Mitigation of Distortions in Radio-Over-Fiber Systems Using Machine Learning

Mitigación de Distorsiones en Sistemas de Radio-Sobre-Fibra usando Aprendizaje Automático

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Abstract

Introduction— The ever-growing number of users connected to internet via mobile devices has driven to increase the research in the paradigm of hybrid optical networks called Radio-over-Fiber. These networks take advantages of the bandwidth given by the optical fiber and the mobility given by wireless transmissions, avoiding the bottleneck of optical-to-electrical conversion interfaces. However, the chromatic dispersion of the optical fiber generates distortions in the radiofrequency signals optically modulated, limiting the reach of transmission.

Objective— To improve the performance of a Radio-over-Fiber system in terms of bit-error-rate, using nonsymmetrical demodulation by means of the machine learning algorithm Support Vector Machine.

Methodology— A Radio-over-Fiber System is simulated in the specialized software VPIDesignSuite. The radiofrequency signals are modulated at 16 and 64-QAM formats with different laser linewidths and transmitted over optical fiber. The Support Vector Machine algorithm is applied to carry out nonsymmetrical demodulation.

Results— The implementation of the machine learning algorithm for signal demodulation significantly improves the network performance, reaching transmissions up to 30 km. It implies a reduction of the bit-error-rate up to two orders of magnitude in comparison with conventional demodulation.

Conclusions— Mitigation of distortions in terms of bit-error-rate is demonstrated in a Radio-over-Fiber system using nonsymmetrical demodulation by using the Support Vector Machine algorithm. Thus, the proposed technique can be suitable for future high-capacity access networks.

Keywords— Asymmetrical demodulation; Machine learning; millimeter wave band; Radio-over-fiber; Support Vector Machine

Resumen

Introducción— El constante crecimiento de usuarios conectados a internet por medio de dispositivos móviles ha conllevado a incrementar la investigación en el paradigma de las redes híbridas conocido como Radio-sobre-Fibra. Estas redes aprovechan las ventajas del ancho de banda de la fibra óptica y la movilidad de las transmisiones inalámbricas, evitando el cuello de botella que se da por la conversión óptico a eléctrico. No obstante, la dispersión cromática propia de la fibra óptica genera distorsiones en la señal de radiofrecuencia modulada ópticamente, lo cual limita su alcance.

Objetivo— Mejorar el desempeño de un sistema de radio sobre fibra en términos de la tasa de error de bit, usando demodulación no simétrica por medio del algoritmo de aprendizaje automático Máquina de Soporte Vectorial.

Metodología— Se simula un sistema de Radio-sobre-Fibra en el software especializado VPIDesignSuite. Se transmiten señales de radiofrecuencia moduladas en formatos 16 y 64-QAM con diferentes anchos de línea de láser sobre fibra óptica. Se aplica el algoritmo Máquina de Soporte Vectorial para la demodulación de la señal.

Resultados— La implementación del algoritmo de aprendizaje automático para la demodulación de la señal mejora significativamente el desempeño de la red permitiendo alcanzar los 30 km de transmisión por fibra óptica. Esto implica una reducción de la tasa de error de bit hasta en dos órdenes de magnitud en comparación con la demodulación tradicional.

Conclusiones— Se demuestra que con el uso de umbrales asimétricos usando algoritmo de Máquina de Soporte Vectorial se logran mitigar distorsiones en términos de la tasa de error de bit. Así, esta técnica se hace atractiva para futuras redes de acceso de alta capacidad.

Palabras clave— Aprendizaje automático; banda de ondas milimétricas; demodulación asimétrica; Máquina de Soporte Vectorial; Radio-sobre-fibra

I. Introduction

Currently, wireless communication systems have covered a large part of the globe, thanks to the high diffusion of mobile devices, since these systems do not depend on a fixed connection to access the internet [1]. However, most of the bands of the electromagnetic spectrum for wireless telecommunications services are occupied and regardless of their efficiency, more bandwidth is necessary for new high-performance applications [2]. For this reason, investigations have been carried out in a region of the spectrum known as the Millimeter Wave band (MMW), which includes a range from 30 GHz to 300 GHz [3]. Mainly the W band (75 GHz - 110 Hz), although the 60 GHz band, as it is not licensed, has been subject of experimentation for more than a decade [4]. The objective of operating in the MMW band is basically since next-generation wireless communication networks must provide very high data speeds, with low latency, a significant increase in Quality of Service (QoS), compared to current 4G LTE networks. To meet the gap between user demand and channel capacity, MMW communication equipment has become a strong attraction for upcoming high-demand networks [5].

For these future networks, it has been proposed to transmit Radio Frequency signals (RF) by optical fiber given its low attenuation, therefore communication between antennas could be only used for the connection with the end user. This proposal is known as Radio-over-Fiber (RoF) (Fig. 1) [6]. In recent years, RoF technology has been considered to support fifth generation (5G) mobile networks, promising high-speed transmissions at more than 10 Gbps [7]. In addition, RoF technology is promising for its ability to provide connectivity in difficult-to-access areas (mountainous, remote, rural, among others).

