Simulation of Free-Space Communication using the Orbital Angular Momentum of Radio Waves

Áron Demeter, Csaba-Zoltán Kertész
Department of Electronics and Comuters, Transilvania University, Brașov, Romania
arond89@yahoo.com, csaba.kertesz@etc.unitbv.ro

***Abstract*—The Orbital Angular Momentum (OAM) property of radio waves can be efficiently used to combine multiple free-space radio-communication channels into a single carrier frequency. This paper presents a study of such a multichannel system using Simulink model of radio-waves with different OAM value combined together. The study focuses on proving that OAM channels remain orthogonal at radio frequencies, and the OAM modulation of FSK, PSK and QAM modulated signals results in bit-error rates close to standard communication channel behavior in noisy environment.**

I. Introduction

In 1902 Poynting discovered, that the circularly polarized light carries Spin Angular Momentum (SAM), which is associated with photon helicity and depends on the polarization, therefore it can be present in left- or right-handed circularly polarized light. The SAM value for one photon is $S = \pm\hbar$, where $\hbar$ is the Planck constant. The other part of angular momentum was identified by C. Darwin in 1932 as the product of linear momentum of photon and radial distance, which is independent of spin [1]. So the total angular momentum A is given by the sum:

$$A = S + J \quad (1)$$

where J represents the Orbital Angular Momentum (OAM) of the photon, which is associated with the orbital phase profile of the beam, measured in the direction orthogonal to the propagation axis [2]. In 1992, Allen et al. discovered that using cylindrical lenses to generate Laguerre-Gaussian (LG) modes from Hermite-Gaussian (HG) modes, a helically phased light beam can be obtained which has got the OAM property. The OAM value for one photon is defined in (2), where l is an integer number.

$$J = \pm l\hbar \quad (2)$$

In a plane perpendicular to the propagation axis, the phase of the electric and magnetic vector fields have an $l \cdot \phi$ dependence (ϕ - angular coordinate), which means that for $l \neq 0$ the phase fronts of beams are not planar but helical [3]. For a given l value, the beam will contain l intertwined helical phase fronts. A forked diffraction grating can also produce helical beams with optical vortex. Allen et al. showed that a ψ_l beam with transversal complex radial amplitude $A(r)$ depending on the radial (r) and angular (ϕ) coordinates, presented in (3), will contain $l\hbar$ OAM state for each photon. [4].

$$\psi_l = A(r) \cdot e^{-il\phi} \quad (3)$$

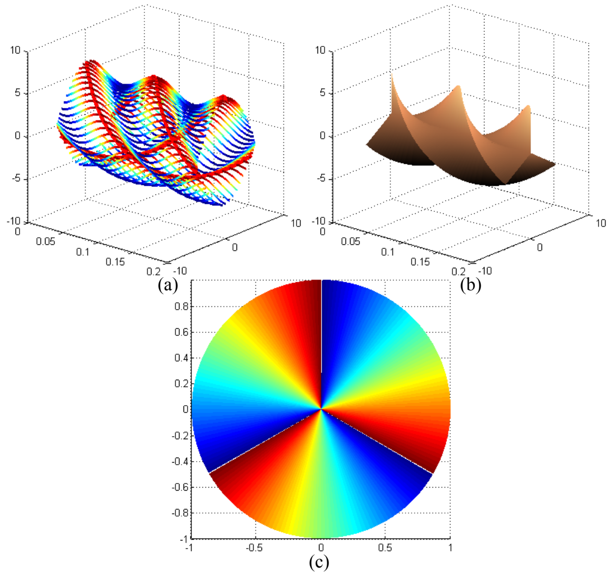

Fig. 1. OAM=3 state. (a) wave structure of 40 waves, where the colors from blue to red are indicating the increasing amplitude and the continuous red line interconnects the same phase points of all waves - in this case at the signal maximum, (b) helical phase structure, (c) phase front, where the colors from red to blue correspond to the phase between 0 and 2π.

Based on (3), the algorithm for generating twisted waves can be implemented, resulting the waveforms on Fig.1. Because the LASER beams are composed of a narrow band of wavelength (monochromatic) and they are collimated, the light energy is restricted in the direction transverse to the propagation direction to form a narrow beam, which is ideal for OAM eigenstates [5].

