal. The receiver points its aperture towards the DR to receive the diffusely reflected light. Then, a high-speed optical link between the transmitter and the receiver is established.

Herein, we adopt ID-FSOC for local area networks and propose three different schemes for medium access control (MAC). The protocols are Single Point, Random, and Selective FSO schemes. In all three schemes, a transmitter projects its communicating laser on a diffuse reflector to request for access and a receiver selects a beam to grant the request. The ID-FSOC MAC schemes establish a link by a different operation at the receiver side. The proposed ID-FSOC network can be used for achieving high rate communications in scenarios where radio communications are congested (e.g., a large number of sprouting Wi-Fi networks), or as a fast-deployment technology for crowded areas or emergency communications. We analyze the performance of the proposed schemes and show that each scheme, even with different complexity, has advantages on different scenarios over the others, such that complexity is not necessarily correlated to higher performance. We compare the performance of the proposed ID-FSOC MAC schemes to CSMA/CD and CSMA/CA in lieu of being these schemes the first to be proposed for such FSOC technology [17].

During the simulation, 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 Wi-Fi) 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.

As mentioned before the goals of the thesis are as follows:

- Propose three MAC ID-FSO schemes based on laser light, ID-FSO communications do not require a direct LOS between transmitter and receiver. I believe that this is the first proposal of such ID-FSOC MAC schemes.
- We propose the use of diffuse reflectors to extend the LOS of FSOC, which enables communications within a wide coverage area, since a receiver with LOS to the reflector may access it with any angle of view (up to 90◦) so that the receiver's location is widely relaxed.
- We show that ID-FSOC is able to achieve high-data rates using an existing sensitive photodiode as receiver and for different distances between the diffuse reflector and the receiver.

3.2 General algorithm

The general algorithm performed by the transmitter is the following (Fig. 3.1), then in the next sections it will be split in three schemes that differ from each other on the used beam selection method at the receiver side.

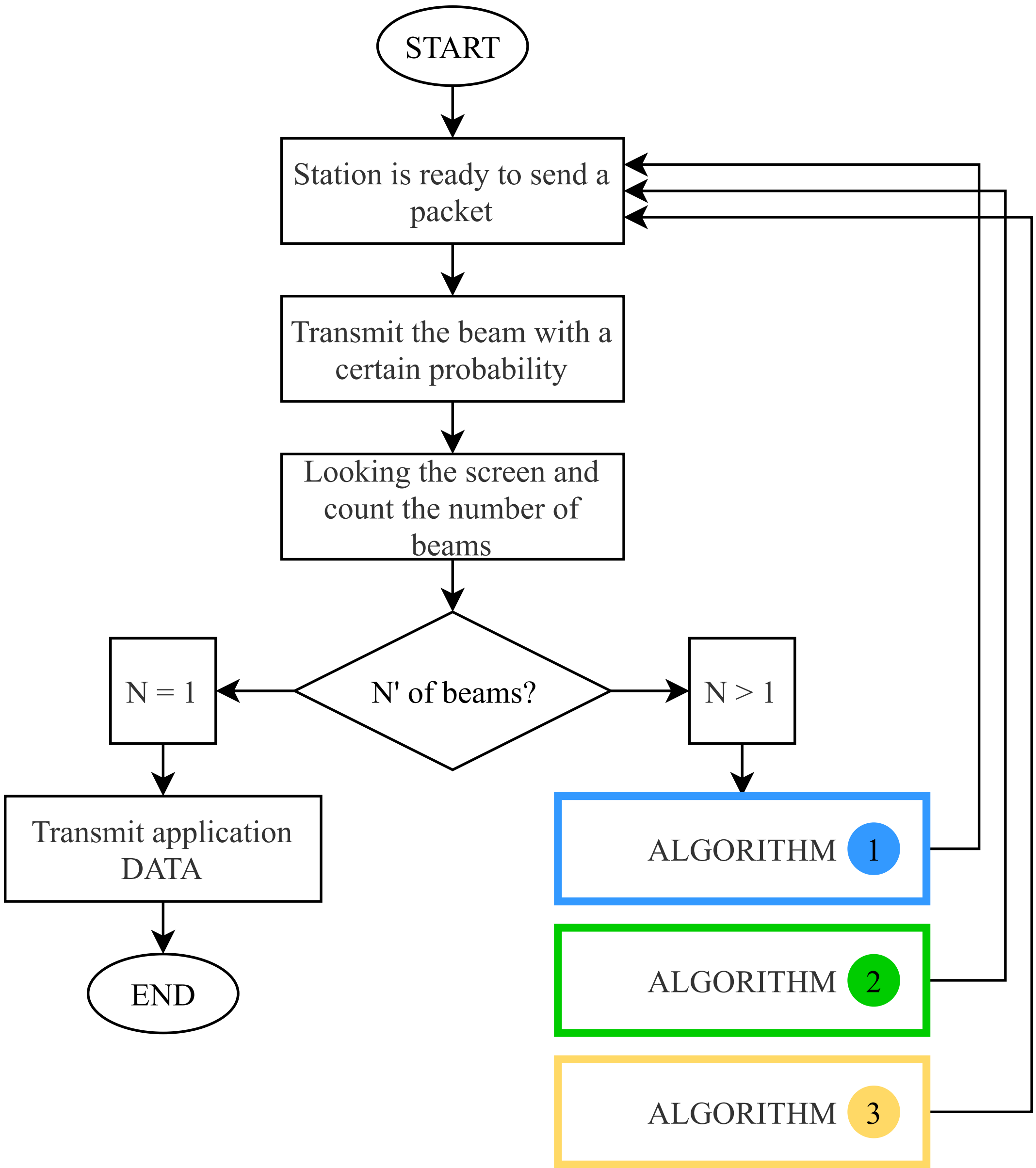

***Fig. 3.1**: General algorithm.*

1. Points towards a precise location on the Diffuse Reflector.
2. Observes (and not "sense" because it is an optical transmission) the channel
   a. If the channel is busy, the transmitter starts a random back-off procedure
   b. 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. Receive an acknowledgment by the AP

Fig. 3.2 shows an example of the occurrence of multiple and simultaneous beam projections on a DR. The receiver zoom-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 (assumed 10 cm). 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 three different adopted MAC scheme, as explained below.