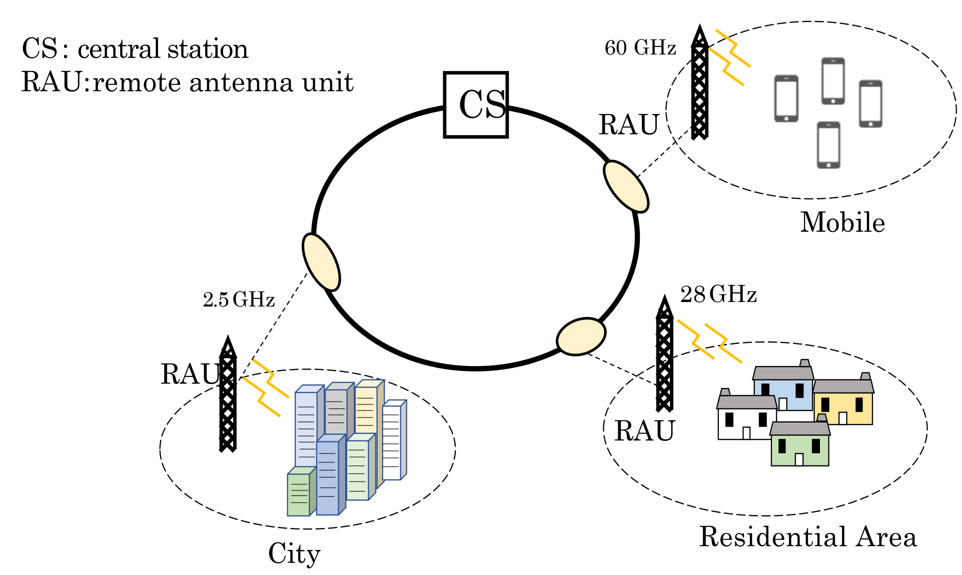


Fig. 1. RoF System.
Source: Authors.

One of the advantages of RoF technology is that it concentrates the most expensive RF equipment in a central station and the rest of the equipment is installed in the nodes or in the end users as can be seen in Fig. 2. In this sense, it is possible to reduce costs in power and complexity [8].

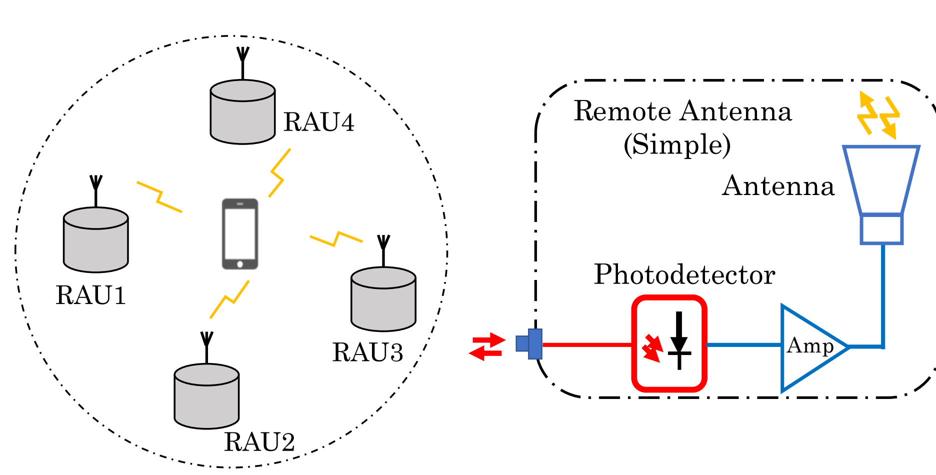


Fig. 2. Architecture proposed by RoF technologies: Central office and Remote Antenna Unit (RAU) as a base station.
Source: Authors.

A wireless access network RoF architecture has also been proposed, implementing the Wavelength Division Multiplexing (WDM) technique for an optimal deployment of base stations in rural areas [9]. Therefore, making use of this type of technology in countries with a high density of remote areas and difficult access could solve their coverage problems. For example, in Colombia about 47% of households do not have internet service [10].

However, in RoF systems there are also problems that affect the quality of the signal, such as the non-linear effects of the optical fiber, dispersions and power fluctuations. For this reason, methods are required to mitigate these effects. In the first place, phase modulation along with coherent optical detection was proposed as an alternative to RoF systems with intensity modulation and direct detection (IM/DD systems). However, coherent detection-based systems are very expensive to be implemented in access networks. Hence, due to IM/DD systems are less tolerant to noise and system imperfections [11], future RoF systems require the use of techniques to mitigate several effects without exceeding costs or computational complexity.

Effects that alter the signal's phase known as phase noise, are seen in a constellation diagram as asymmetric distortions, unlike white noise. Therefore, asymmetric demodulation methods have emerged in optical communication systems, so that they can reduce the Bit Error Rate (BER), adjusting to the geometric behavior of the distortions. In researches from Denmark [12] the authors proposed for the first time the demodulation of signals using Machine Learning (ML) with the k-means clustering algorithm on an 8PSK modulated RoF signal, being effective in a 40 km fiber optic link. Furthermore, algorithms such as: neural networks [13], k-Nearest Neighbors (KNN) [14] and k-means [12], have been proposed in the recent state of the art to minimize errors in purely optical systems. On the other hand, in colombian studies [15] a minimization of BER is exposed using ML techniques as a function of the Optical Signal to Noise Ratio (OSNR), where it is possible to see gains in both BER and OSNR, for example, at lower values of OSNR the same BER values can be achieved by using ML algorithms. Among the studies carried out in RoF communications in the MMW band, they have achieved gains of up to 1.8 dB for multilevel modulations at distances of up to 15 km of optical fiber [16].

Thus, in this work, we propose the adaptation of the well-known machine learning algorithm called Support Vector Machine (SVM) as an asymmetric digital demodulator to reduce the BER in RoF systems operating in spectral bands above 60 GHz. The system is simulated in the specialized software VPDesignSuite®.

The manuscript sections are organized as follows: in Section II the operation and trends of RoF systems are exposed, in Section III the proposal for asymmetric demodulation using SVM is presented. In Section IV the results and discussions are shown, finally, the conclusions are presented in Section V.

II. Architecture and Trends in Radio Over Fiber (RoF) systems

Classic RoF systems are characterized by transmitting information by two transmission media: free space and fiber optics. The signals transmitted through free space are RF signals, which are modulated in the optical regime and transmitted through the optical fiber. The purpose of transmitting RF signals through the optical fiber is to compensate the high losses of the wireless medium, since optical fiber is an excellent transmission medium, thanks immunity to electromagnetic interference and its attenuation is considerably low around 0.2 dB/km-0.5 dB/km [17]. With the aim of achieving more efficient RoF systems, it is intended that the distances to be transmitted by optical fiber are as extensive as possible without incurring in amplification stages as well as without increasing the launch power to avoid the stimulation of non-linearities derived from the Kerr effect of optical fiber itself [18]. However, chromatic dispersion describes a cyclical behavior resulting in power losses [19], [20] (Fig. 3).

