A Blind Adaptive Equalizer for SOQPSK : A Unique System to Combat Both Multi-path and Antenna Daisy Pattern

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***Abstract*—this article proposes a simple and pragmatic solution to combat the two-antenna problem and the channel multipath effect at the same time. This solution exploits the delay diversity and the capability of the blind and adaptive equalizer that we developed to correct it. We already proposed this system for the PCM/FM modulation but, since the SOQPSK modulation has become the reference modulation for telemetry, we developed a blind equalizer designed for the particularities of the SOQPSK modulation. Finally with the help of some lab experiments, we prove that the solution we propose is relevant and performing well.**

Keywords—Equalization; SOQPSK; Antenna Daisy Pattern

I. INTRODUCTION

During the flight of a test article, the availability of the telemetry link should be maintained as far as possible. A LOS (Line-Of-Sight) signal transmission between both transmitting and receiving antennas is thus needed to guarantee an optimal signal reception. In case of complex aircraft maneuvers, the telemetry signal is generally sent over two (or more) different antennas in order to constantly keep a direct signal path. This signal is sent over the same central frequency for an optimal spectral occupancy. However, a “two-antenna problem” arises: if the receiving antenna points at the aircraft with given angles, the telemetry signal can be lost because both signals may have opposite phases.

At the same time, during a flight test, an aircraft finds itself in different configurations: it is first motionless on its parking position, then slowly moves on to its take-off position (taxiing), then takes off, starts an ascent phase and finally goes to high speed cruise. An efficient telemetry system is able to guarantee an available data link for each maneuver. However, these different phases correspond to very different channel paradigms, with unequal margins for the budget link, several Doppler ranges and various types of multipath, with different spreading of delay and Doppler. The reader may refer to [1-2] for further details. In many cases, the transmitted signal is heavily distorted leading to a significant degradation of the telemetry quality.

Several strategies may be adopted to mitigate these effects. One can use a natively robust waveform, or tune the coding schemes of each antenna. But what is left if we do not want to modify the onboard configuration with a single transmitter and a constant envelope waveform? Improvement of the reception algorithm by introducing equalization is the answer.

Zodiac Data Systems has formerly developed a blind and adaptive equalizer for the PCM/FM modulation, with pretty interesting performance to be found in [1] and [3] in case of multipath. We also showed in [4] that delay diversity is a smart solution to solve the 2-antenna issue. The effect of one time symbol or more delay added to one antenna is to artificially create an echo that cancels coherent interference. Therefore, an equalizer is perfectly suited to correct the multipath effects, the two-antenna problem and any combination of both disturbances as they simply look the same.

The increasing need of high data rates in telemetry has shed light on the consideration that the PCM/FM modulation has too low of a spectral efficiency regarding the bandwidth allocated to test ranges. The SOQPSK modulation, presented in the IRIG106 recommendation [5], is the preferred solution for modern telemetry. This is why we also developed a blind and adaptive equalizer for the SOQPSK modulation. This paper aims at proving by laboratory tests that our equalizer is a simple and pragmatic solution to combat the two-antenna problem. As for PCM/FM, the basic idea is to introduce a small delay between both emitted signals in order to guarantee a non-destructive signal recombination. By doing this, the receiving antenna sees the transmitted signal as if it passes through a transmission channel with two paths. We then exploit the capability of the blind and adaptive equalizer to correctly equalize this signal and to recover the initial data.

This paper shows the lab experiments we made to demonstrate the feasibility of this solution. It also gives some clues to properly tune the delay between both antennas and, if necessary, the attenuation of the second path. We finally measured the system performance in the presence of a multipath environment.

II. Two-Antennas Problem

A. Problem statement

As previously explained in the introduction, the two-antenna problem is the consequence of the fact that telemetry signals have to be sent over two different antennas in order to avoid the telemetry loss. So, the transmitted signals arrive at the ground station with different phases due to the difference of time propagation delay. This phase difference also depends on the value of the carrier frequency. In some configurations, this phase difference has no great impact on the received signal. But, for certain angles of observation between the ground antenna and the aircraft, it may happen that the transmitted signals have an opposite phase: the received signal might be then cancelled or nearly cancelled. This phenomenon is illustrated on Fig. 1.