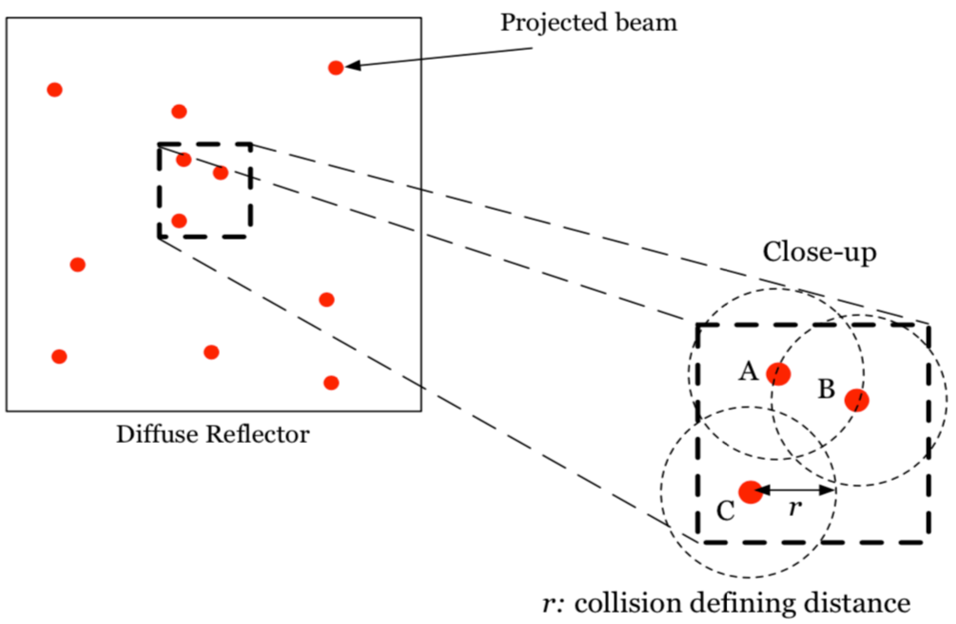

Fig. 3.2: *Diffuse reflector screen seen by the receiver.*

3.3 Single point scheme

The single point protocol is the first one I want to speak about, also because it is the simpler one (Fig. 3.3). If more than one beam is present on the DR, a collision is declared and a random-back-off procedure is performed. Single point means that all the transmitter can transmit only in one point of the screen, and there are any kind of movement need to be done by the receiver, because obviously if the spot is always the same, as shown in Fig. 3.4, the receiver does not need to search and find the beam. Obviously this is an easy protocol, and then it is also not so useful when the number of station increase. Let us suppose that there are twenty nodes inside a WAN, and only two of them start the transmission simultaneously, using this single point protocol at the receiver side, there may be always collision, because the two active stations transmit on the same spot of the DR screen. The good thing of this protocol is that if a low number of stations compose the network, or the time synchronization is good enough it is very fast.

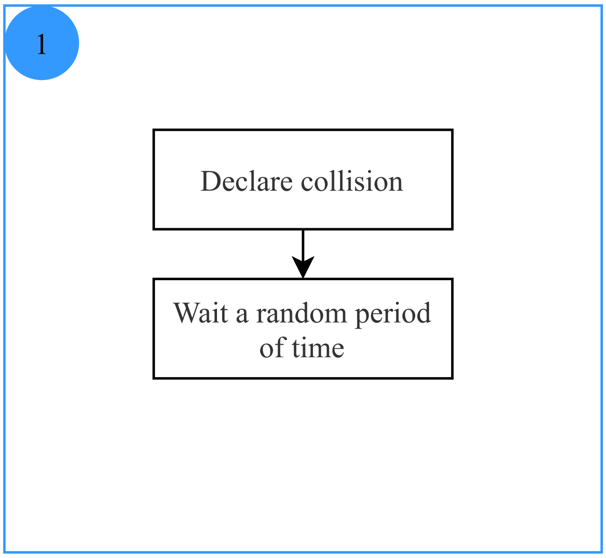

Fig. 3.3: Single point protocol.

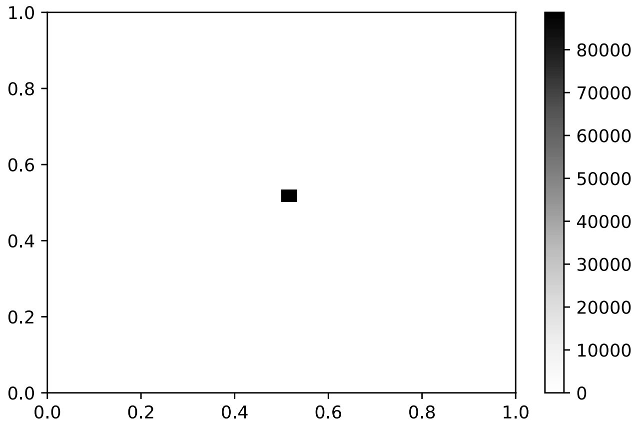

Fig. 3.4: Distribution of beams on the screen for single point protocol.

