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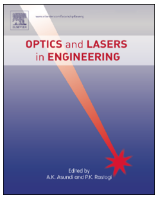

New challenges in wireless and free space optical communications

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ABSTRACT

This manuscript presents a survey on new challenges in wireless communication systems and discusses recent approaches to address some recently raised problems by the wireless community. At first a historical background is briefly introduced. Challenges based on modern and real life applications are then described. Up to date research fields to solve limitations of existing systems and emerging new technologies are discussed. Theoretical and experimental results based on several research projects or studies are briefly provided. Essential, basic and many self references are cited. Future researcher axes are briefly introduced.

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1. Historical facts and applications

The recent spread of cellular systems (smart sensors, mobile phones, base stations, satellites, surveillance devices, traffic radars, etc.) has increased the complexity of processing algorithms and pushed the existing technologies to their limits. Detailed analysis of the raised issues and/or deep discussion of any of the proposed solutions is nearly impossible in a single article. Nevertheless, the objectives of this paper are to shed light on the main applications, present recent research fields and summarize some of our obtained results in various research projects and studies.

Before discussing recent applications and the limitations of existing technologies, we would like to mention the dusk of wireless communication systems. At the beginning, there was a research study divided into 4 parts to discuss “the physical lines of force” published in 1861 by a Professor of the King's college in London. The author of this study was the imminent scientist J.C. Maxwell [1–4]. In his early study, Maxwell predicted the existence of “Electromagnetic Waves”. Few years later (1887), a German physicist, H. Hertz, proved the existence of such waves. After that, it took Marconi less than 10 years to invent the first radio transmission system in 1896 and to patent his idea one year later [5]. The first radiotelephone service was introduced in the US at the end of the 1940s [6]. However, the first standard of radio mobile was introduced in the s1970s of the last century.

In the first transmission system of Marconi, the considered antennas were bigger than the building of Marconi's laboratory and the electrical circuits of the transmitter occupied the whole room. However, engineers and researchers have been very creative in the invention of new applications, shrinking the electronic circuitry and improving and diversifying proposed services. Since the beginning of the last century, telecommunication societies have proposed a great number of commercial services. In the beginning, wireless transmission systems were related to huge applications such as radio and TV broadcasting, military radars, and maritime radars. Analog transmission systems were very popular till the beginning of the 1980s of last century. These technologies became very limited to handle all the needs of modern societies.

Actually, our every day life is full of applications related to wireless communications. The list of such applications and

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services are very long and it cannot be restricted to the following major applications of wireless communication systems: mobile phone, tablets, portable media player, radios and televisions, wireless remote devices, several communication protocols (such as: Wifi, Wimax, Zigbee, etc.), robotics, smart cars and smart roads [7], smart Grid [8], many biomedical devices use wireless technologies, satellites, etc. Radars are also used in various purposes such as: land radars for airplanes surveillance in civil or military goals, security road traffic, meteorology, ground Penetrating Radar, Astronomy,[1] Airborne Warning and Control System (AWACS),[2] etc.

2. New challenges in wireless communications

Using the standards for frequency allocation published by 3 different standard bodies (International Telecommunication Union (ITU) [6], European Conference of Postal and Telecommunications Administrations (CEPT) [12], Inter-American Telecommunication Commission (CITEL) [13]) and some information from NASA [14], the main applications with the allocated wavelengths and the frequencies of major electromagnetic waves (EM) are illustrated in Fig. 1.[3] The relationship between the wavelength of an EM with respect to its frequency is given by:

$$\lambda = \frac{C}{F} = \frac{3*10^8\ \text{m/s}}{F\,(\text{in Hz})}$$

Fig. 1 clearly shows that the spectrum is very congested and that there exists no room for new applications and services. We should also mention that Short Message Service (SMS) which is relatively a recent application for mobile phones has been generating benefits around 110 billions US$/year worldwide [15]. This fact proves that the communication markets is massive. According to the independent, a UK newspaper on Tuesday 7 October 2014, “There are officially more mobile devices than people in the world. The world is home to 7.2 billion gadgets, and they're multiplying five times faster than we are”. Besides, customers become more exigent. Communication industries try to cope with the increasing number of customers and their exigencies. The First Generation (1G) of a mobile phone has been introduced in the market between 1970 and 1984. 1 G could only handle basic voices and it was based on analog protocol, i.e. Frequency Division Multiple Access (FDMA). The speed of this standard was around 2.4 Kbps [6]. Almost a decade later, the 2nd Generation (2G) was introduced (1980–1999) to improve the coverage and the capacity. 2G considers two different standards: Time Division Multiple Access (TDMA)/Code Division Multiple Access (CDMA) and it reaches a transmission rate of 64 Kbps. At the beginning of the 1990s, the third generation (3G) was introduced to deal with voices and data (multimedia, text, the Internet, etc.). It was based on CDMA and had a bit rate of 2 Mbps. The fourth generation (4G) has been deployed since the beginning of this century and it is using an Internet Protocol (IP) and Long-Term Evolution (LTE) standard. 4G is mainly optimized for data that can reach around 100 Mbps. Actually, many standard bodies are developing the fifth Generation (5G). This generation should reach around 1 Gbps and it should be adapted to handle the Internet of Things (IOT). The IOT is a major challenge for our communications networks. In fact, IOT will allow the communication among devices, which will be massively deployed in [16]: smart cars, smart roads, smart cities, smart houses and buildings (in the context of homes and building automation), security and safety (surveillance, alarm, site networking), and industrial M2M communication. It is anticipated that in 2020, there will be around 50 Billion connections. According to Cisco [17], “Fifty billion things will connect to the Internet of Everything in just a few years. The value this could create for service providers by 2022 is US$1.7 trillion”. Fig. 2 presents the dilemma of the telecommunication industries, where the increasing of the customers' number will definitely impact the spectrum bands which are already congested.

3. Prosper research fields

To resolve the problems of wireless communications, researchers and engineers from all around the world are actively prospering new research fields and proposing new technologies. It is worth mentioning that the creation of new technologies can help solving some issues. Indeed, the broadcasting of digital terrestrial television (DTTV) instead of the old analog television one liberates some spectrum bands, called the “White Spaces”, as the DTTV consumes smaller bandwidths comparing to the ones required in the analog case. The technology progress is out of the scope of our manuscript and it will not be considered hereinafter. In this section, the major new axes of research related to wireless communication systems and networks are considered.

3.1. Smart and cognitive radios

Cognitive radios (CRs) can scan and analyze their environment and adapt their transmission/reception parameters to better convey and protect transmitted data [18,19]. CR can be mainly divided into two categories: smart individual radios and smart networks (largely considered as cognitive radios). A smart radio can dynamically be auto-programmed and configured. Smart networks optimize the total use of available physical resources among its members. Fig. 3 presents the three main functions of a smart radio. In the case of a cognitive radio, the main decision function can be made in the central unit while the scanning and the analysis procedures can be done in each individual unit (a transmission unit can be affected to a primary or a secondary user). In order to optimally share the physical resources, CR classifies the transmitters (the users) into two categories: primary and secondary users. A primary user (PU) is the user holding a license of a defined spectrum. He is allowed to use his bandwidth any time as far as he is respecting the cover area and the transmission power. As many primary users do not broadcast all the time, their protected bandwidths are not used optimally. Therefore, an opportunistic user (i.a. a secondary user (SU)) can use the best available bandwidth as far as his signal does not interfere with the signal of PU at any time. This process is discussed further in Section 3.4.

As CR should scan their environment and get adapted to it; they should have the capability to identify, classify and analyze signals in the context of non-data aided. In previous Communication Intelligence (COMINT) projects and research studies, several algorithms to estimate unknown parameters of intercepted signals were proposed. An intercepted signal can be detected using a spectrum analysis or an energy detector. However, this operation

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[1] It is worth mentioning that the huge antenna on Earth belongs to the USA radio telescope, the Arecibo observatory in Puerto Rico, which is the world's largest single-aperture telescope (above 300 m). “It is used in three major areas of research: radio astronomy, atmospheric science, and radar astronomy.” [9]. We should also mention the new and great project of the Square Kilometer Area (SKA) [10].