The first known successful experiment in communications, with OAM-carrying waves, was done in 2004 by Gibson et al., the information encoded in OAM states was transmitted in air over 15m using computer generated holograms on Spatial Light Modulators (SLM) [6]. In 2012, a 2.56 Tbit/s data transfer rate was successfully made over 1m using OAM Multiplexing (OAMM). The spectral efficiency can be increased combining OAMM with polarization multiplexing [7].

In radio domain only a few experiments has been made, but without much success. In 2011, Bo Thidé and his team demonstrated that it is possible to simultaneously transmit more radio channels on the same frequency band over 442m, by encoding them in different OAM states [2]. However, there were lots of reports of disagreement about this experiment declaring, that it was just an implementation of the Multiple In Multiple Out (MIMO) technology. In the above experiment, a modified dish has been used to transmit the helical waves, and a two-antenna interferometer to receive them. In most of the articles, the circular antenna arrays are considered as the best solution for generating OAM-carrying radio beams [8], which can lead to the same results as in optics [9].

To evaluate the performance of the circular antenna arrays we created a Simulink model. It simulates the propagation of the helical waves using different types of modulations.

II. The Simulation Model

Because the system is very sensible to the phase changes, we assume, that the transmitter and receiver antenna arrays are perfectly facing each other in the line-of-sight, like a fixed wireless system. At lower frequencies and lower OAM states greater mismatch is allowed. For signal modulation and demodulation, existing Simulink digital baseband blocks has been used, containing the complete implementation of the selected modulation, including the coherent or non-coherent energy detection at the receiver part. Therefore, the main parts of the model are the Helix Modulator and the Helix Demodulator blocks, presented in Fig.2. They contain a Matlab function block which implements the wave-twisting and -untwisting algorithms. The buffers are storing N samples from the incoming complex signal incorporating at least one full period. The clocks are required to control the output frame indexes per simulation step. They are assumed to be perfectly synchronized, considering that the phase shifting can be done passively or using phased-array controllers, which are not part of the simulation.

The Helix Modulator's Matlab function clones the incoming signal to the number of waves and shift each of them with $l \cdot \phi$, where l is the OAM value and ϕ is the phase, uniformly distributed between the antennas. In other words, the transmitter is a serial to parallel converter and a phase shifter at the same time. Every shifted signal feeds one antenna from the array. While the optical beams contains a lots of waves, in radio domain the number of antennas is limited. To ensure a similar

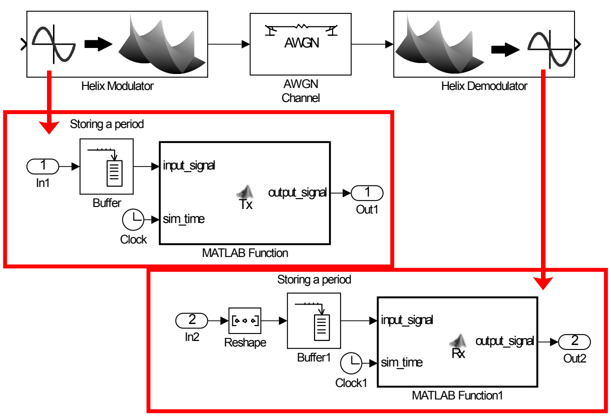

Fig. 2. The *Helix Modulator* and the *Helix Demodulator* connected to the communication channel