3.4 Random scheme

The random scheme is really similar to the single point scheme, but here the difficult part resides in the movement of the receiver, because we do not know a priori where the transmitting station will send the beams on the screen, so we need to find them. After all the beams have been found by the receiver, the core of the algorithm is applied. Fig. 3.5 shows the flow chart of the operation of Random scheme protocol. The distance between the randomly chosen beam and all the other beams is computed. Then the program checks if this evaluated distance is lower or greater than a given threshold. If the selected beam collides (distance < threshold) with at least another beam, no CTS is issued. Otherwise, the AP issues a CTS and the transmission of the data can start. After the successful transmission of data, the receiving station goes to the initial step of the algorithm, waiting for another transmission.

Random protocol 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 beam is selected, Fig. 3.6 shows the distribution of the beams during an entire simulation, darker is the spot higher is the concentration of beams in that area of the screen. The distribution of beams is similar for Random and Selective protocol.

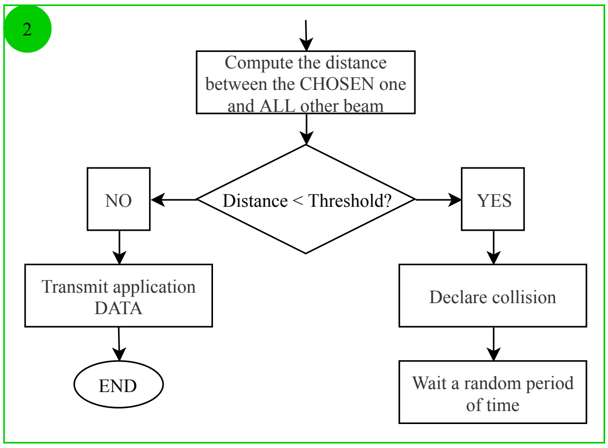

Fig. 3.5*: Random protocol*

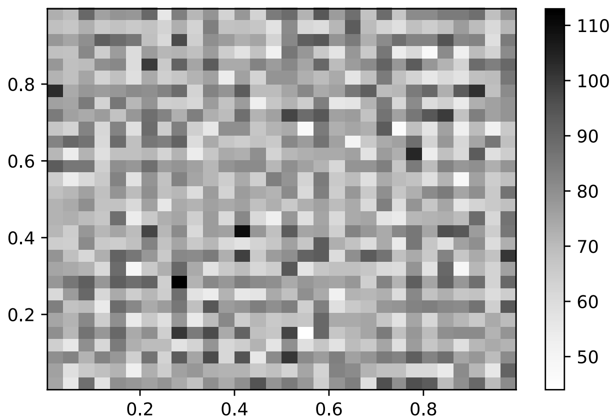

Fig. 3.6*: Distribution of beams on the screen for random and selective protocol.*

3.5 Selective scheme

Selective (Fig.3.4) is a more complex scheme than Random. It also uses spatial diversity and may be more effective than Random. However, it requires a more complex receiver that can scan the DR in the search for a collision-free beam. The distance between all the beams present on the screen is computed, if there is at least one beam that is not subjected to a collision (distance between beam < threshold) than this one is chosen for the transmission of data. If no beam is excluded by this computation, than collision is declared and back-off procedure is performed. Therefore, the receiver may require both a mechanical/software-based ATP mechanism but also a longer response time.

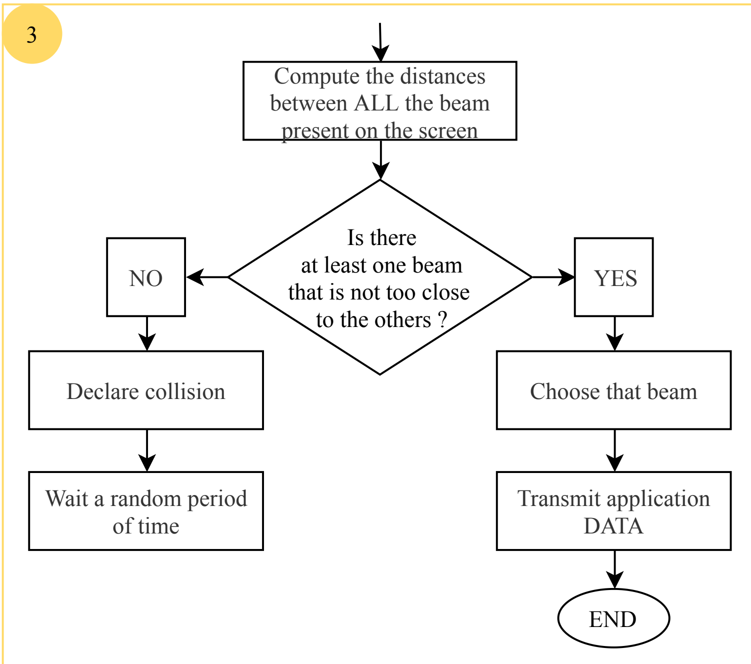

***Fig. 3.7**: Selective protocol*

In the next chapter we explain how 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 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 thesis, to the best of my knowledge. I comment on the differences and similarities among these schemes. Pt is called transmission probability, 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).