[2] “The E3 look-down radar has a 360' view of the horizon, and at operating altitudes with a range of more than 320 km. The radar can detect and track air and sea targets simultaneously.” [11].

[3] Where 1 atto = 1 a = 10^{-18}, 1 femto = 1 f = 10^{-15}, 1 pico = 1 p = 10^{-12}, 1 Angstrom = 1 Å = 10^{-10} m, the diameter of an hydrogen atom is estimated to be 1 Å, 1 nano = 1 n = 10^{-9}, 1 micro = 1 μ = 1 u = 10^{-6}, 1 milli = 1 m = 10^{-3}, 1 centi = 1 c = 10^{-2}, 1 Kilo = 1 K = 10^{3}, 1 Mega = 1 M = 10^{6}, 1 Giga = 1 G = 10^{9}, 1 Tera = 1 T = 10^{12}, 1 Peta = 1 P = 10^{15}, 1 Exa = 1 E = 10^{18}, 1 Zetta = 1 Z = 10^{21}, 1 Yotta = 1 Y = 10^{24}.

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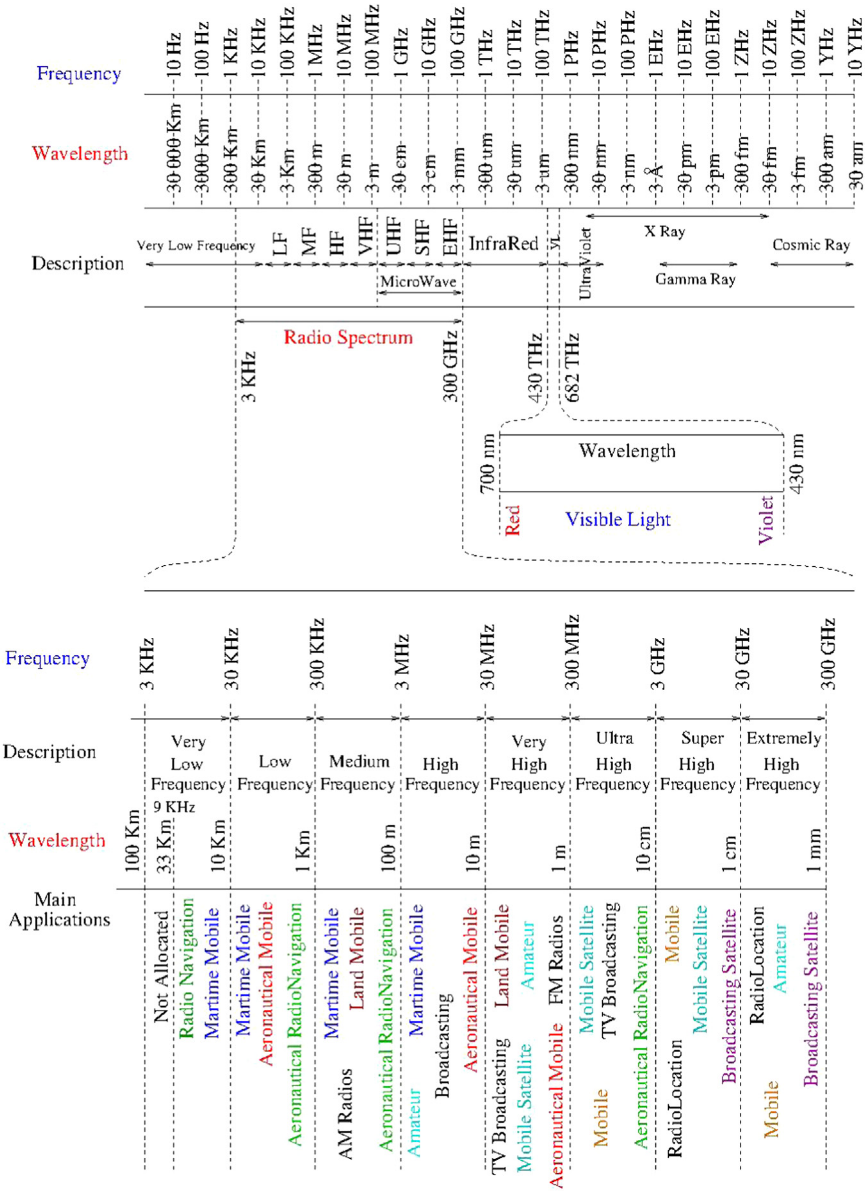

Fig. 1. Spectrum allocations, according to their wavelengths λ, frequencies F and applications.

Fig. 2. Wireless communication dilemma.

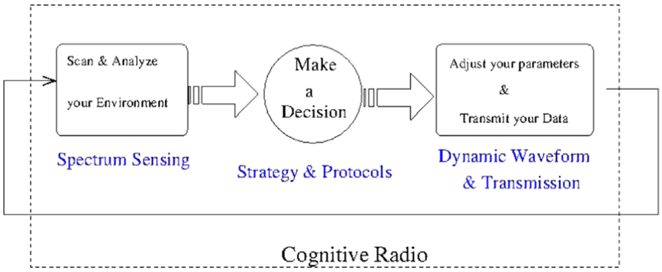

Fig. 3. Smart radio.

cannot estimate the unknown parameters of that signal. To conduct a Broadband High Dynamic Range Surveillance, several circuits were proposed. A part of our study appears in [20].

In order to classify, identify or recognize an intercepted signal, one should at first precisely estimate the carrier frequency of such signal, see Fig. 4 published in [21].

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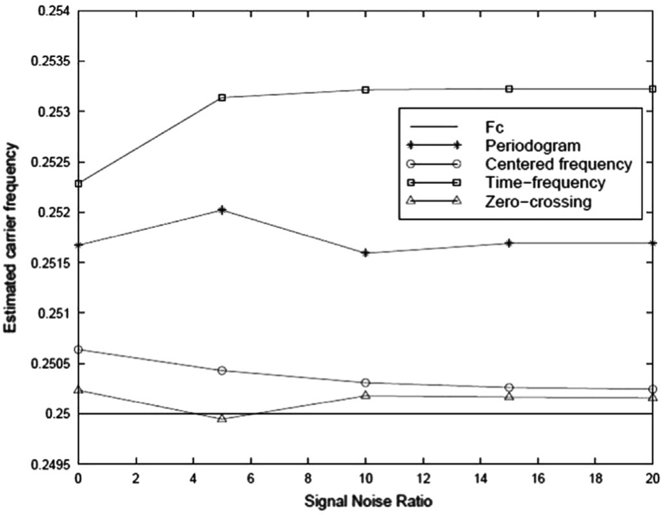

Many algorithms have been implemented and tested.

Fig. 4. Estimation of carrier wave frequency.

In [22], an algorithm consisting of two steps was proposed, see Fig. 5:

- A preliminary estimation can be performed using Welch spectral estimation algorithm, see [23].
- By minimizing a cost function based on the probability density function (PDF), $p(x)$ of the signal $x(t)$, and Reny's entropy with a parameter $0 < \alpha \neq 1$ [24]:

  $$H_R^\alpha = \frac{1}{1-\alpha} \log\left(\int_{-\infty}^{\infty} p^\alpha(x)\, dx \right)$$

  It is well known that $\lim_{\alpha \to 1} H_R^\alpha = H_S$ and that $H_R^\beta \leq H_S \leq H_R^\gamma$ where $0 < \beta < 1$, $\gamma > 1$ and $H_S = -\int_{\mathbb{R}} p(x) \log(p(x))\, dx$ stands for Shannon's entropy [25].

In some situations, one cannot intercept a message that well identifies the signal. In [26], we proposed an algorithm to estimate the carrier wave frequencies of two Binary Phase Shift Keying (BPSK)[4] mixed signals using one observed signal. Our algorithm maximizes two objective functions based on High Order Statistics (HOS) [27]. Fig. 6 shows the performance of our algorithm called $\sigma_w^2 -$ HOS comparing to the well known classic frequency estimation algorithm (i.e; MUltiple SIgnal Classification (MUSIC) algorithm) [28].