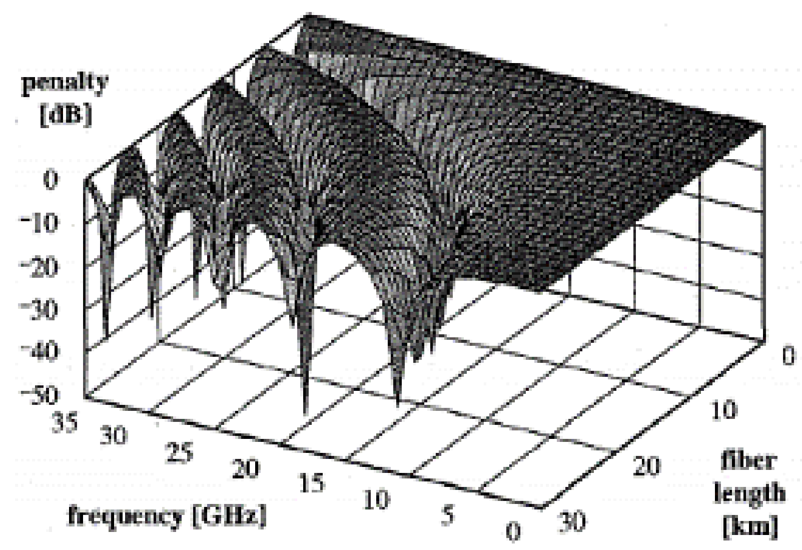


Fig. 3. Cyclical effects by chromatic dispersion.
Source: Taken from [20].

In RoF systems, modulation occurs in two stages, one electrical and one optical. In the first one, the RF electrical signal is modulated in traditional modulation formats: in amplitude, frequency or phase. In the second stage, once the RF signal has been modulated, it is delivered to the optical modulator, where it is responsible for modulating the optical intensity, in an On-Off format. At the receiver side, a photodetector is used to perform the optical to electrical conversion before being radiated. It is common to use optical amplifiers before the modulation and emission stage in the receiver (Base Station) [8]. Finally, the RF signal is emitted, and the wireless receiver captures the signal to proceed with the information recovery (Fig. 4).

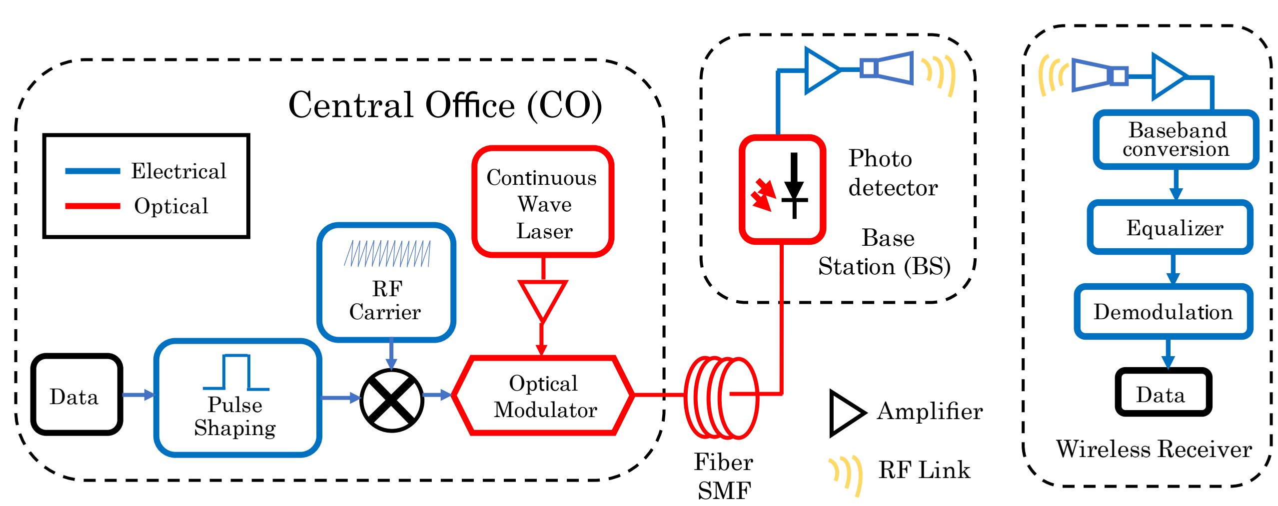


Fig. 4. Radio Over Fiber schematic.
Source: Authors.

Although the RoF systems are also an alternative to minimize some costs, there are still the expenses associated with the operating equipment and the licenses required for its operation, which could be expensive; this results in a barrier for an organization to be willing to offer broadcasting services [21]. An alternative to reduce further costs is the implementation of Software Defined Radio (SDR).

SDR equipment are devices in which most of the functions of a communications system are implemented through the use of programmable boards such as USRP (Universal Software Radio Peripheral). Its implementation in communications systems would considerably reduce the costs associated with the hardware [22]. Studies have shown the use of SDR to generate multiplexed signals, being SDR a good candidate in terms of BER for 5G networks [23]. Numerous designs of communication systems based on SDR implementing paid software or open source have been implemented [24]-[27], presenting results that make SDR attractive in conjunction with the next generation, in which networks are intended to be robust in terms of bandwidth and latency [28].