4 Simulator in Python

In this chapter we will briefly explain how the simulator work and which are the main functions and parameters.

4.1 Simulator

During the very first step of the work we had explored different event simulator on the market, as MATLAB, Simpy, FNSS, sim2net, ns2 and ns3 but no one of them fit my needs. After lots of research we decided to write down one by draft and that is why we need to give a brief introduction of how the simulator works and which are the parameters used. Any pieces of code is written in Python 3.6.2 and the main used libraries are: numpy, matplotlib and pandas.

4.1.1 Parameters

As every event based simulator the most important thing to take care of is the timing, the duration of the simulation can be chosen as input of the main program, and obviously the more a simulation lasts the more the results are precise; each event takes one time slot that is incremented at the end of the computation of all the steps.

Depending on which protocol we need to simulate the string in which the program enter at the very first step of the simulation was varied; five different simulations are possible, with the following acronyms:

- CA → CSMA/CA
- CD → CSMA/CD
- R → RANDOM
- S → SELECTIVE
- SP → SINGLE POINT

Upon the simulation starts other parameters are needed to be chosen, being a network simulator the number of station is another thing we needed to take care of. Chosen the number of node we need to decide with which value of probability each node generates packets (P_g) and with which probability the node transmits the generated packets (P_t). Other important parameters are inside each created class, but we will focus on them in the sub-chapter.

4.2 Script

Three different scripts have been written, useful to run the simulator in an optimal and intuitive way.

4.2.1 Main.py

Main.py is the principal program, in which the protocol to be used is chosen and the principal parameter are set up.

The structure of the simulator is basically the following one (Fig. 4.1):

Algorithm

```
Initialization of the variables:
TransmissionProbability : Pt
GenerationProbability : Pg
NumberOfNodes : N
Network : Net
Output:
File.txt
Statistics
procedure SIMULATOR(protocolType)
    for (i = 1, i++, i < SimulationTime) do
        if (protocolType == CD) then
            Check the wire
            Run the CD Algorithm
        if (protocolType == CA) then
            Check the channel
            Run the CA Algorithm
        if (protocolType == R) then
            Check the screen
            Run the R Algorithm
        if (protocolType == S) then
            Check the screen
            Run the S Algorithm
        if (protocolType == SP) then
            Check the screen
            Run the SP Algorithm
        return Statistics
        return File.txt            ▷ Values used to plot the resulting graphs
```

Fig. 4.1: Pseudocode of the simulator, main program.

4.2.2 Class_sim.py

Inside Class_sim.py program are present all the functions and classes useful to run the simulator, let's discuss them one by one.

4.2.2.1 Functions

allScreen(n,pos): This function is only a plotting one that given the number of beam and the position of the given beams takes care of plot them in a "screen", in order to obtain a visual results of what the screen is in a given time instant.

get_pos_beam(): This function is the function used to generate random position on the screen for each beam it generates one x and one y coordinates.

compute_distance(position1, position2): This function is responsible for the computation of the distance between the position of two different beams and it has to return it.

4.2.2.2 Classes

Packet: This class is only a random generator of packet, the probability with which the packets are generated depends on the input given in the main program by the user.

Node: This class is the most important one because it has the goals to handle all the characteristics of the nodes present in the network, so this is also the one with the higher number of parameter to be initialized.

```python
class Node():

    def __init__(self,idN,P_gen,P_tran,status = "free"):
        self.idN = idN
        self.Pg = P_gen
        self.Pt = P_tran
        self.collision = 0
        self.generated = 0
        self.attempted = 0
        self.available = 0
        self.transmitted = 0
        self.status = status
        self.CA = 0
        self.backoff = 0
```

***Fig. 4.2**: Section of the script of the class Node.*

self.idN: the identification number of the node

self.Pg: generation probability of a packet self.Pt: transmission probability of a packet

self.collision: number of collision interesting this node

self.generated: number of packet generated by this node

self.attempted: number of time this node has attempted to transmit

self.transmitted: number of packet successfully transmitted by this node

self.status: status of the node; “free”, “collision”, “attempt”

self.CA: Boolean variable used to say if there is the handshake or not

self.backoff: backoff value regarding this node

check_packet_available(): this is the function responsible for check if a packet is generated, then it has to increase the generation and attempted counter of the selected node.

check_attempt(): this is maybe the most difficult function of the class because it has to handle all the different status of the different nodes and decide if they are allowed to transmit or they have to stay off.

Network: This is the class used to handle all the parameter of the class Node, but without knowing them, it performs all the functions that an analyzed network had to do.

decrease backoff(): for each node this function need to check the status and then decide what to do with the back-off. If the node is “collision” decrease the back-off, if the node is “free” but the back-off is still greater than zero decrease the back-off and set the status to “collision”.

gen_att(): this is only a call of the two functions that handle the generation and the transmission probability off the packet per each node, so if one packet is generated and then it could be transmitted, the status of the node is set to “attempt”, if it is generated but not transmitted, nothing happen and the status remains “free”.

reset_nodes(): when called this function has to set the status of a node “free” and set the handshake variable to zero.

handshake(): when called this function has to check if the status is “attempt”, and set the handshake parameter to 1, and enable the transmission

transmit(): when called this function has to check if the status is “attempt”, and increase the counter of the transmitted packet.

collision(): when called this function has to check if the status is “collision”, and increase the counter of the collision packet.

perform_backoff(): when called this function has check if the backoff has already a value, if it has one it only set the status "collision", if there is no value initialized it gives one random valu inside the CW, and then set the status "collision".

random_P(): This is the function to perform the FSO random algorithm (explained in details in the previous chapter).

selective_P(): This is the function to perform the FSO selective algorithm (explained in details in the previous chapter).