Once the carrier frequency has been estimated, then one should estimate the Symbol Period. Using Time Frequency Representation [29,30], $\mathrm{TFR}(t, f) = \int_\tau s(t + \frac{\tau}{2}) s^*(t - \frac{\tau}{2}) h(\tau) e^{-2j\pi f\tau}\, d\tau$, We proposed many estimators based on various concepts [31], see Fig. 7:

- TFR derivative: $Der(t) = \sum_{f=1}^{M} |TFR_{t+1}(f) - TFR_t(f)|$
- Vector Product of two TFR slices: $VP(t) = N_t N_{t+1} \sin(\alpha_{t,t+1})$
- A modified Shannon Entropy: $Ent(t) = \frac{-1}{\log_{10} M} \sum_{f=1}^{M} \overline{\mathrm{TFR}}_t(f) \log_{10} \overline{\mathrm{TFR}}_t(f)$
- Kullback's Divergence: $Div(t) = \sum_{f=1}^{M} \overline{\mathrm{TFR}}_t(f) \log_{10}\left(\frac{\overline{\mathrm{TFR}}_t(f)}{\overline{\mathrm{TFR}}_{t+1}(f)}\right)$
- Instantaneous mean frequency: $CV(t) = \mathrm{TFR}(t, f_c) = \mathrm{TFR}_{f_c}(t)$

Since the end of the 1980s, many researchers have been investigating the automatic identification and recognition of modulated communication signals [32]. A classification procedure can be used to separate intercepted signals into different modulation families (PSK, QAM, FSK, OFDM, TCM). While a recognition step is needed to estimate modulation subclasses (8 PSK, 4 PSK). Both of them, classification and recognition algorithms, are based on Features or Patterns analysis. Using second order statistics, we modified in [21] a classification scheme proposed in [32], see Fig. 8.

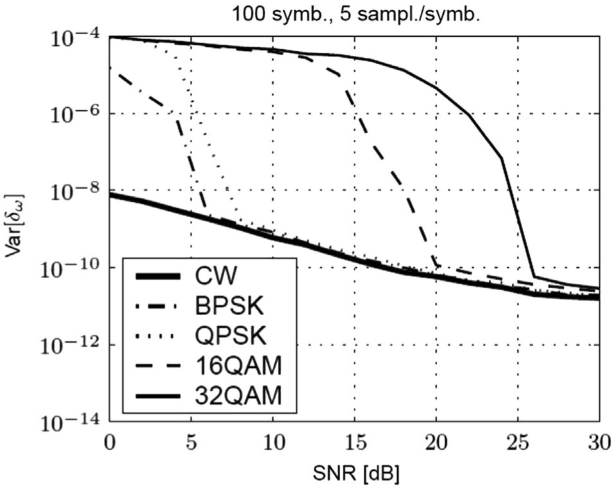

Fig. 5. Two-step algorithm for the estimation of carrier wave frequency (horizontal axis represents the signal to noise ratio, vertical axis showing the variance of the estimation error, for further details see [22]).

Further experimental results showed that the algorithm proposed in [21] is very sensitive to SNR, the estimation of the Symbol period or the Symbol number. Using Time Frequency Representation, we proposed another classification algorithm [31], see Fig. 9. To reach this goal, extra features have been proposed:

- A modified Power Spectral Density (PSD) has been used to conduct a preliminary classification. This feature is very sensitive to SNR.
- A power function based on PSD to discriminate intercepted signals into two sets: Mono-Modal (PSK, QAM) and Multi-Modal (FSK, OFDM)

  $$E_{mean} = \frac{1}{W_{size}} \sum_{f=f_c - Wf_{size}}^{f=f_c + Wf_{size}} \mathrm{PSD}(f)^2$$

  $Wf_{size} = \frac{W_{size}}{2} < M - f_c$ is the width of the estimation window and f_c is the carrier wave frequency.
- A Power Derivative Function is used to classify PSK and QAM signals.

We should mention that TFR (Time-Frequency Representation) approaches suffer mainly two drawbacks:

- Computing efforts (processing time, needed memory).
- High sensitivity to modulation parameters (i.e. symbol period, synchronization, transmission channel, etc.).

For these reasons, we proposed a classification algorithm based on HOS [33]. We should mention here that good results have been obtained with a low SNR, i.e. SNR=5 dB. The main idea of that algorithm consists in using (Principal Analysis Component) algorithm in order to project 8 features based on HOS of instantaneous amplitudes and phases onto a decision plan. An automatic modulation recognition of MPSK signals using constellation rotation and its 4-th order cumulant has been presented in [34], see Fig. 10.

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[4] BPSK signals are widely used in satellite communications as in double-talk scenario.

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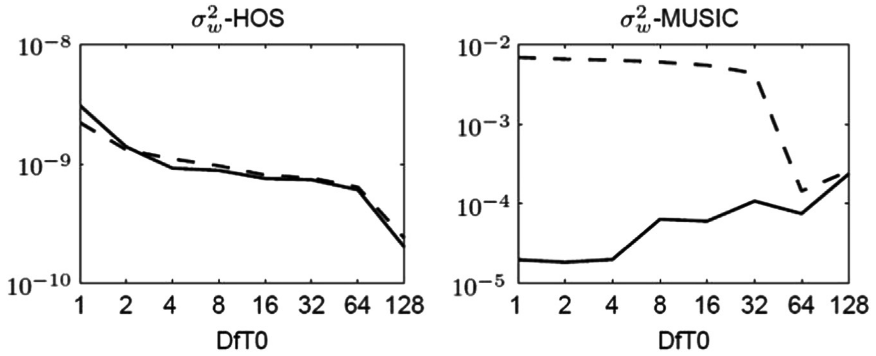

Fig. 6. Estimation of two carrier wave frequencies (horizontal axis represents the shift between two frequencies, the correct and the estimated one, $\Delta_f T_0 = |f_2 - f_1| T_0$ and T_0 is the observation period. Vertical axis shows the variance of the estimation error, for further details see [26]).

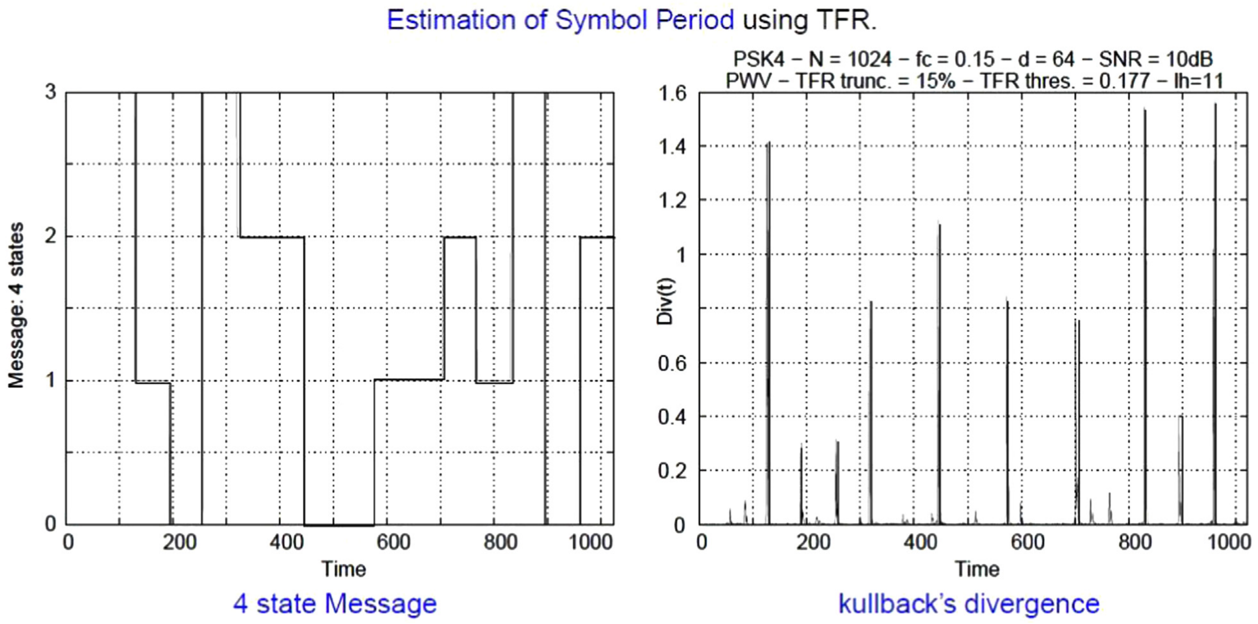

Fig. 7. Estimation of symbol period using TFR.