The requirements for next-generation networks, in terms of bandwidth and delays, are not the only characteristics that must be taken into account, the issues in network deployment should also be considered. Rural and remote areas are another factor that impede the connectivity of certain places [29], RoF systems based on SDR are an alternative of minimal complexity and cost-effective design to give access to areas where the optical fiber deployment is impractical or poor. In Colombia [23], Malaysia [27] and Denmark [30] the authors agree that the future of 5G networks comes from the combination of RoF systems with SDR due to its easy implementation and acceptable performance, achieving latency close to 1 ms and BER lower than .

II. Asymmetric demodulation in RoF systems using Support Vector Machine

Contrary to traditional demodulation that establishes fixed decision thresholds, asymmetric demodulation applies nonsymmetric adaptive thresholds by using ML algorithms [31]. This is most easily applied and understood by analyzing constellation diagrams. Fig. 5 shows three diagrams of a QPSK constellation, resulting from three types of noise, respectively: Additive Gaussian White Noise (AWGN), changes in phase, and non-linear phase noise (predominant in optical fiber transmissions [15]). Note that in the three cases, fixed decision thresholds for demodulation are established, which for the first two cases are functional, however, as the linear and non-linear phase noise increase, the symbols tend to become more distorted. Furthermore, they rotate angularly, moving away from the quadrants established by the fixed thresholds and causing a considerable increase in BER.

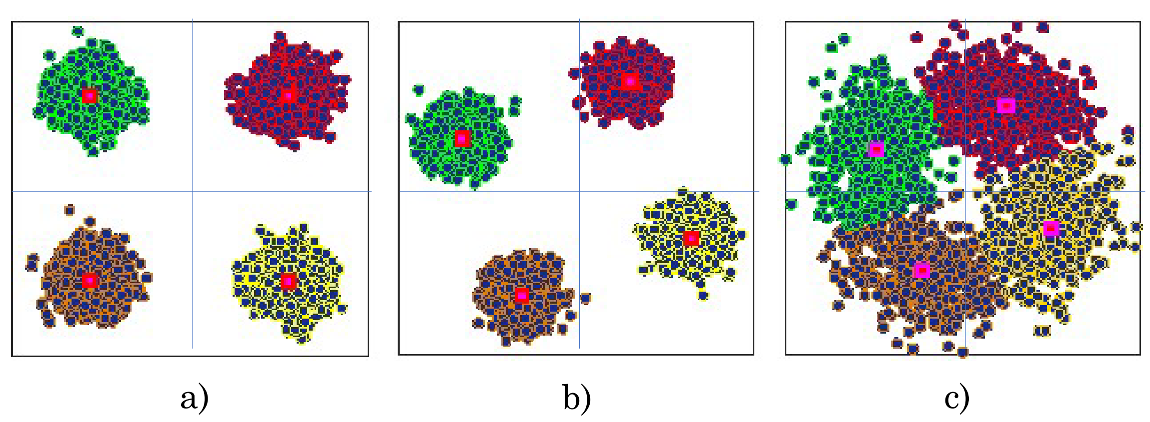


Fig. 5. Constellation diagrams affected by noise a) AWGN b) Phase Noise and c) Non-linear Noise.
Source: Taken from [15].

SVM is a ML algorithm widely used in different fields for data classification and regression. SVM classifies the data using a hyperplane that separates the training data. These training data, in the demodulation case, are the received symbols that suffered distortions by transmission effects and arrived in undesired positions. Likewise, hyperplanes are built making use of support vectors which are certain training data that are usually found in the limits of one class and another (Fig. 6) [32]. In our proposal, the algorithm operates using 2,250 symbols (5%) of a received frame for training and the rest for demodulation.

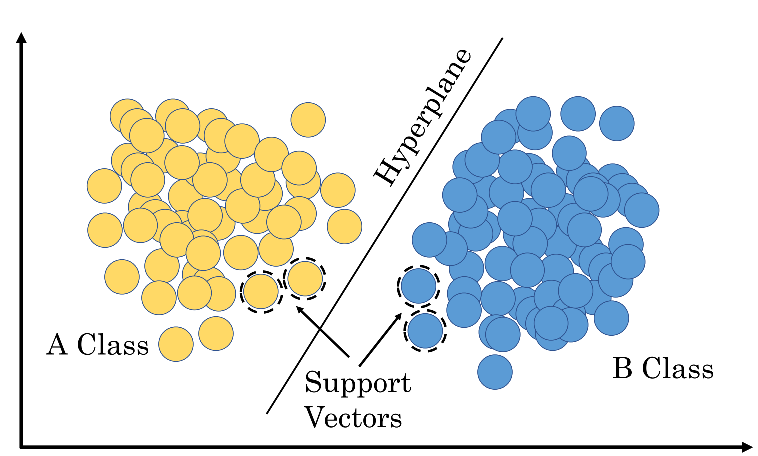


Fig. 6. Data classification using SVM.
Source: Authors.

In certain cases, when the data is not separable, it is mapped by means of mathematical functions known as kernels, which seeks to find a non-linear separation between classes. The kernel functions move the data to a dimensional space larger than the original (Fig. 7), looking for a separation of the data in this larger space [33].

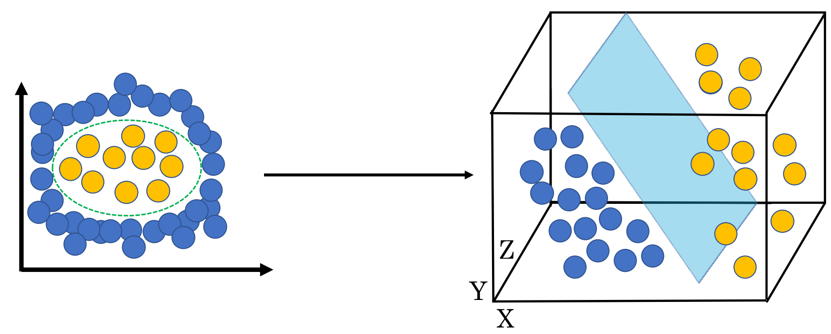


Fig. 7. Kernel function in SVM classification.
Source: Authors.