4.2.3 Graph.py

Graph.py is the program responsible for the generation of all set of graphs, it takes as inputs the results of each simulation done by the Main.py as a .txt file and it elaborates them. All the graphs, as the simulator, are produced using Python language.

5 Simulations and results

In this chapter we will present and comment all the results obtained by the simulation done in Python environment with the simulator previously presented.

5.1 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 with a step of 0.005. Fig. 5.1 shows the throughput of the studied schemes. Random and Selective outperform the other schemes as these two schemes allow multiple stations to transmit RTS frames and yet, a receiver can establish a link with one projected beam. For this reason, 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. As we can see the performance of the Single Point protocol is between CSMA/CA and CSMA/CD, because it is really similar in the way in which a collision is handled, since the point in which the laser beams can be transmitted is only one (in this case the center of the screen).

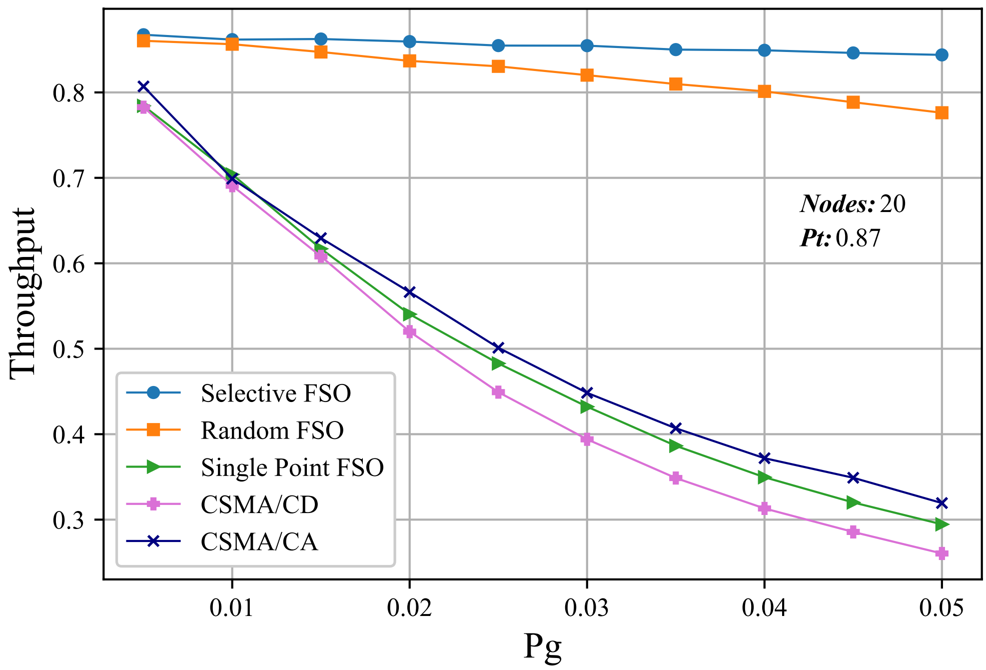

***Fig. 5.1**: Throughput of the proposed MAC schemes and compared schemes as a function of the packet generation probability.*

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. Fig. 5.2 shows the throughput of the compared schemes with 2 to 40 stations, where each station generates traffic at $\frac{1}{20}$ 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 $1 < N < 20$ 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 and obviously this is a great achievement for the throughput of our network.

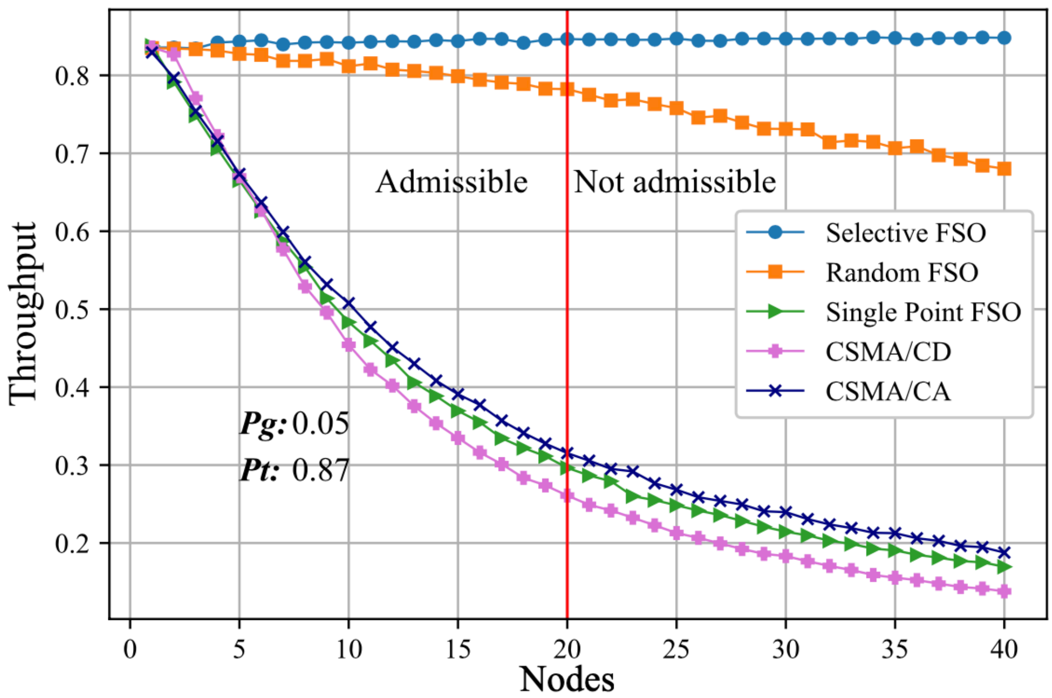

Fig. 5.2: Throughput of the ID-FSCO MAC and CSMA schemes as a function of the number of stations in the network.