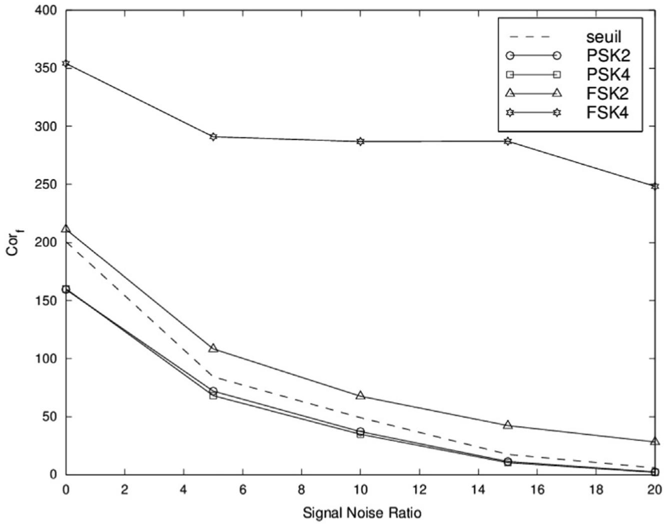

Fig. 8. The new proposed feature Cor_f is used to discriminate between MPSK and MFSK signals. Vertical axis represents a frequency feature Cor_f based on modified correlation function, see [21].

3.2. *Software defined radio (SDR)*

Cognitive Radio and Software Defined Radio are strongly related to the pioneer works published by Mitola in [35]; for further details on this subject, we advise readers to read that reference and its cited references. Software Defined Radio (SDR) is the new mode of radio transmission system where the majority of electronic parts (amplifier, detector, filters, MODEM, equalizer, mixer, etc.) of a conventional system are replaced by software codes [36,37]. SDR and cognitive radio are essential concepts for the Joint Tactical Radio System (JTRS) [38] and the Joint Tactical Networking Center [39]. The Software Communication Architecture (SCA) standard is a main international standard for SDR. SCA uses the Common Object Request Broker Architecture (CORBA) as middleware to allow the integration and the cooperation among various systems and softwares. CORBA is based on Object Request Broker (ORB) to ensure the communication among different applications. Design New and complex waveforms such as the Future Multiband Multiwaveform Modular Tactical Radio (FM3TR) or P25 [40].

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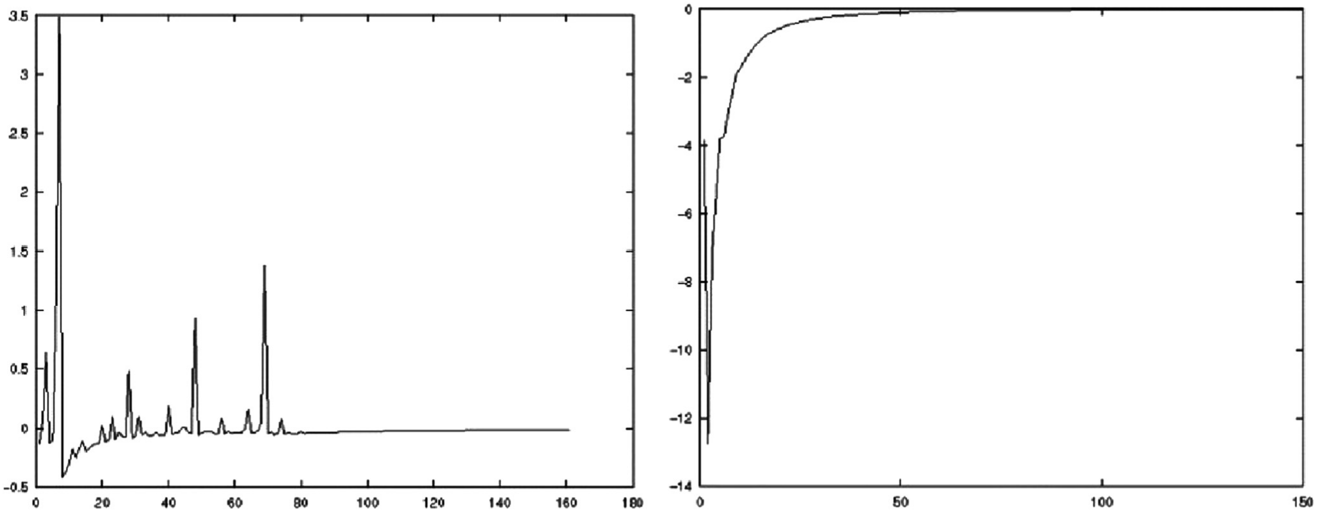

Fig. 9. Classification approach based on time-frequency representation. Left figure represents the case of FS4, while the right one is for a PSK4.

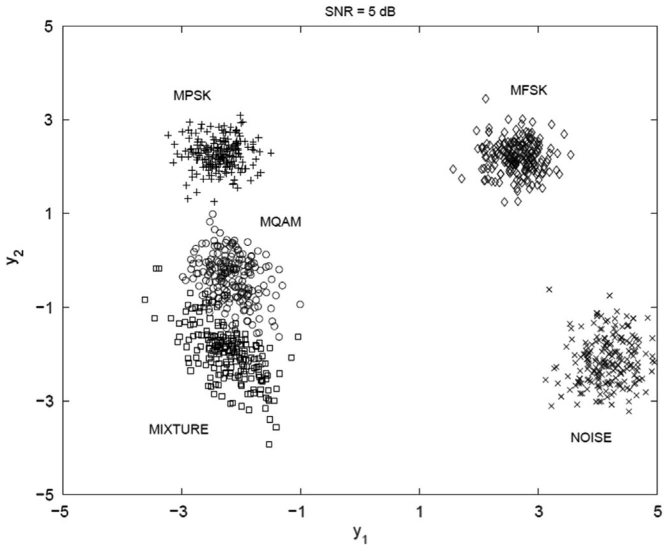

Fig. 10. Signal classifications.

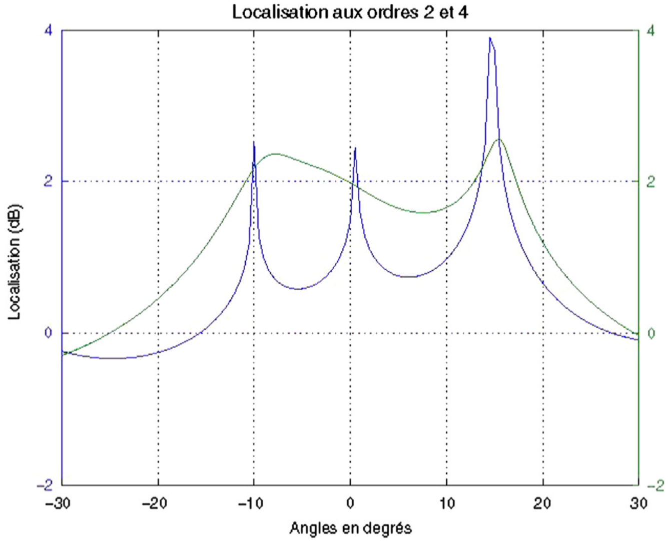

Fig. 11. DOA estimation by MUSIC-4, in blue, and MUSIC-2, in green, with AWGN and a SNR=0 dB, in the case of 5 sensors and 3 sources. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

3.3. *Smart antenna and software defined antenna*

Smart Antenna and Software Defined Antenna (SDA) allow the wireless devices to adapt the antenna to its environment for different modes and frequencies. While the main idea of SDA [41] is similar to the one of SDR, the concepts are quite different [42]. In this section, we only emphasize the signal processing along with beam forming approaches to realize smart antennas.

The first radar detection techniques were based on the spectrum and Fourier-based-methods. Later on, high-resolution methods have been proposed such as ARMA modeling, Prony methods, MUSIC (Multiple Signal Classification) or ESPRIT (Estimation of Signal Parameters via Rotational Invariance Technique). In [43], we explored several algorithms based on HOS criteria and Independent Component Analysis (ICA) to enhance the Direction of Arrival (DOA) of radars' detection. Fig. 11 shows clearly that in some scenarios classic MUSIC algorithm can be compared to MUSIC4 (based on 4th order statistics). Indeed, MUSIC4 was successful in locating the three targets while classic one could not.