For demodulation, the classes to be separated would be 16 or 64 (according to the modulation format) and the thresholds of each class are calculated by doing “one vs the rest” (Fig. 8) for each modulation format.

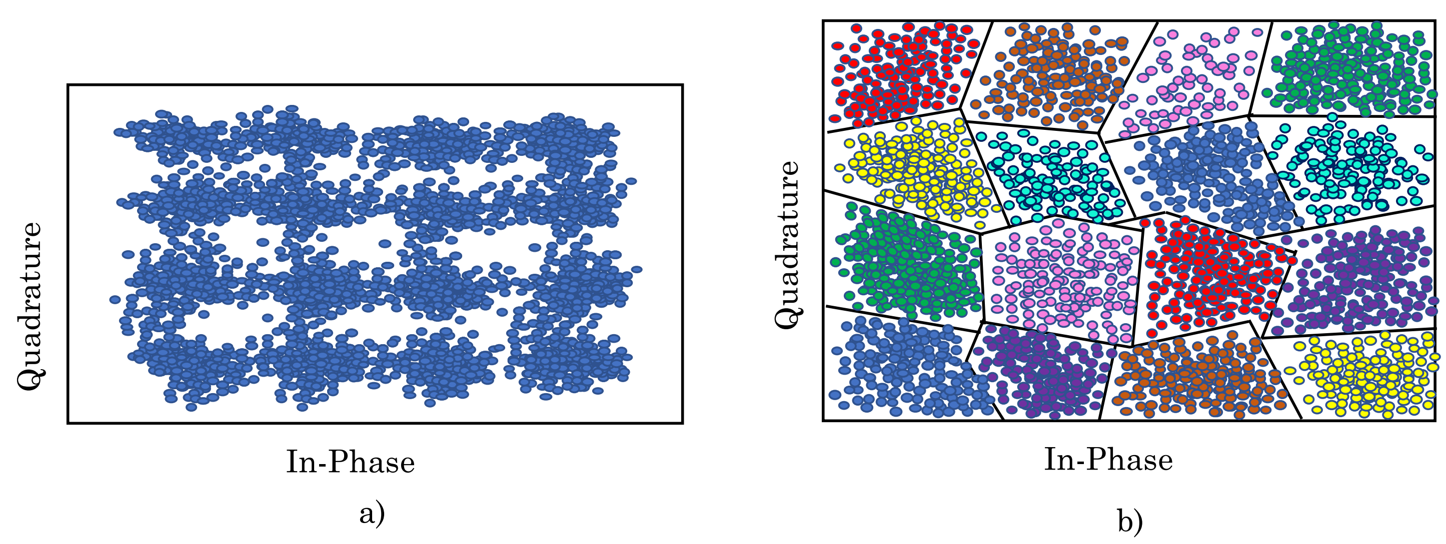


Fig. 8. Constellation diagram 16-QAM a) before and b) after SVM classification.
Source: Authors.

Hence, the SVM establishes asymmetric borders for symbol classification. In this sense, the SVM-based demodulation can reduce errors being agnostic to the type of distortion that affected the transmitted symbols.

III. Simulation scenario

A RoF system was simulated in the specialized software VPIphotonicsDesignSuite, where RF frequencies were generated in the MMW band at 60, 75 and 82 GHz, for 16-QAM and 64-QAM modulation formats. In the receiver, asymmetric demodulation based on the SVM algorithm was applied in co-simulation with Matlab®. Fig. 9 shows the simulated RoF scheme, where a sequence of ~45 thousand symbols were transmitted for each modulation format. The bit sequence is represented by raised cosine pulses which were modulated in the traditional electrical m-QAM format, then the electrical signal was amplitude modulated in the optical regime, using a Mach-Zehnder modulator (MZM) with ideal parameters. The MZM modulates a continuous wave laser centered at 1550 nm. The laser Linewidth (LW) and the transmission rate were varied from 1 KHz to 100 MHz and from 1 to 10 Gbps, respectively. Once the signal was optically modulated, it is transmitted through 30 km of standard single-mode optical fiber (distance greater than the 20 km of the GPON standard), with commercial parameters (dispersion of 16 ps/nm-km and attenuation of 0.2 dB/km).