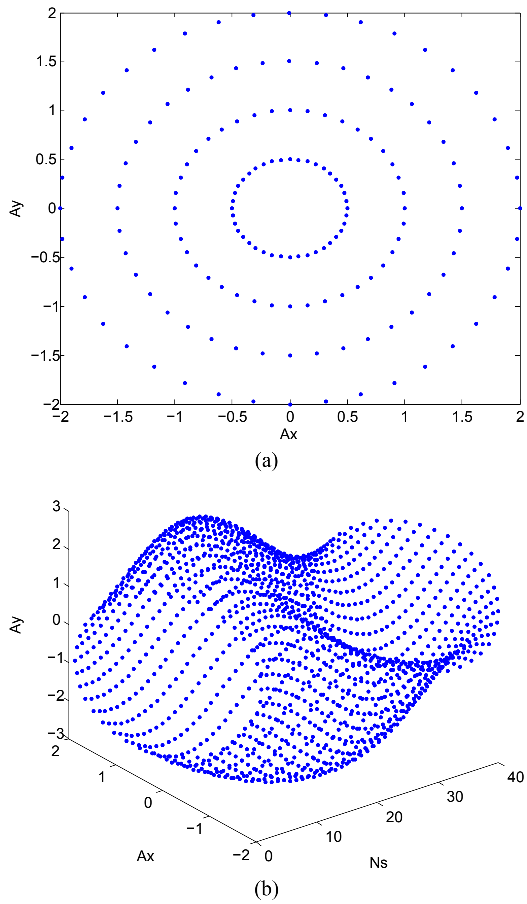

Fig. 3. Helix modulator output frame (a) in the case of 4 circles and 40 antennas. (b) is the 3D representation of the same wave for one period and one antenna circle (Ns is the samples used in one wave period).

phase profile to the LG beams, at least $2 \cdot l + 1$ antennas are required [9]. The Helix Demodulator's Matlab function shifts the incoming waves to the same phase and makes the sum of them, acting like a parallel to serial converter and phase shifter at the same time. In every simulation step, the transmitter outputs a frame which contains $antennanumber \times circlenumber$ samples. For example if there are four concentric circles, each of them with 40 waves (antennas), the outgoing frame will look like the one on Fig.3. These frames are connected to an AWGN channel simulating noisy environment. Also a multipath propagation channel was tested using Rician fading blocks to simulate reflected signals. Because the OAM works only in line-of-sight transmission and reflected signals also change OAM states, multi-path effects were studied more in terms of interference to the generic OAM transmission channel. The optical beam width scales with $\sqrt{l}$ which means, that the receiver aperture will have a physical limitation on higher OAM values [6]. In a similar manner the antenna array dimensions (circle radius) in radio domain will also result in the same OAM limitation [9].

There are several methods for detecting the OAM states of radio waves [3], which are not part of our aim, so the simulation uses well defined states in the Helix Modulator

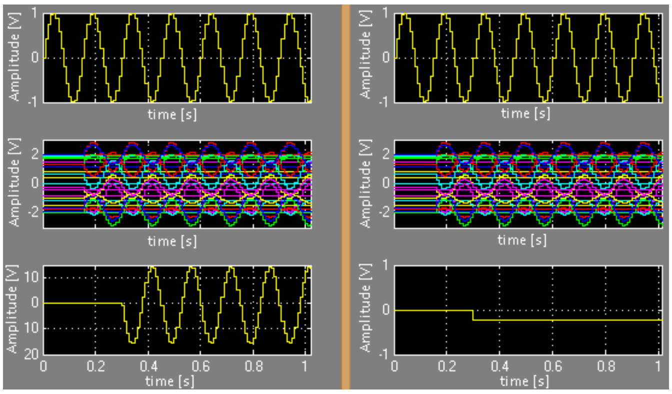

Fig. 4. Results of the twisted (center) and untwisted (bottom) waves of an incoming sine wave (top) in case of matched OAM state (a) and unmatched OAM state (b)

and Demodulator blocks. When the OAM states are set to the same value at the transmitter and the receiver, the sum will give a strong signal, but when they are set different, the result will be unrecognizable, or close to zero. Even if the OAM states are set to adjacent, the result will be wrong, so it is easy to distinguish them. Fig.4 shows what happens with a simple sinusoidal carrier wave if the OAM states are matched or non-matched. This proves that our simulation model is consistent with the theoretical orthogonality of the OAM states.

III. The Simulation

A. FSK modulation

The Bit-Error Rate (BER) curves of the baseband modulation are very close to the theoretical non-coherent BER curve. Fig.5 shows the scheme of the simulation model and the BER of the 2-FSK signal for $l = 3$, $l = 6$ and $l = 9$. The simulations were made with the minimum number of waves for every OAM state.