Smart antenna can be developed using digital beam forming algorithms. Beam forming algorithms are divided into two main categories: Blind and non-blind algorithms. Generally, blind algorithms are more complex than non-blind ones and they cannot reach the performance of non-blind ones. In the literature, one can find several non-blind approaches, such as [44–47]: Least Mean Squares (LMS) algorithms, Recursive Least Squares (RLS), XLMS, Extended Kernel Recursive Least Squares Algorithm, etc. We proposed two new beam-forming algorithms [48–50]: LLMS and RLMS. RLMS algorithm is an Adaptive Array Beam forming using a combined RLS-LMS Algorithm, see Fig. 12.

In [49], the performance of RLMS Adaptive Beam forming Algorithm is analyzed when it is implemented with Finite Precision. In [51], our LLMS Adaptive Array Beamforming Algorithm was adapted for Concentric Circular Arrays. Fig. 13 shows the performance of RLS comparing to RLS with respect to SNR.

It is well known that non-blind beam forming algorithms require a reference signal to reach the convergence. On the other hand, these algorithms can estimate their channels and they can then generate their own references. To test this idea, we conducted several simulations. In these simulations, we assumed that a reference signal was generated during a fixed period of time T_0. We tried to reduce T_0 as possible, then we evaluated the convergence of the algorithms. Fig. 14 showed that for some T_0, RLMS algorithm

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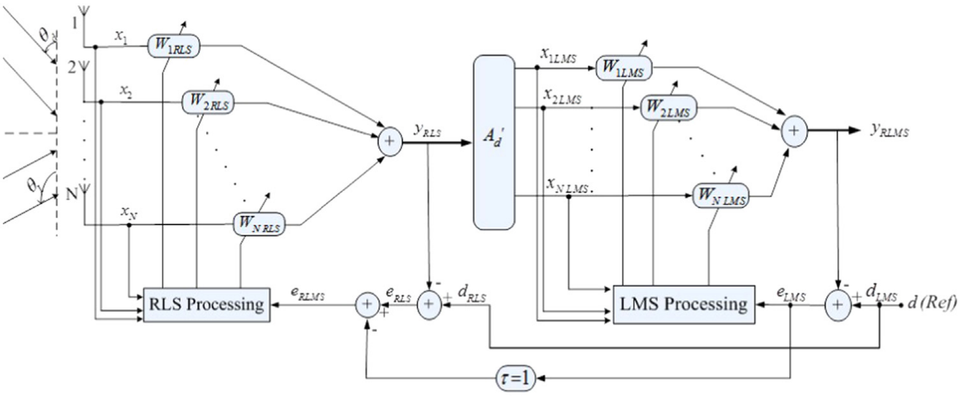

Fig. 12. RLMS: a combined RLS-LMS Algorithm.

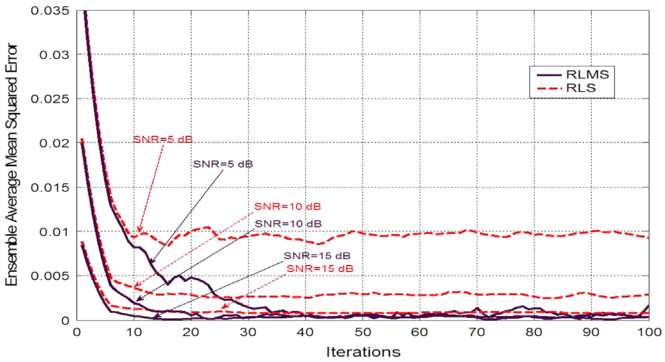

Fig. 13. RLMS: convergence.

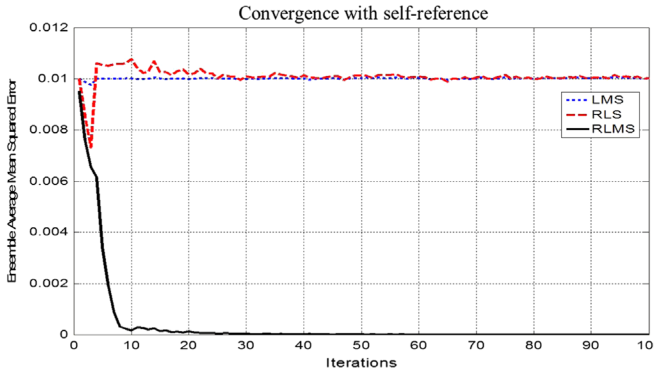

Fig. 14. RLMS: convergence with self reference.

performs better than LMS or RLS that were unable to reach the convergence once the reference signal was lost.

3.4. Compressive sensing and dynamic spectrum access (DSA)

It was mentioned before that Cognitive or Smart Radio Systems can detect unused bandwidths attributed to licensed users (Primary User : PU) to allocate them to unlicensed users (Secondary User: SU). In this case, secondary users should have a dynamic access to available spectrum bandwidths.

Fig. 15 represents an overview of time-frequency plan to consider the following scenario where we have 5 primary users (PU_i, $i \in \{1, 5\}$ and two secondary users (SU_1 and SU_2). Let us consider that PU_2 is transmitting all times, however, the other primary users are not using their licensed spectrum bandwidths for some time periods. We will also assume that SU_2 has more priority than SU_1, but his need for the spectrum bandwidths is dynamic (i.e. the amount of data to be transmitted by SU_2 are not constant over time). In this case, the central unit of our cognitive radio should allocate empty spectrum bandwidths with the signals of the two secondary users.

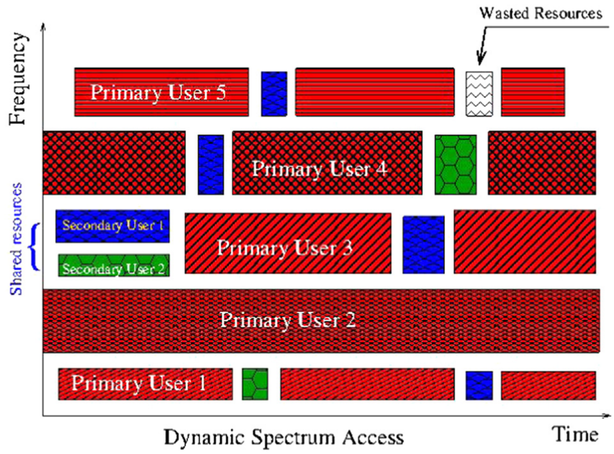

Fig. 15. Spectrum sensing and dynamic spectrum access.

Spectrum sensing aims to detect the presence of PU [52,53]. This operation is crucial in order to apply for an efficient dynamic spectrum access. Spectrum sensing algorithms can be divided into two categories [54]:

- Cooperative techniques [55] such as: Wave Form (WF) and the Cyclo-Stationary Detection (CSD) methods, which are the most widely used. In [56], we proposed an efficient spectrum sensing approach based on waveform detection, see Fig. 16. Our criterion is called Range Decision Test based WF (RDT-WF).
- Blind techniques do not require any a priori information [57] such as: Energy Detection and the Blind Source Separation techniques. In [58], we proposed a spectrum sensing algorithm based on Cumulative Power Spectral Density.