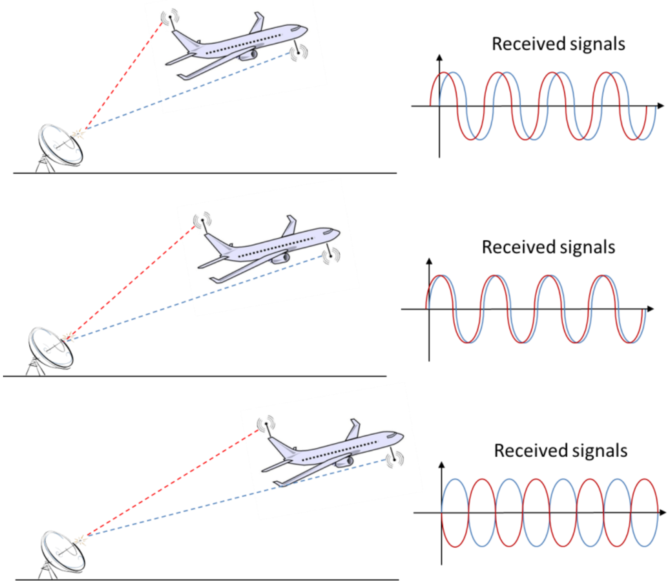

Figure 1: illustration of the two-antenna problem. In some configurations, the overall received signal can be reinforced while in others ones, it can be fully cancelled.

It is then possible to define the set of the antenna pointing angles for which the telemetry might be lost. The shape of this diagram looks like an antenna daisy pattern. An example of this kind of diagram is given in Fig. 2 and is extracted from [6].

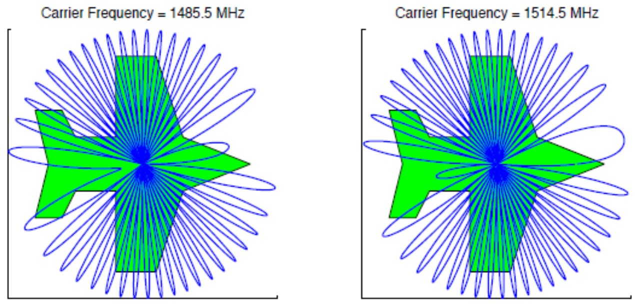

Figure 2: radiation diagram for the emission of two telemetry signals.

B. Available solutions

A basic solution (label as *classical solution* in the following) is to significantly reduce the power of the signal on one of the antennas. Indeed, by doing so, even if the signals are in opposite phase when they recombine, the amplitude difference ensures that there is no signal cancellation. It is regularly admitted that we avoid the two-antenna problem if a difference of amplitude between 6 and 10 dB is inserted. Actually, the angle sector for destructive interference is reduced, but the transmission range of the antenna fed with less power is also shortened. An alternative is to have one antenna in horizontal polarization, while most antennas are blades in vertical polarization. This shows to be much effective as the sector of interference is limited to areas of diffraction that modify the transmitted polarisations. But horizontal polarization antennas are bigger, more fragile and require some distance from the fuselage, hence they are not popular on fighters.

Another solution has been proposed by M. Rice in [6-7], based on space time coding. This solution is only proposed for the SOQPSK modulation. The basic principle is to avoid the destructive recombination of the transmitted signal by creating signal diversity i.e. the signal emitted by the first antenna sends the original binary data flow while the signal on the other antenna carries a different version of the original binary data flow. Since two different data flows are transmitted on each antenna, the probability of destructive signal recombination at the receiver side is almost zero.

A dedicated demodulator has to be implemented in order to retrieve the original data stream within the mixed signal collected at the reception side. To do so, a pilot sequence of 128 bits is inserted after each block of 3200 bits. This sequence is used to detect the beginning of data block. After this detection, an estimation of the signal frequency offset is performed in order to synchronize the signal in the frequency domain. Then an equalization of the signal, based on the minimum mean square criterion, is performed. A space-time decoding, based on trellis decoding, is finally made in order to obtain the original data stream.