For the antenna array, the 2-FSK passband modulation uses the same configuration as the baseband model, but the baseband signal is upconverted to 1GHz carrier frequency. The BER curves and the simulation model are shown on Fig.6 in a similar manner to the baseband simulation.

In the OAM-based communication the focus is on the orthogonality of the OAM-states which makes possible to transmit more information on the same carrier frequency. The simulation model on Fig.7 is demonstrating, that different communication channels can be used on the same frequency band without any interference. This model is using a single Helix Demodulator whose OAM parameter is the one of the parameters set in the Helix Modulators. In this case, the demodulator in the figure was set to decode the OAM = 5 modulated channel. Every channel is containing different information generated by the Bernoully Binary blocks with different probability of zero. The system is using the minimum

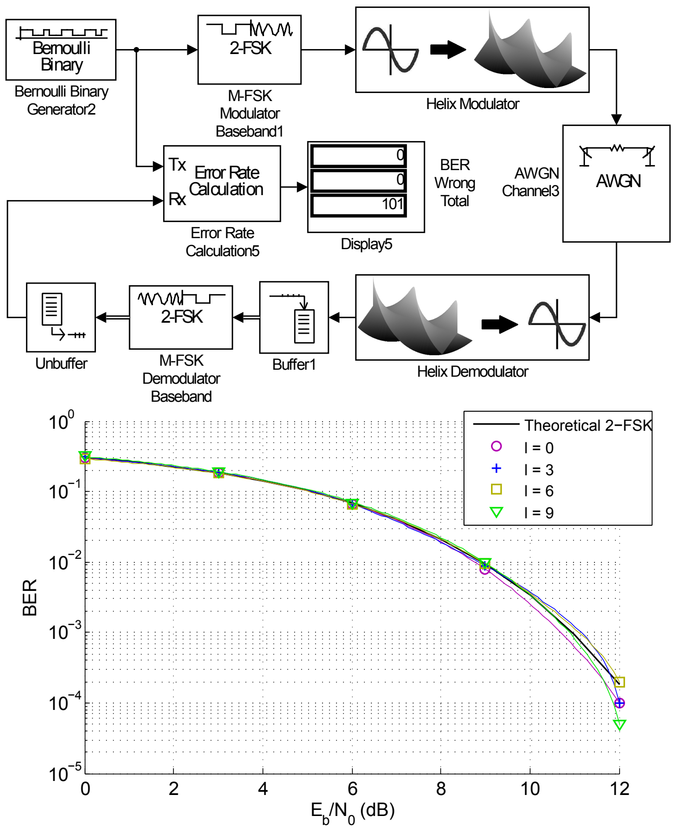

Fig. 5. Baseband FSK simulation model and the BER diagram of the baseband 2-FSK signals