3.5. Compressive sampling

It is well known that the sampling frequency f_s of a digital signal $x(n)$ should respect the Nyquist threshold, i.e. $f_s \geq 2B$ where B stands for the maximum frequency of the analog signal $x(t)$. Recent studies showed that the threshold can be reduced if the signal is sparse [59]. In [60], we showed that the f_s of sparse signals in the frequency domain can be less than $2B$ using Multicore Sampling techniques. This process can be generalized for any sparse signal. Indeed, this process is equivalent to sample the

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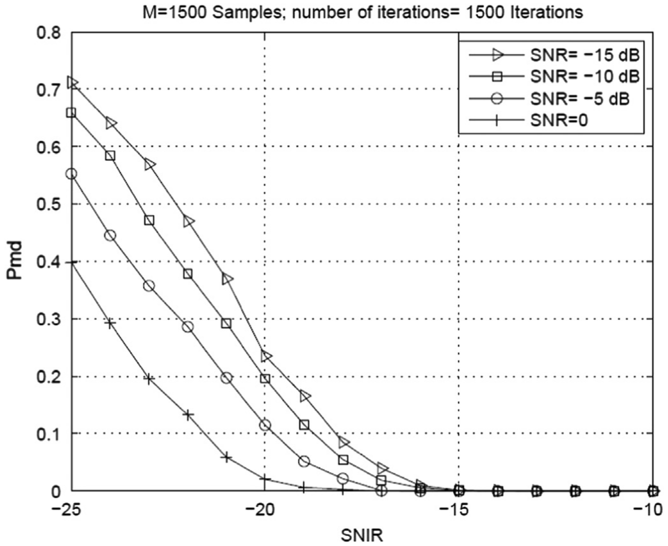

Fig. 16. Performance of proposed approach for various SNIR (dB) (i.e. signal-to-noise-plus-interference ratio).

signal with non-uniform sampling or with uniform sampling but one should just keep periodically p samples out of L [61]. An introduction to Compressive Sampling is provided in [62]. Compressive Sampling is very useful technique for Cognitive Radio, as they can sample, process and reconstruct compressed signals that mean less processing time and less needed memory. Besides that, as the sampling frequency is reduced, therefore one can use these techniques to easily perform a surveillance for large bandwidths [63].

3.6. Free-space optical communications

Free-space optical (FSO) communication is a wireless communication system that uses an optical carrier to transfer information through free space i.e., inter-building connections.

3.6.1. How it works?

The transmitter of FSO communication modulates the source data onto an optical carrier which is then propagated through an optical channel to the receiver. The simplest modulation is the intensity modulation (IM) in which the source data is modulated on the intensity of the light. The telescope at the transmitter focuses the transmitted signal towards the receiver telescope. The commonly used source in FSO systems is LASER. The main function of the receiver is to estimate the transmitted data from the received optical signal. The receiver consists of a receiver telescope, an optical band-pass filter, a photodetector, and a detection circuit. The receiver telescope collects and focuses the received signal onto the photodetector and the optical band-pass filter reduces the background noise. The photodetector converts the received optical signal into an electrical signal such as PIN and avalanche photodiode (APD). Finally, at the detection circuit, the received signal is recovered after amplification and filtering [64,65].

FSO communication is a line-of-sight (LOS) technology operating at wavelengths of 850 nm, 1300 nm and 1550 nm corresponding to the optical communications 1st, 2nd and 3rd transmission windows, respectively as these wavelengths have low attenuation, less than 0.2 dB/km, can use the same commercial components of an optical fiber and safe for eye and skin [64,66].

3.6.2. History

Alexander Graham Bell invented the photophone in 1880 and he considered it his greatest invention. Photophone transfers signal from transmitter to receiver using sunlight as a carrier. It never came to a commercial product due to the lack of good light sources. After the invention of the laser in 1960, a lot of experiments were performed for military and aerospace applications. With the invention of low-loss fiber in 1970, all optical research was focused on it. Currently, FSO systems attract great interest as a powerful complementary to radio frequency [64,67].

3.6.3. Advantages

FSO communication system is a promising candidate for the next generation wireless communication systems as it offers an efficient solution for last mile access, free license, high data rate i.e., 10 Gbps links are already in the market, green communications, cost-effective, back-haul for expensive optical fiber communication, easy to deploy, back-haul for cellular communication and secure [64,66,67].

3.6.4. Market

In a recent market study, it was anticipated that FSO market will grow from $ 116.7 Million in 2015 to $ 940.2 Million by 2020 [68]. FSONA, one of the leading FSO companies in Canada, provides Crédit Agricole French bank with FSO links of 10 Gbps. Four 2.5 Gbps links were deployed rather than using an expensive fiber optic link for their new building of the bank in Paris. The new link provides a service for more than 1600 employees [69]. In Lebanon, FSONA provides a mobile backhaul connectivity for the fourth generation long-term evolution (LTE) services to customers with a link of 1.25 Gbps without the delay of a laying cable [70]. Northern Storm, one of the leading FSO companies in the US, installed a hybrid FSO/RF link in California city of FSO link with 10.31 Gbps and RF link with 1 Gbps as a backup for a distance of 238 m. For the considered system, an availability of 99.999% is achieved for different weather conditions [71].

3.6.5. Challenges

The transmitted optical signal is affected by various challenges before arriving at the receiver such as misalignment errors, geometric losses, background noise, weather attenuation losses and atmospheric turbulence.

Geometric loss: This can be defined as the optical beam divergence due to propagation, divergence angle, and the receiver aperture size [72].

Misalignment error: Many reasons can cause misalignment errors including but not limited to: Wind, earthquake, and building vibrations [73]. A laser with a wide divergence angle can reduce the effect of misalignment error for short range applications. While a laser with a narrow divergence angle must be used with an automatic tracking system for long rang applications [73,74].

Weather attenuation loss: FSO communication systems are affected by different weather attenuation losses such as haze, dust, fog, rain, smoke and snow [75,76]. Unlike RF, FSO links suffer from the highest attenuation in the presence of fog while they are less affected by the rain. Hence, hybrid RF/FSO systems [77] and mixed RF/FSO systems [73,78] are employed to take the advantages of both technologies. In hybrid RF/FSO, both FSO and RF are employed between two nodes [77]. However, in mixed RF/FSO, RF and FSO are deployed together for different hops [78]. The attenuation coefficient (α in dB/km) of different weather conditions are provided in Table 1.

Background noise: The exposure of the receiver to direct or indirect sunlight or artificial lights leads to background noise. Background noise reduces the signal-to-noise ratio gain and can be eliminated through bandpass filter before photo-detection [74,79].

Atmospheric turbulence: The random fluctuation of the received signal results from the inhomogeneity in temperature and pressure causes atmospheric turbulence. This turbulence degrades the

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performance of FSO communication systems [80]. The turbulence effect depends on the link distance, the wavelength of the light source and the refractive index constant, C_n^2 ($m^{-2/3}$) [81]. C_n^2 increases by temperature so it has the peak value at noon and it has the minimum value at midnight [82].

3.6.6. *Mitigation techniques*

In this subsection, mitigation techniques at physical layer will be discussed. Several modulation schemes are employed in FSO systems to mitigate turbulence effect according to the required energy efficiency, target spectral efficiency and coherent or non-coherent detection. The most common schemes are on-off keying (OOK) [83], pulse position modulation (PPM) [84], multiple PPM (MPPM) [85], pulse width modulation (PWM) [86], digital pulse interval modulation (DPIM) [87] and binary phase shift keying (BPSK) [88]. Another useful mitigation technique for atmospheric turbulence is forward error correction (FEC) such as Reed–Solomon (RS) codes [89], concatenated RS codes [90,91], turbo codes [92] and low-density parity-check codes [93]. Spatial diversity is also considered as a promising solution to mitigate atmospheric turbulence and enhances the data rate of the system [94,95]. To further mitigate turbulence and path losses effects, relay-assisted systems such as multi-hop systems and cooperative relays are used due to its advantage of shorter hops that yields significant performance improvements [96].

Table 1
Weather attenuation coefficient of FSO.

Weather conditions	α[dB/km]
Clear air	0.43
Haze	4.2
Moderate rain (12.5 mm/h)	5.8
Heavy rain (25 mm/h)	9.2
Light fog	20
Moderate fog	42.2
Heavy fog	125

3.6.7. *Our contributions*

Our contributions for FSO communications are summarized in Fig. 17 [97]. Two challenges facing FSO are considered: Weather attenuation with geometric loss, and atmospheric turbulence.

Weather attenuation with geometric losses leads to power loss and relay-assisted FSO systems can mitigate these effects by using shorter hops. Two schemes are employed for these challenges as follows:

(a) Best relay selection for cooperative relays using full-duplex (FD) relays under different turbulence conditions, misalignment error and path loss effects is considered. Our results show that FD relays have the lowest average bit error rate (ABER) and the outage probability (OP) compared with the direct link and best relay selection for cooperative relays using half-duplex (HD) relays [98].
(b) Decode and forward (DF) multiple-input single-output (MISO) multi-hop FSO systems are proposed and the obtained results show the superiority of the considered system over single-input single-output (SISO) and MISO systems considering correlation effects at the transmitter [99,100].