The overall system performance is good, which was confirmed by on-field tests in the Air Force Flight Test Center at Edwards [6]. More advanced tests made in [8] also suggested that this solution remains sensitive in the presence of multipath channels.

Zodiac Data Systems has also developed a proprietary solution for Airbus based on the well-known COFDM (Coded Orthogonal Frequency Division Multiplexing). Here, the use of orthogonal sub-carriers over long period symbols gives the opportunity to insert a guard time intended to absorb the inter symbol interference created by the delay spread of the channel response. As the guard time is larger than the difference of delay between echoes, each received sub-carrier can be properly demodulated. The receiver only has to estimate the transfer function for each sub-carrier thanks to sync words and pilots. This process is in fact equalization.

COFDM also gives the opportunity to solve the two-antenna issue. By delaying an antenna with a fraction of the guard time, the two antennas are seen as multiple echoes that the receiver natively equalizes.

To summarize, cancelling the effect of the two-antenna interference in all directions requires to transmit different signals. But another takeaway of this section is that multipath requires some specific equalization algorithm in the receiver to be mitigated, whatever the waveform and the number of on-board antennas are. So a clever way to handle the two antenna issue may be the other way round: when equalization is performed at the receiver, it may be solved by just making this problem looks like equalization.

III. Blind Equalizer Based Solution

A. Description of the proposed solution

We here propose a solution for the limitation of the two-antenna problem that is based on delay diversity. The basic idea is to send the same signal over both antennas but with a fixed delay between them. For instance, antenna 1 sends the useful signal $s(t)$ while antenna 2 sends the signal $s(t-\tau)$ with a given attenuation α. The delay between both antennas is inserted to avoid the destructive signal recombination that is illustrated on Fig. 1.

Consequently, if the signal is transmitted on a noiseless perfect channel, the signal that is received on the ground station can be written as follows:

$$r(t) = s(t) + \alpha s(t-\tau) \qquad (1)$$

Where:

- α is a complex-valued coefficient of attenuation.
- τ is the value of the delay between both antennas.

We set $\boldsymbol{\alpha} = |\boldsymbol{\alpha}| e^{j\varphi_0}$ where $|\boldsymbol{\alpha}|$ is an amplitude attenuation and $\boldsymbol{\varphi_0}$ is a phase offset between both transmitting antennas. Denoting $\boldsymbol{\alpha_{dB}} = -\mathbf{20}\log|\boldsymbol{\alpha}|$, $\boldsymbol{\alpha_{dB}} = \mathbf{0}$ dB means that both antennas transmit the signal with the same power. Likewise, $\boldsymbol{\alpha_{dB}} = \mathbf{3}$ dB means that the signal on the second antenna is transmitted with half the power of the first antenna. Phase $\boldsymbol{\varphi_0}$ reflects the fact that there is a random phase offset due to the different propagations of both emitted signals.

From Eq. (1), we obtain:

$$\boldsymbol{r(t) = (\delta(t) + \alpha\delta(t-\tau)) \otimes s(t) = (h \otimes s)(t)} \qquad \mathbf{(2)}$$

From this latter equation, we can conclude that transmitting a signal with delay diversity on antennas is strictly equivalent to transmitting a signal over a multipath channel (here with one path only). This is illustrated on Fig. 3.

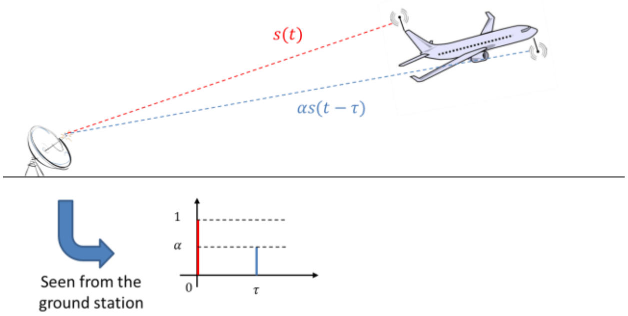

Figure 3: effect of the delay diversity from the receiver point of view

In fact, a basic demodulation of $r(t)$ may lead to low performance in terms of BER (Bit Error Rate) because $s(t-\tau)$ is seen as interference for the useful signal $s(t)$. Consequently, as the receiver sees the delay diversity as a multipath channel, it is interesting to exploit the properties of an equalizer to mitigate the interfering part of the received signal.