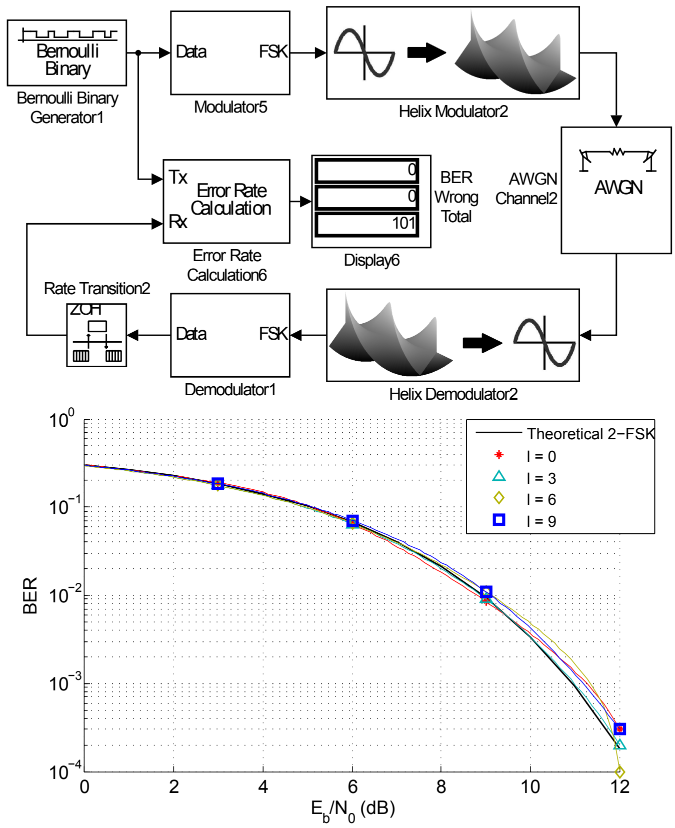

Fig. 6. Passband FSK simulation model and the BER diagram of the passband 2-FSK signals

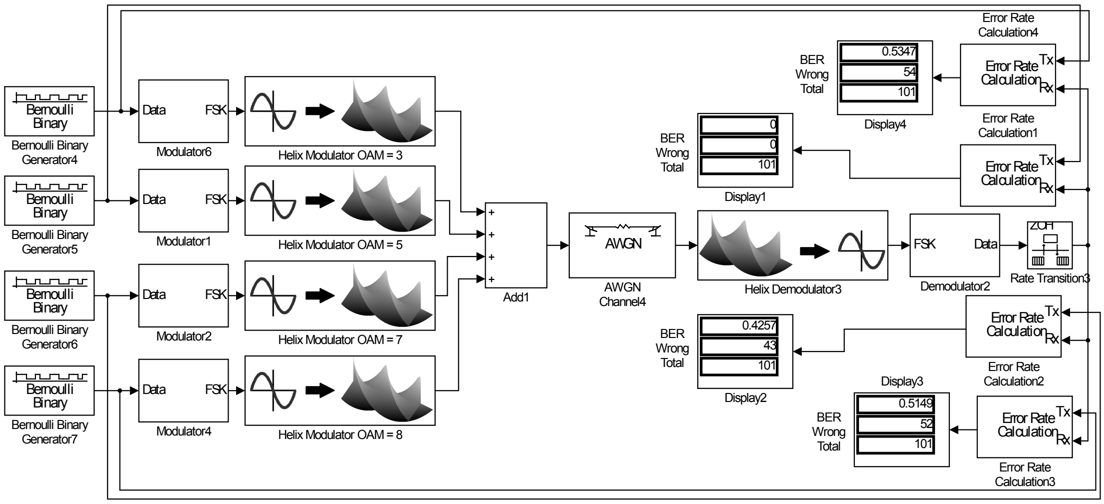

Fig. 7. Passband FSK simulation model for a 4 combined communication channels with single channel demodulation