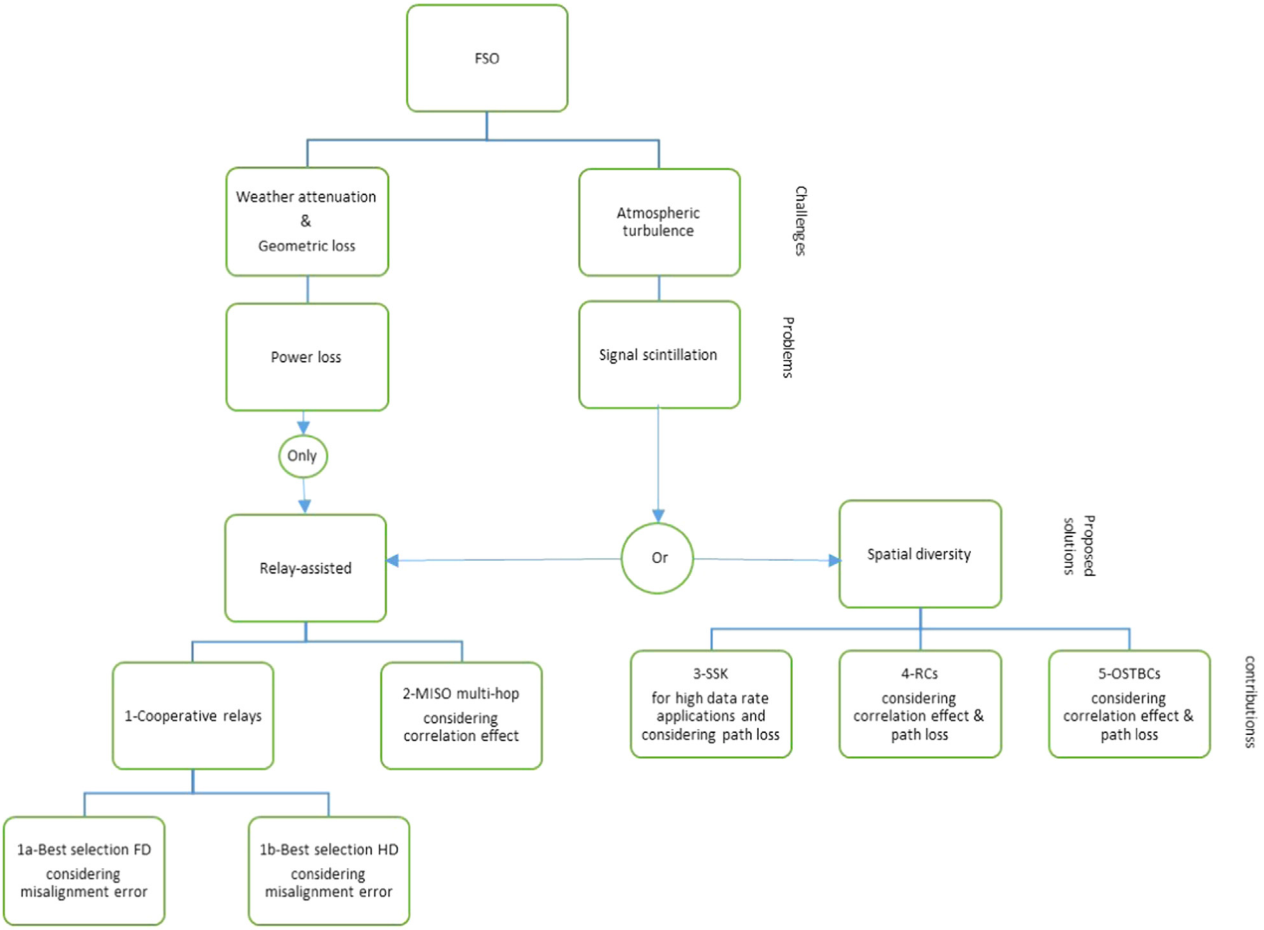

Fig. 17. Our contributions in FSO [97].

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In the case of atmospheric turbulence, which leads to signal scintillation, spatial diversity and/or relay-assisted can be employed to mitigate such impairments. Space shift keying (SSK), orthogonal space–time block codes (OSTBCs) and repetition codes (RCs) are employed as follows:

(c) SSK is considered achieving a high spectral efficiency for FSO links. SSK outperform direct link and RCs multiple pulse amplitude modulations (M-PAM) techniques for higher spectral efficiency applications and for moderate-strong turbulence channels. Tight upper and lower bounds for ABER expressions corresponding to negative exponential and log-normal (LN) channels, respectively are obtained [101,102].

(d) Correlation among multiple transmitters leads to signal-to-noise ratio (SNR) losses. Hence, separating the transmitters by few centimeters decreases the correlation effect. However, the required separation may be difficult in practice as available space for the transmitters may not be sufficient for this requirement. Hence, correlated LN channels, as well as path loss due to weather effects using intensity modulation and direct detection schemes, have been considered. Additionally, an approximated ABER expressions for RCs and OSTBCs are derived. Under the considered scenarios, results show that RCs outperform OSTBCs by at least 3 dB [103,104].

3.7. *Multiple-input multiple-output (MIMO) and millimeter wave (mmWave)*

A technology that promises enhancement in the achievable throughput and the overall spectral efficiency is MIMO systems. The scarcity of the wireless spectrum is the main factor that hinders the vision for wireless access everywhere anytime, and perhaps the toughest challenge that wireless research has to undertake. Overcoming this challenge requires innovations in various areas including novel ways for spectrum sensing and reuse, as discussed in previous sections, mechanisms for using higher frequencies such as (mmWave) and the visible light as in FSO, novel ideas for dealing with interference, MIMO, and generally more efficient protocols and systems [105–107].

MIMO systems are one of the most promising technical advances in wireless communications in recent years. Such systems facilitate high-throughput transmission in various recent standards including LTE, WIMAX, WINNER, and others [108–110].

Existing radio frequency technologies utilize a spectrum ranging from 300 MHz to about 3 GHz [111]. In such a small bandwidth, huge number of wireless applications exist that support high quality and moderate–latency multimedia services. However, the rapid increase of mobile applications and wireless services pose unprecedented challenges for future wireless systems. The major challenge is to overcome the shortage in the global bandwidth, and develop high-bit-rate multimedia services and applications. A promising solution to overcome such a challenge that captures significant and rapid interest is millimeter–wave (mmWave) communications and MIMO systems [112]. Millimeter–wave communications offer a plentiful frequency spectrum, ranging from 3 to 300 GHz, that can be exploited to achieve multi-gigabits per second data rates [111,113]. Specifically, the unlicensed 60 GHz band spectrum has induced a significant interest in multigigabits data rates for short range wireless communications [111]. As such, several recent standards have been developed based on mmWave technology including mmWave WPAN (IEEE 802.15.3c-2009) [114], WiGig (IEEE 802.11ad) [115], and WirelessHD [116].

Space modulation techniques, as space shift keying (SSK) and spatial modulation (SM), are MIMO methods that use the multiple transmit antennas in an innovative fashion. Transmit antennas are considered as spatial constellation points and utilized to carry additional information bits to boost the overall spectral efficiency. Each antenna index is utilized to carry additional information bits and a spatial multiplexing gain of base-two logarithm of the overall number of transmit antennas is achieved. Besides, activating single transmit-antenna at a time eliminates inter-channel interference, relaxes inter-antenna synchronization requirements, reduces receiver complexity, and allows the use of a single RF chain at the transmitter. In addition, it has been shown that space modulation techniques enhance error performance with a moderate number of transmit antennas as compared to other conventional MIMO techniques. In addition, it is demonstrated that these techniques are more robust to channel imperfections, such as spatial channel correlation and channel estimation errors, as compared to other MIMO techniques, since the probability of error of space modulation systems is not determined by the actual channel realization, rather by the differences between channels associated with the different transmit antennas [117–119].