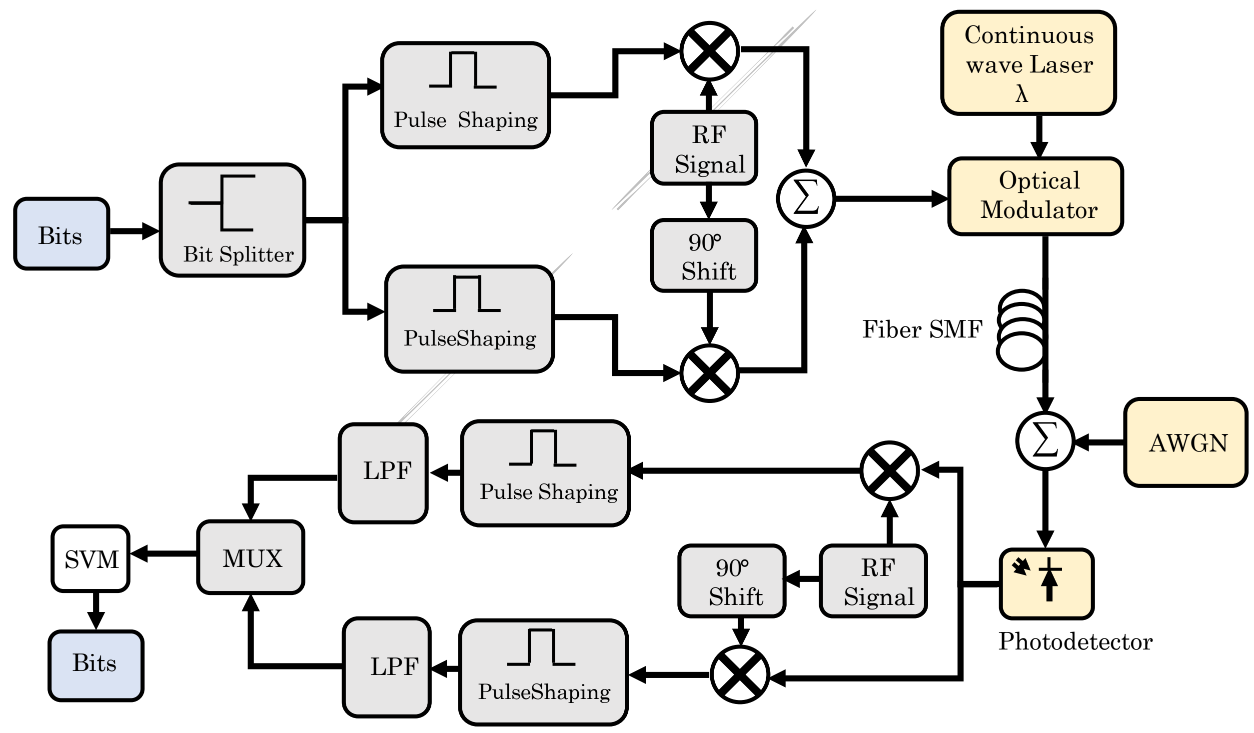


Fig. 9. RoF system based on m-QAM modulation.
Source: Authors.

Then, the conversion from the optical to the electrical domain is performed by a PIN photodetector. Asymmetric demodulation using SVM is carried out after applying equalization based on the Least Mean Square (LMS) algorithm. Finally, the BER is estimated.

IV. Results and discussions

Fig. 10 shows a demodulation analysis for 16-QAM after LMS equalization, with SVM and using traditional demodulation. In traditional demodulation (Fig. 10a) without equalizing, the received symbol is classified according to its position in the fixed grid. On the other hand, the use of equalization (Fig 10b) allows a mitigation of channel effects. Besides, in Fig. 10c it is plotted the constellation diagram with symbol classification using SVM. We can identify difference among the three cases, when detailing in the overlapped regions.

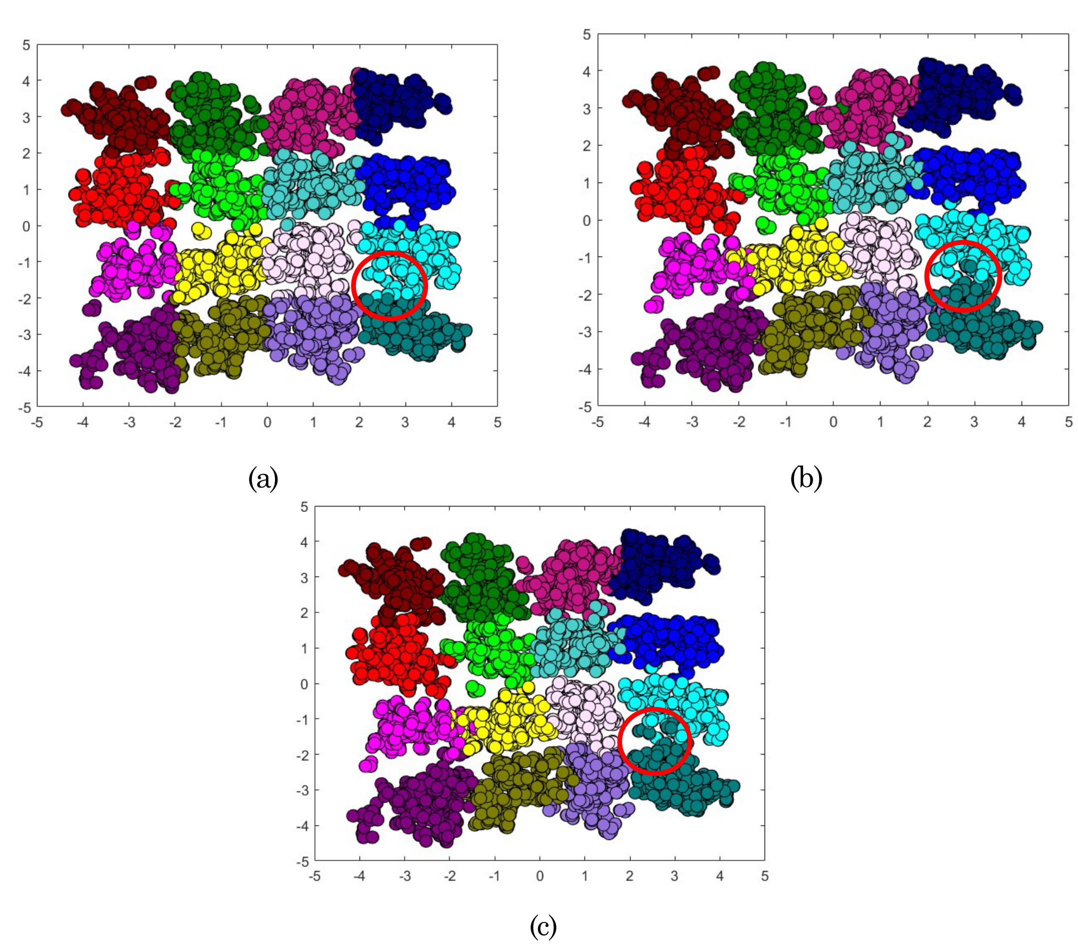
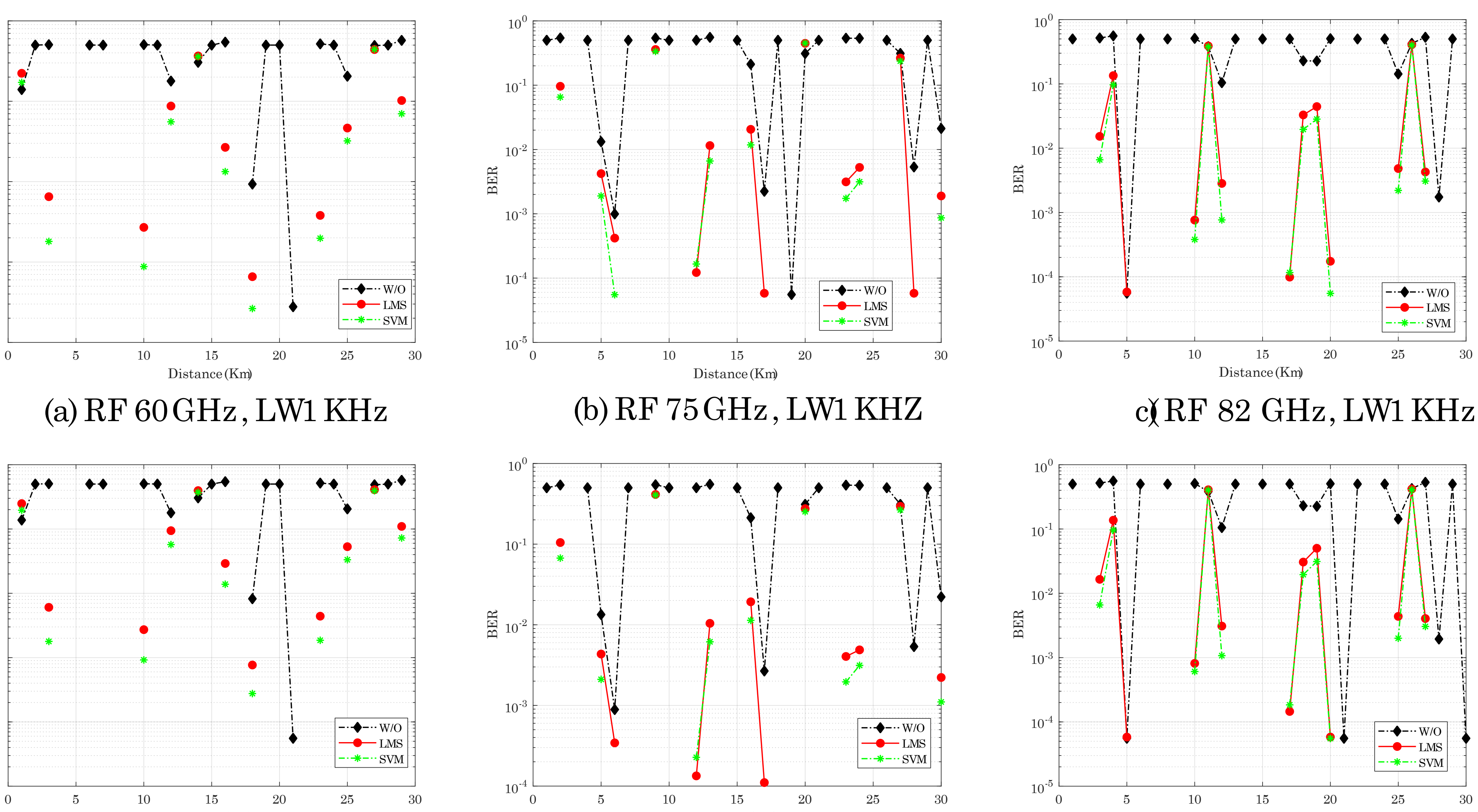