5.2 Utilization

Network utilization is the amount of traffic on the network compared to the peak amount that the network can support. There are various times throughout the normal course of business when a network is busier, i.e., the network utilization is high. As a result, users experience a slow down when the network utilization is high enough. Response times grow greater than expectations preventing normal business processes from operating efficiently. Performance degradations are generally a nuisance but can become significant enough to result in lost of revenues. It is important to understand the factors that can cause high network utilization and how to manage the network preventing it from negatively impacting the business [17]. In this paragraph 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. Fig. 5.3 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.

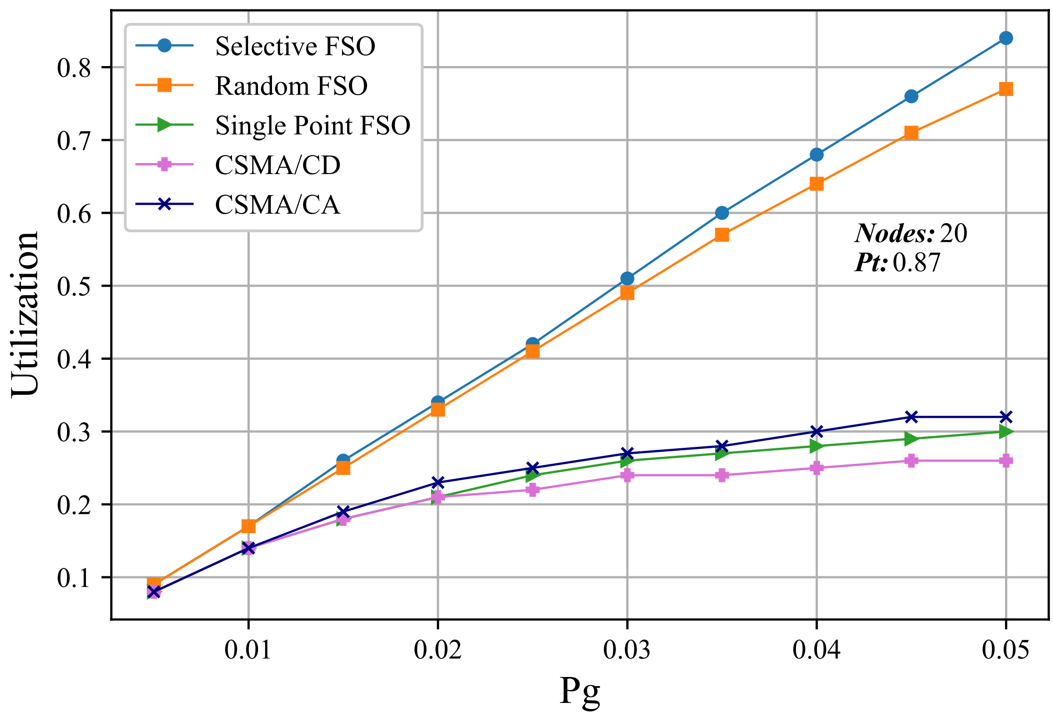

***Fig. 5.3**: Utilization of the proposed MAC schemes.*

5.3 Flow success rate

We call flow success rate of a MAC scheme the ratio of the number of successful transmissions over the number of attempts made by the network stations. This metric indicates the efficiency of a station to avoid collisions in transmissions. Fig. 5.4 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. To support these observations, we counted the number of collisions experienced by the considered schemes during simulation time. Fig. 5.5 shows the number of experienced collisions which 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.