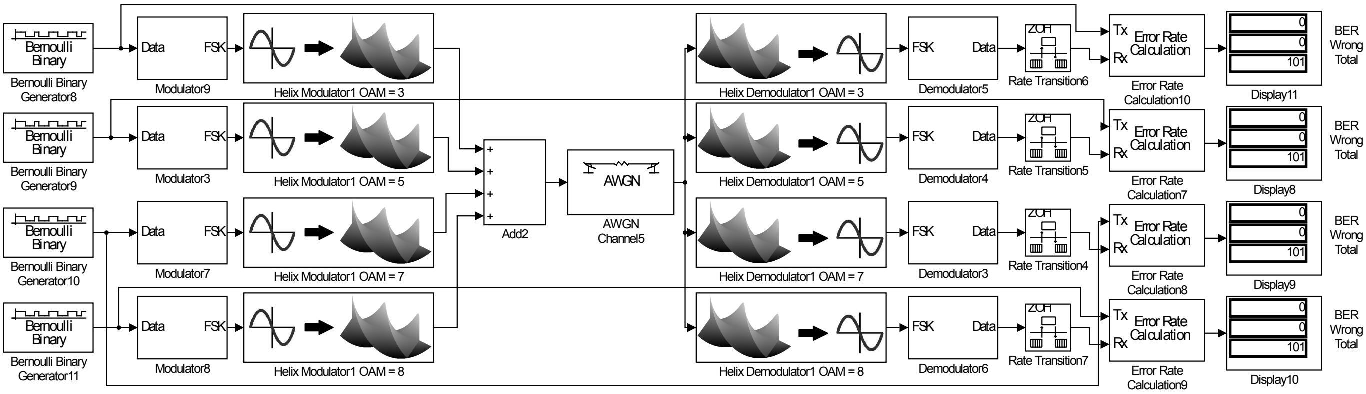

Fig. 8. Passband FSK simulation model for a 4-channel simultaneous communication

number of antennas for the maximum OAM state, in this case 19 antennas. The BER calculator shows zero for the selected channel, but the other channels BER values are high. With 19 antennas the system is capable to distinguish 9 channels; therefore every introduced antenna is increasing the total capacity. Another simulation model is shown on Fig.8, where are four Helix Demodulators, one for each channel. Every antenna array is receiving all of the vortex channels, but each decodes only one of them. In this case, the BER results are zero in every calculator block.

The OAM state orthogonality was also tested on single channel transmission with multi-path effect simulated with Rician fading blocks. These enable simulating various reflection path between the transmitter and the receiver. The ratio between the power in the line-of-sight component and the power in the diffuse component was set to $k = 6$, and also considering some moving objects near the system, the maximum diffuse Doppler shift was set to 40Hz. Theoretically signals reflected loose their OAM state, so only the line-of-sight channel will be picked up by the receiver, however in practice the reflected signals also present a large incoming interference which increases BER levels. This increase is on the other hand less than the effect of multi-path on the plain FSK signals. The model and result of multi-path analysis is presented on Fig.11.

B. *PSK modulation*

The PSK passband simulation model and the BER diagram for the passband simulation is shown in Fig.9.

It can be seen, that the results are close to the FSK modulation's curves, but compared to the theoretical 2-PSK curve, they are worse at higher E_b/N_0 ratio. This shows the sensibility of the system to the phase shifting operation. It is expected that the imprecision introduced by the the floating point calculations within all the phase shifting operations to influence also the PSK demodulation. This also implies that on physical implementation a greater care is needed on the phase shifting lines leading to the antennas.

The figures are terminating at the E_b/N_0 point where no more errors are detected at 100 kbits. Because of the one period process at each Helix block, the Error Rate Calculation block is set to delay the detection by two bits. As the number of period processing increase, the delay also increase, but this does not affect the BER result.

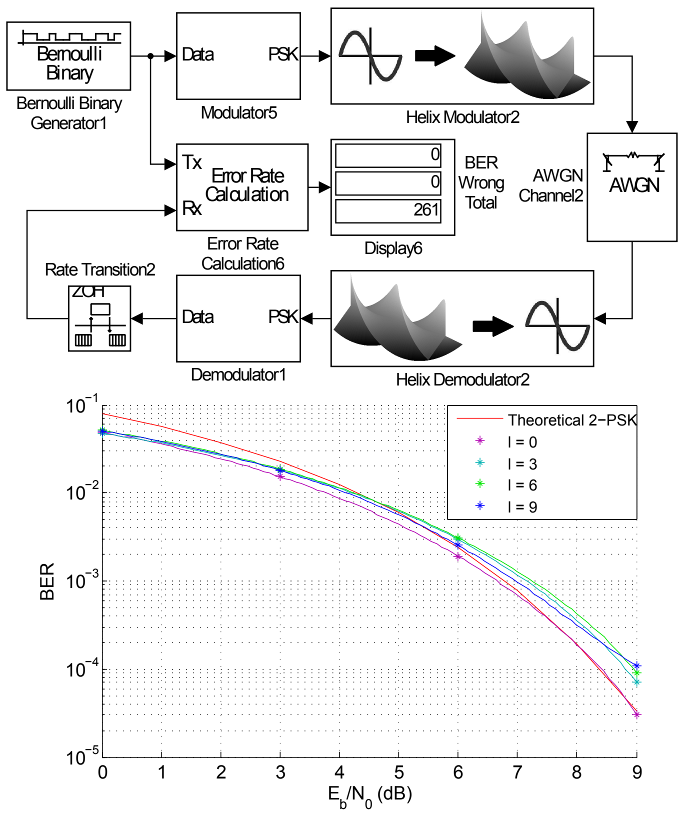

Fig. 9. Passband PSK simulation model and the BER diagram of the passband 2-PSK signals