Fig. 10. 16-QAM constellation diagram of received symbols classified by different demodulation techniques: a) conventional b) after LMS c) after SVM.
Source: Authors.

In Fig. 11 it is shown how the BER varies as the length of the optical fiber increases in the RoF system transmitting at 1 Gbps in 60 GHz (Fig. 11a; Fig. 11d), 75 GHz (Fig. 11b, Fig. 11e), and 82 GHz (Fig. 11c; Fig. 11f) for 16-QAM. A BER comparison is made: when demodulating in a traditional way, applying LMS equalization and when demodulating using SVM. A simile is also presented in the transmission carried out by a laser with a LW of 1 KHz, which has better characteristics than a commercial laser seeking to avoid phase noise in the characterization of the system. In this scenario, almost the same results can be obtained using LMS equalization and asymmetric demodulation. In Fig. 11f it is observed that for a transmission distance of 30 km using an 82 GHz RF carrier, with traditional demodulation, a BER of 1×10^{-4}) is achieved, whilst both, LMS equalizer and SVM achieve error-free transmission. It can also be noticed that using equalization or SVM, the BER is improved for all distances, this demonstrates that the chromatic dispersion is mitigated. Similarly, the same analyzes were carried out for a 64-QAM format, Fig. 12 shows a pattern similar to the 16-QAM format, since in both cases the demodulation using the SVM algorithm generally presents the best results in terms of BER when compared to traditional demodulation. However, for the latter format, demodulation with SVM is slightly worse compared to demodulation using LMS, with a value of for SVM and for LMS. It is also evidenced that for the 64-QAM format, using equalization or asymmetric demodulation, it can be guaranteed that the communication is error-free at certain distances independent of the RF carrier. On the other hand, it should be considered that by using 64-QAM format we can transmit more information, but the signal is more sensitive to distortions.