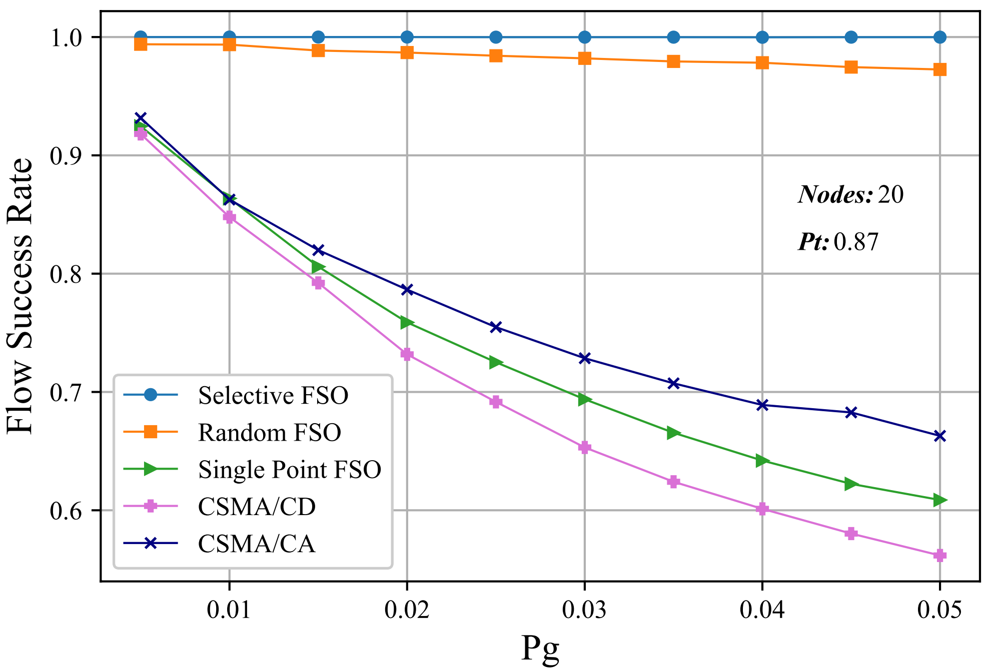

***Fig. 5.4**: Flow success rate of the proposed MAC schemes.*

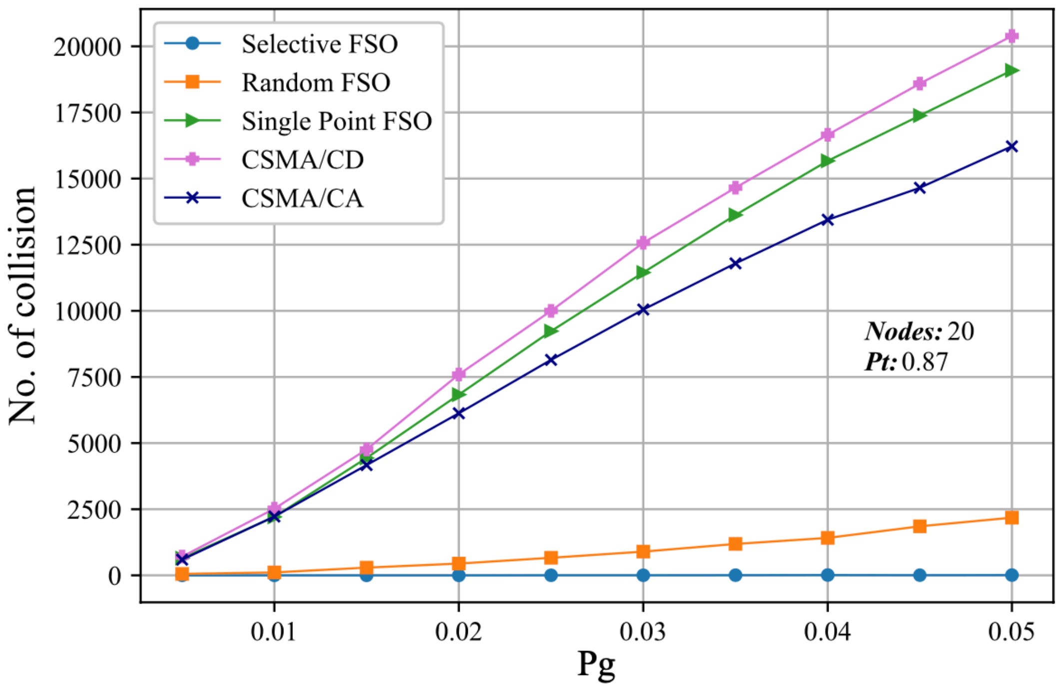

Fig. 5.5: Number of collisions experienced by the proposed MAC schemes.

5.4 Response time on beam detection

The ID-FSOC MAC schemes proposed, 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) 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 CSMAs schemes. Fig. 5.6 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. Note that the number of collisions alone may not reflect the achievable data rate of the proposed schemes.

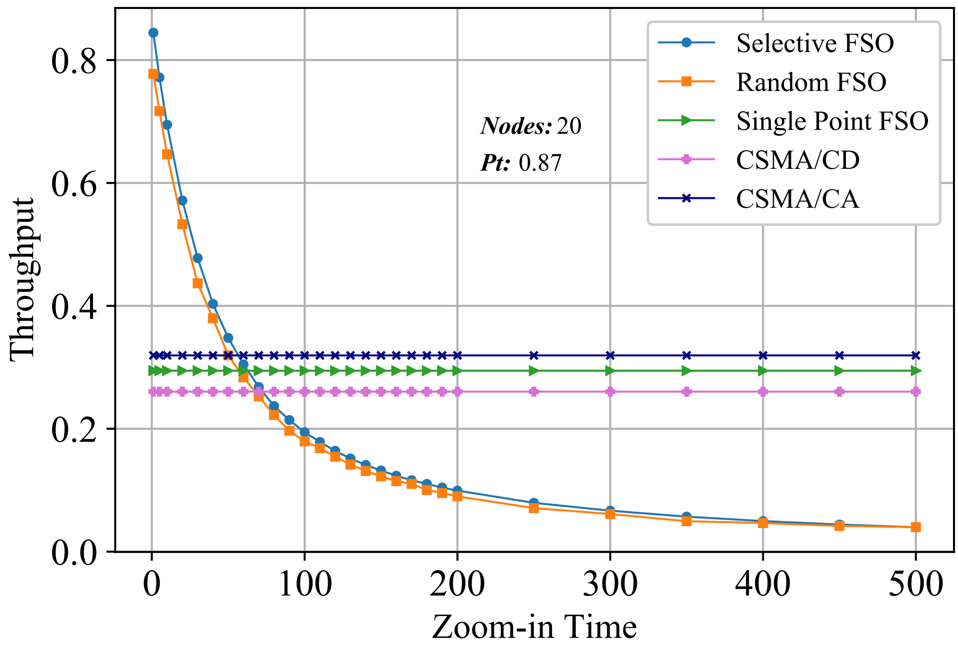

Fig. 5.6*: Throughput of the proposed MAC schemes under different zoom-in times.*

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. Fig. 5.7 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. In Fig. 5.7 is shown basically the reason why the potential of a MAC protocol for FSO is so high. Only observing the figure, without consideration on which are the protocol applied we can see that the three new MAC protocols for ID-FSCO are considerably higher than the two implemented with radio frequency. The best one, (theoretically) based on the assumptions of 20 Nodes, Pt equal to 0.87 and considering a zoom-in time of 100 time slots seems to be the single point protocol that can achieve up to 800 Mb/s data rate.