B. Blind and Adaptive Equalizer for SOQPSK

Zodiac Data System has developed a blind and adaptive equalizer for PCM-FM. The concept and performance of this equalizer have already been presented in [1] and [3].

Now, Zodiac Data Systems introduces a blind and adaptive equalizer for SOQPSK. The SOQPSK modulation is more sensitive than PCM-FM to the multipath effects. Indeed, the SOQPSK demodulator is coherent: it must be able to lock on and track the carrier frequency. The multipath effect creates a frequency selective channel and instantaneous variations of the received signal phase. Having an SOQPSK equalizer is a tremendous advantage, not only because it helps to correct frequency selective fading, but also because it reduces the instantaneous phase variation of the received signal, easing the work of the demodulator. This avoids loss of lock of the demodulator and wide burst of errors.

Preliminary lab tests have proved the capacity of the developed equalizer for SOQPSK to greatly improve the performance of the RTR (Radio Telemetry Receiver – the telemetry receiver developed by Zodiac Data Systems) in terms of BER on the channel scenarios proposed in [1]. In addition, the proposed SOQPSK equalizer brings sufficient performance improvement to guarantee quasi-error free transmission when combined with a LDPC code. This is particularly interesting as LDPC codes are now included in the latest release of [5].

The solution for combating the two-antenna problem using delay diversity and an equalizer has been presented previously for PCM-FM in [4]. The purpose of this article is to study if this solution can be adapted to SOQPSK, using the recently developed equalizer.

C. *Mitigation of the 2-Antenna Problem*

In this paragraph, we prove by simulation that the delay diversity allows the mitigation of the 2-antenna problem. Fig. 4 shows the average power of the received signal $r(t)$ as a function of the delay between the signals on the two antennas τ (expressed as a fraction of a bit time duration), with the same power on both antenna (i.e. $\alpha_{dB} = 0$ dB). On this figure, both signals $s(t)$ and $s(t-\tau)$ are simulated as RF signals with a central frequency $f_0 = 2.5$ GHz.

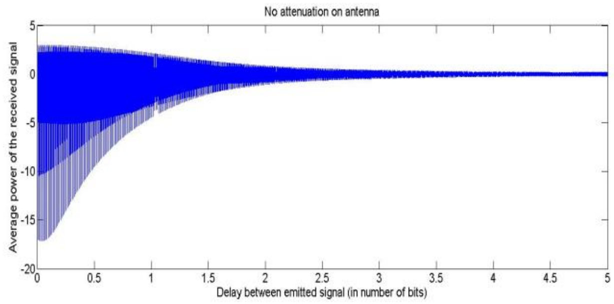

Figure 4: Average power of the received signal as a function of the delay between signals on antenna (no attenuation on second antenna)

When the delay τ, introduced between both signals, is low and up to 2.5 bits, we observe some important fading in the mean power of the received signal. The explanation of this is illustrated on Fig. 1 as a destructive signal recombination may frequently occur in this case. If the inserted delay is now greater than 2.5 bits, we observe that the mean power does not strongly fluctuate anymore, which means that the sum of both emitted signals is never fully cancelled: the two-antenna problem is then solved.

Nevertheless, if $\alpha_{dB} = 0$ dB, the channel frequency response presents very deep or even infinite fading which cannot be corrected by any kind of equalizer. In this case, an attenuation of a few dB on one of the antennas is required for the equalizer to optimally perform, and retrieve the original data flow. Fig. 5 shows that, with an attenuation of 2 dB on the second antenna, the two-antenna problem is still solved if the delay between the signals is greater than 2.5 bits.