The past few years have witnessed a tremendous development on space modulation techniques [117,120–131]. The authors in [120] provided an analytical solution for the optimum constellation breakdown between space and signal domains. Based on SM scheme, a new scheme to modulate the information onto the constellation points, which is called superposition coded modulation-aided spatial modulation (SCM-SM) is proposed in [121]. In the same work, a low-complexity iterative detector for the SCM-SM system is developed. The authors in [122] derived an optimal detector for SM systems. The detector is based on the maximum likelihood (ML) detector and jointly detects the antenna indexes and the transmitted symbols. Another modulation scheme known as space shift keying (SSK), which is a special case of SM is proposed in [123]. In SSK, the antenna index used during the transmission solely conveys the information without sending any data symbol. Another schemes proposed in [124] use the knowledge of the channel information at the transmitter to design the transmit vectors such that the distance between each pair of constellation vectors at the receiver becomes larger. An extended spatial modulation (ESM) techniques in which the number of active transmit-antenna is variable with low-complexity near-optimal detection scheme was proposed in [125]. Another low-complexity symbol detector for generalized space shift keying (GSSK) based on ℓ_∞ minimization technique was proposed in [126]. In this technique, the signal detection of GSSK is converted into a binary symbol recovery problem which can be solved via a convex optimization tool. A novel detection algorithm for the generalized spatial modulation (GSM) system with multi-active antennas is proposed in [127]. The proposed algorithm exploits the inherent sparse property of the SM signal and combines it with the sparse reconstruction theory. An upper bound for the average bit error probability (BEP) of a differential SM system equipped with two transmit-antenna over Rayleigh fading channels was derived in [128]. A computationally efficient concentrated ML (CECML) algorithm is proposed to efficiently compute a newly proposed ordering metric for the ordered-block minimum-mean-squared-error (OB-MMSE) detector in a GSM system [129]. The proposed algorithm avoids redundant computations and enables early termination without noticeable performance degradation. The authors in [130] analyzed large-scale GSM-MIMO systems. Specifically, an analytical upper bounds for the code-word error probability (CEP) and BEP performance were derived. In addition, a complexity reduction scheme that allowed the computation of the bounds for large GSM-MIMO systems is proposed. An optimum transmit structure for SM systems that balances the size of the spatial constellation diagram and the size of the signal constellation diagram is proposed in [131]. Instead of using exhaustive search, a novel two-stage transmit antenna selection (TAS) method was proposed to reduce the computational complexity, where the

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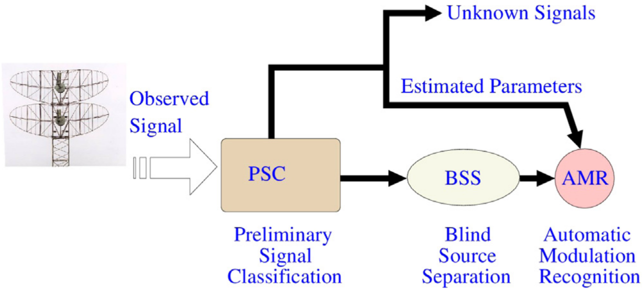

Fig. 18. A scheme of a proposed interception system [141].

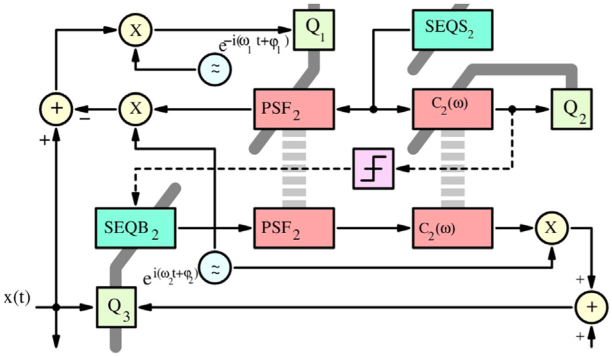

Fig. 19. A scheme of receiver which can extract 2 BPSK signals using one observed mixed signal. the transmission channel is considered as a MISO multi-path one. PSF=Pulse Shaping Filter, Q_1=SOS, Q_2= Constant Modulus Algorithm, Q_3=Quadratic Error.

optimal number of transmit antennas and the specific antenna positions are determined separately. Recently, an SM technique called quadrature spatial modulation (QSM) has been proposed in [132,133]. Performance analysis over Rayleigh fading channel with perfect and imperfect channel estimations were considered.

Nonetheless, a major criticism of space modulation techniques is that the data rate enhancement is proportional to the base-two logarithm of the number of transmit antennas. This is unlike other spatial multiplexing techniques, where data rate increases linearly with the number of transmit antennas. To overcome this limitation, several attempts were made to enhance the overall spectral efficiency of such techniques. In [24], a generalized SM algorithm is proposed where a combination of transmit antennas is activated at each time instant. A similar algorithm is proposed in [25] for SSK system. However, the performance of these systems is shown to be slightly worse than the conventional SM/SSK systems. In QSM, the spatial constellation symbols are expanded to in-phase and quadrature components. The in-phase and quadrature spatial modulation dimensions are orthogonal representing the in-phase and the quadrature components of the carrier signal. Consequently, SM advantages such as entire inter-channel interference avoidance, single RF chain at the transmitter and low complexity receiver are maintained. But an additional base two logarithm of the number of transmit antennas as compared to SM is achieved. Previous analyses of QSM demonstrate the several enhancements as compared to SM and other MIMO schemes.

3.8. *Spatial diversity*

The Independent Component Analysis (ICA) is a relatively new branch of signal processing proposed to solve the Blind Source separation (BSS) [134]. In the last two decades, many researchers have been involved in this fields and actually, one can find many algorithms and applications for ICA and BSS, see the following references [135–138] and their cited references. Recently, this problem was introduced in the context of port surveillance [139]. We had mentioned before that ICA and HOS have been used in the context of Cognitive Radio, Electronic XWarfare and Spectrum Sensing.

To our knowledge, all classification algorithms assume that the intercepted signal is a single unknown modulated signal. In our days, this assumption becomes a very strong one. In wireless applications, the interception of MIMO signals is a serious challenge for the scientist community. We proposed a system that can extract two BPSK signals from one mixed signal of them. In order to achieve the separation, we introduced an auxiliary signal based on a frequency rotation and a squared error minimization. It is worth mentioning that with a 5 dB of SNR, good experimental results have been obtained [140], see Fig. 18.

Finally, we proposed a scheme to separate convolutive mixtures in an undetermined scenario [142], see Fig. 19.

4. Conclusion

This manuscript addresses the limitation of actual communication systems and describes the recent challenges of such systems. It discusses as well major research fields proposed to solve the rising problems. Future wireless systems are supposed to meet several challenges for which intense research is needed to develop future wireless systems. Disruptive network designs (sensor networks, cognitive communication, etc), signal processing at the physical layer (FSO, mm wave, hybrid systems, beam forming, etc), implementation of information theory aspects (network coding, physical layer security, interference and energy management, etc). Hardware implementations and testbeds are crucial for future system design. Finally, we hope that this manuscript will be useful for the readers understanding different recent wireless systems.

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[8] A smart grid is a system which includes a variety of operational and energy measures including smart meters, smart appliances, renewable energy resources, and energy efficiency resources. ⟨https://www.smartgrid.gov/⟩.
[9] T.A.O. is part of the National Astronomy, U. Ionosphere Center (NAIC), a national research center operated by SRI International, u. a. c. a. w. t. N. S. F. N. T. N. i. a. i. f. a. w. a. i. t. p. s. UMET, engineering progress in the United States. NSF funds research, education in most fields of science, engineering. Additional support is provided by the National Aeronautics, and S.A. (NASA). ⟨http://www.naic.edu/⟩.
[10] T.S.K.A.S. is a radio telescope project that will be built in Australia and South Africa. ⟨https://www.skatelescope.org/⟩.

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[13] Inter-American telecommunication commission is the telecommunications/ICT advisory body of organization of American states. ⟨https://www.citel.oas.org⟩.

[14] National aeronautics and space administration. ⟨https://www.nasa.gov/⟩ and ⟨http://missionscience.nasa.gov/⟩.

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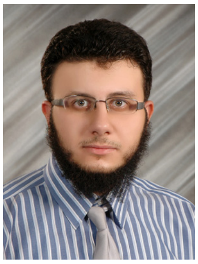

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