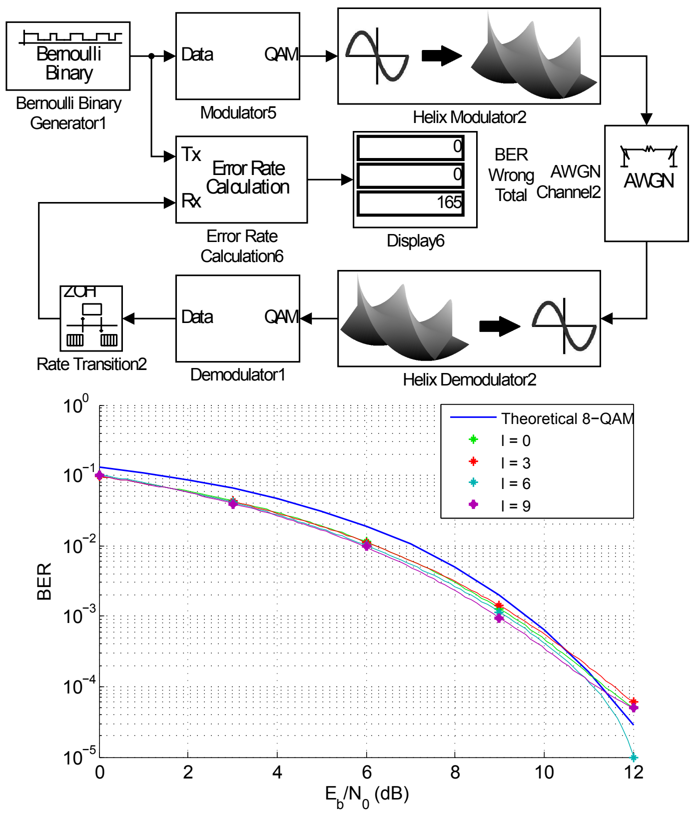

Fig. 10. Passband QAM simulation model and the BER diagram of the passband 8-QAM signals

The Rate Transition block is not necessary, but useful when the difference between the carrier frequency and bit rate is high. To get closer to the theoretical 2-PSK curve, the number of samples and the amplitude of the waves can be increased.

When simulating the multiple channels of OAM states combined with a similar model as presented for the FSK modulation, the results were nearly the same meaning that the OAM multiplexing has no further effect on the signals. Multi-path effect on PSK signals is also similar to the FSK case (Fig.12), but with BER values higher comparatively to theoretical values than were with FSK due to the sensibility to phase changing of the PSK modulation.

C. QAM modulation

In radio frequency free-space communications, the FSK and PSK modulations are not so frequently used as QAM modulation. A QAM modulated channel has much higher bit rate capability than the PSK modulated channel, and the error probability is much lower than at the FSK. The passband QAM simulation model together with the BER diagram of the passband model is shown in Fig.10.

As at the other simulations, the simplest constellation, 8-QAM was used. If the number of waves (antennas) increase, then the amplitude of the waves in the Helix Demodulator and the QAM Demodulator will also increase. The simulation needs the processing quantity to be one period of carrier frequency in order to change the phase correctly even if phase+amplitude modulation is used. To get closer to the theoretical 8-QAM curve, also the amplitude and the number of samples can be increased.

IV. Conclusions

The simulation presented in this paper prove that OAM-based radio channels remain orthogonal with acceptable BER on well-known modulation types. The OAM multiplexing of radio waves does not bring anything basically new, as long as it can be implemented with the traditional beam forming techniques using MIMO antenna matrixes or phased arrays. The simulated BER curves shows that there are no big differences between the different OAM states, so theoretically an infinite number of channels can be used without any BER degradations. Compared to the modified parabolic dish, a circular antenna array can generate more than one OAM state without any mechanical modifications, given that at least $2 \cdot l_{max} + 1$ antennas are used.