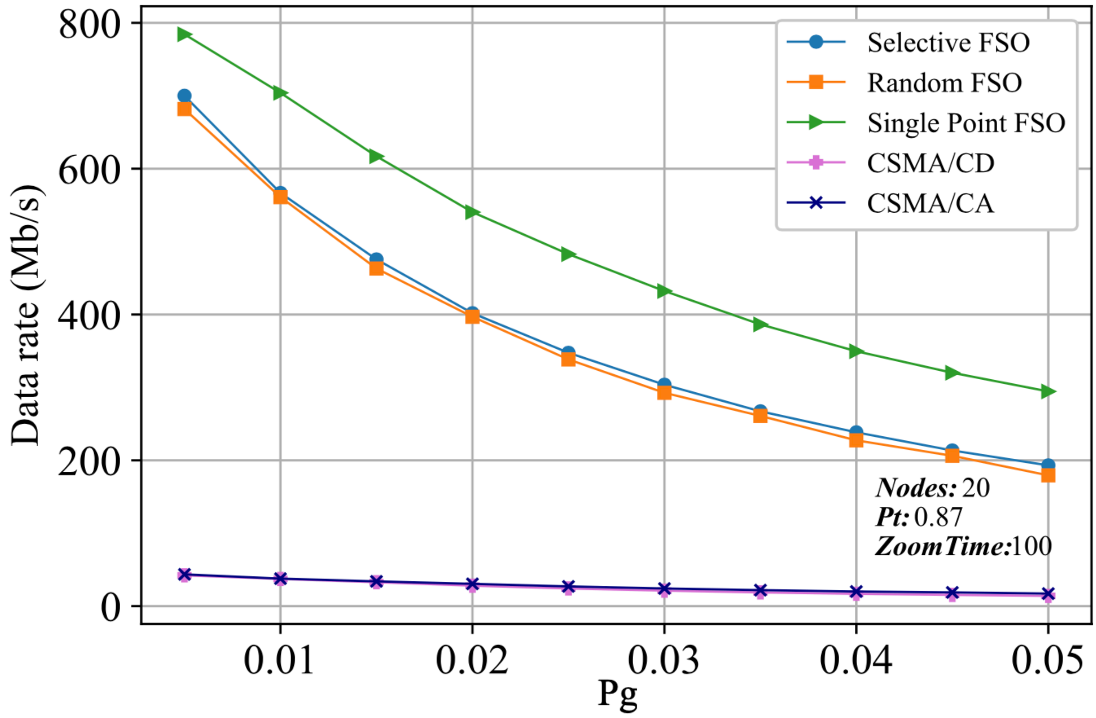

***Fig. 5.7**: Data rates according to both the active cycles used by MAC scheme and the feasible data rates.*

6 Conclusions and possible developments

This thesis focused on the development of new MAC protocols that can be used on Free Space Optical Communication physical layer; not the classical one, but the Indirect Diffused light system previously described. These are the first ID-FSOC MAC schemes, and for this reason they are very interesting to analyze, and on the other hand, difficult to evaluate.

Since ID-FSO communications do not require LOS between transmitter and receiver, the field of application and the extension of the local area in which this system can be applied really increase its dimension. The introduction of the analyzed diffuse reflector inside the architecture enables the communications within a wide coverage area, since a receiver does not need to be in LOS with the transmitter but it is enough the viewing of the DR.

The choice of an FSO system to communicate between stations has been made because of its potentiality and novelty, but also because it is able to achieve unparallel high-data rates using existing sensitive photodiode as receiver and for different distances between the DR and the receiver. The order of magnitude of the achievable rate is about 1 Gbps wireless network access, and this is the main point that we had focuses on.

All the previous results are obtained without considering the climatic events, so the system is in a certain way protected from experiencing loss and being, therefore ideal, and collision are considering now only by the multiple station collisions and not by the deterioration of the channel. The next step to be done in this field of research can be the inclusion inside the simulator of all the parameters needed to study the performance of a real system, for example using a simulator of atmospherical events such as sunlight, snow, rain and so on. Another enhancement could be done on the computational time needed by the receiver to process the information about the beams present on the screen of the DR, here inside this work the timing are analyzed starting from 0 to 500 time slot, but they are only rough data, since no mechanical analysis has been done to obtain a precise time slots occupation.

After that the simulator has been tested in a real environment, the next step is, of course try the application of these MAC protocols on some moving objects, such as vehicles. The ease of deployment of transmitter receiver and diffuse reflectors makes this architecture easily adaptable at every environment and attachable to every structure. Let’s imagine an architecture comprising vehicles and traffic lights, objects already existing on the market; transmitter and receiver can be easily attached to the machine, and the DR can be “painted” on the side of a wall along the street, or on the side of a traffic signal.

vii Figures

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