(a) RF 60 GHz, LW1 KHz

(b) RF 75 GHz, LW1 KHZ

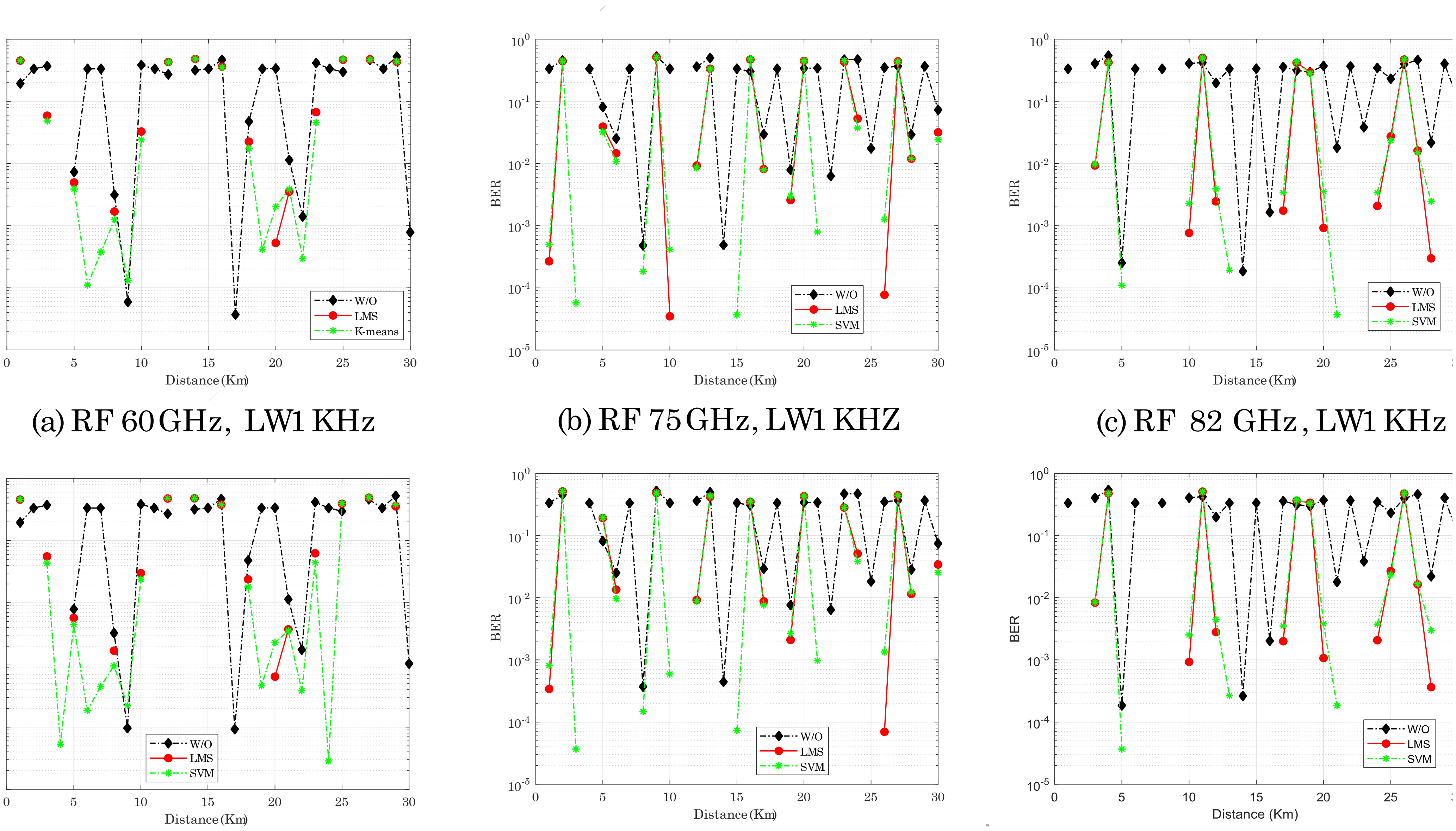
c) RF 82 GHz, LW1 KHz

(d) RF 60 GHz, LW1 MHz

(e) RF 75 GHz, LW1 MHZ

(f) RF 82 GHz, LW1 MHz

Fig. 11. BER vs Transmission Distance for different demodulation techniques using 16-QAM.
Source: Authors.



(a) RF 60 GHz, LW1 KHz (b) RF 75 GHz, LW1 KHZ (c) RF 82 GHz, LW1 KHz

(d) RF 60 GHz, LW1 MHz (e) RF 75 GHz, LW1 MHZ (f) RF 82 GHz, LW1 MHz

Fig. 12. BER vs Transmission Distance for different demodulation techniques using 64-QAM.
Source: Authors.

Table 1 summarizes minimum BER values achieved for the different configurations. It can be noticed that for the case of 1 MHz LW, 30 km of transmission distance, using 64-QAM, information can be recovered error-free if the LMS equalizer or SVM-based demodulation is used with a 60 GHz or 82 GHz RF carrier.

Table 1. BER for transmission over 30 km with different modulation formats and a LW of 1 MHZ.

Format	60 GHz	75 GHz	82 GHz
16-QAM without equalizing	0	2.216*	5.556*
64-QAM without equalizing	1.052*	2.221*	1.011*
16-QAM with LMS	0	1.104*	0
64-QAM with LMS	0	7.433*	0
16-QAM with SVM	0	3.412*	0
64-QAM with SVM	0	2.535*	0

Source: Authors.

V. Conclusions

A RoF system was simulated applying asymmetric demodulation based on the SVM algorithm. The results showed mitigation of channel effects when using the ML algorithm, which allowed longer transmission distances than conventional demodulation. The proposed asymmetric demodulation technique presented better performance than traditional demodulation, regardless the carrier frequency or the laser linewidth. For 16-QAM, reductions in BER of up to 2 orders of magnitude were achieved. Besides, with 64-QAM, operating in the MMW band, error-free transmission was obtained in 30 km of transmission distance (RF carrier of 82 GHz).

Moreover, using the proposed demodulation technique in systems with laser linewidth around 1 MHz, the BER showed very similar results as the one whose laser linewidth was 1 kHz, this indicates that the use of asymmetric demodulation can reduce equipment costs. Finally, the mitigation of distortions carried out by the SVM algorithm is transparent to the channel or system impairment, it means that this technique can be implemented in any m-QAM optical communication system, therefore, we can point out that the use of this asymmetric demodulation in optical communication would be useful for incoming RoF implementations.

Acknowledgment

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