The results shows that the OAMM is compatible with the digital multiplexing techniques even if they are phase-changing modulations. However the phase shifting circuits has to be implemented with high precision to avoid introducing error into the phase fronts needed by the latter. Also the phase-changing modulations are much more susceptible to multi-path effects, which need to be addressed in the design of the communication system. Compared to the optical domain, only one circle of waves is enough to generate the OAM states.

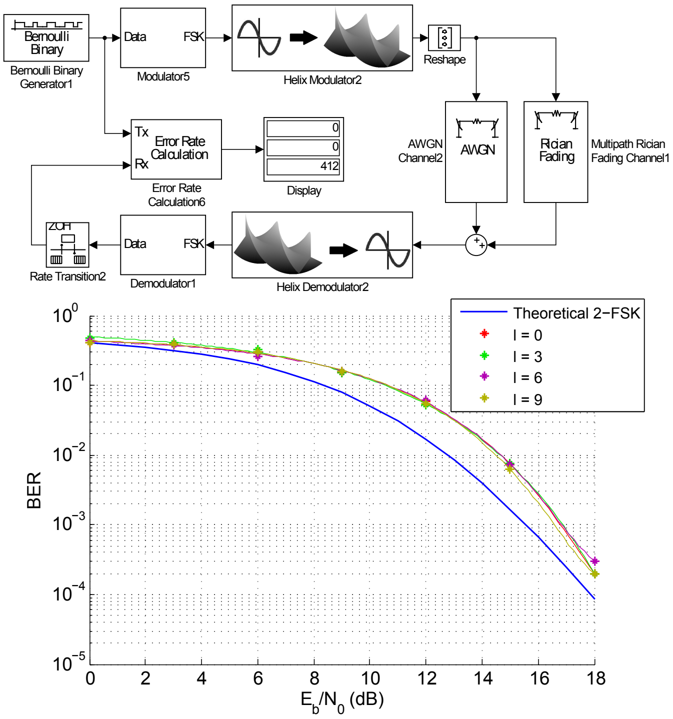

Fig. 11. Multi-path FSK simulation model and the BER diagram of the passband 2-FSK signals affected by multi-path effect

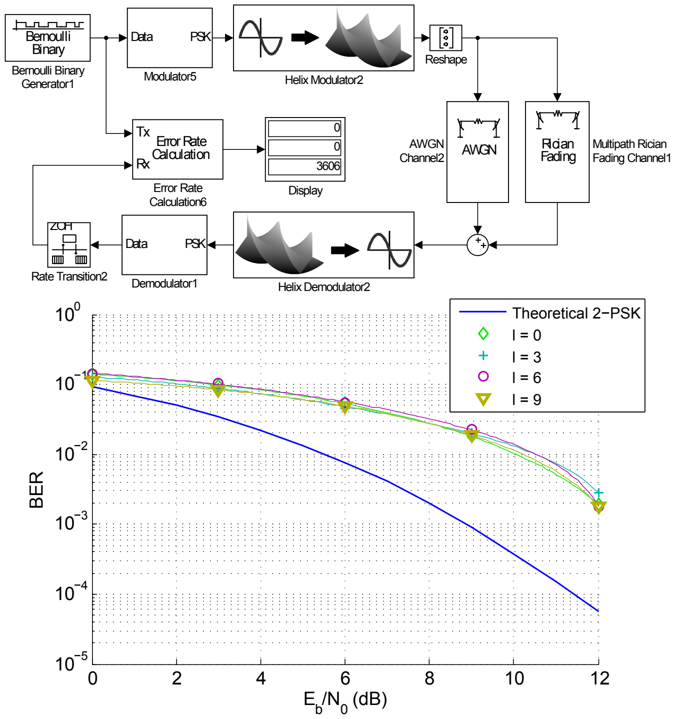

Fig. 12. Multi-path PSK simulation model and the BER diagram of the passband 2-PSK signals affected by multi-path effect

As with the optical domain, the line of sight it is also important in the radio domain, as the OAM of the reflected waves can be affected making impossible the correct decoding in the receiver. This can mean that the channel security is increased (eavesdropping out of the line-of-sight is impossible) on the other hand practical use is limited to fixed wireless communications. There is a possibility to use intelligent antennas for beam-forming purpose, however this needs further studies.

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