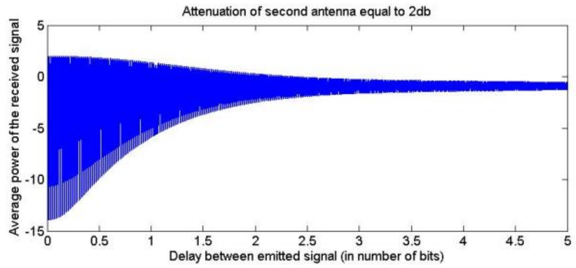

Figure 5: Average power of the received signal as a function of the delay between signals on antenna (2 dB attenuation on second antenna)

This solution is very similar to the *classical solution*, since it significantly attenuates the power of one of the antennas. Instead of attenuating up to 10 dB in order to guarantee a possible demodulation, the blind equalizer allows an important improvement of the gain on the second antenna.

IV. Laboratory Experiments

A. *Laboratory bench test*

We set up a laboratory bench test in order to validate the theoretical idea proposed hereinabove. The test utilized:

- A SMBV 100A from Rohde & Schwarz as signal generator.
- An AMU 200 from Rohde & Schwarz as transmission channel simulator.
- A RTR (Radio Telemetry Receiver) from Zodiac Data Systems with a blind equalizer for signal demodulation and BER evaluation.

The bench test synoptic is displayed on Fig. 6.

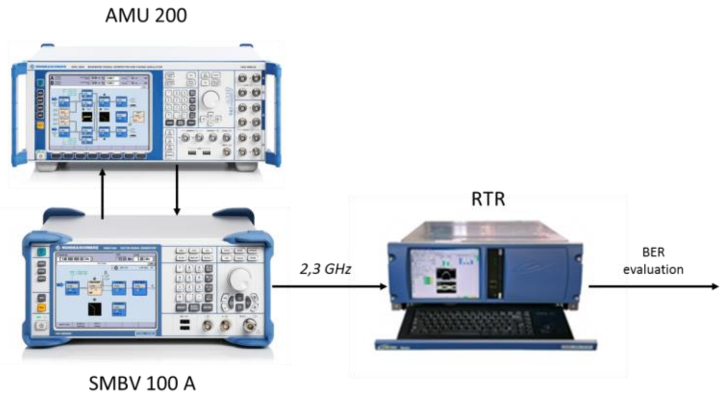

Figure 6: laboratory bench test for validation of the proposed solution.

From this bench test, we attempt to estimate the best set of parameters (α, τ) so that the signal could be perfectly demodulated after equalization. The constraints on the parameters to be determined are as follows:

- In order to improve the link budget compared with the *classical solution*, the power attenuation α shall be as low as possible.
- In order to remove the interferences between the two antennas causing important signal power loss, the delay between the two antennas τ shall be greater than 2.5 bits.
- The delay between the two antennas τ shall not exceed the correction span of the equalizer.

The best combination of (α, τ) will be obtained utilizing the three above conditions with a BER remaining at zero.

B. Parameter settings

As shown on Fig. 7, the propagation time difference between both antennas on the aircraft and the ground antenna is different if the distance between both transmitting antennas is significantly large and has to be taken into account in our study.

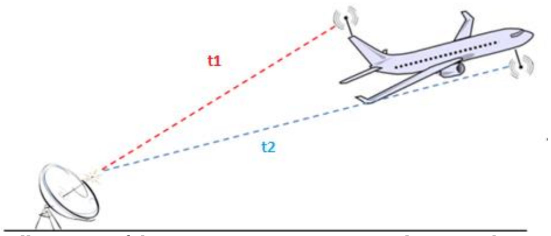

Figure 7: Illustration of the propagation time corresponding to each antenna (t1 and t2 are the individual travel times corresponding to each antenna)

We set $\tau_d = |t_2 - t_1|$. This time shift is time-varying, depending on the maneuvers of the aircraft. The maximal value of this time difference is given by:

$$\tau_d^{max} = \frac{d}{c}, \tag{3}$$

Where:

- d is the distance between the transmitting antennas,
- c is the speed of light.

This upper bound is reached if the two antennas and the ground station are perfectly aligned. If we consider a distance of 75 meters between the two antennas (which corresponds to a long airplane like Airbus A380), τ_d is approximately equal to 0.25µs. Then, if the signals between the two antennas are delayed by τ, the actual time difference between the two antennas seen by the ground station will dynamically vary between $\tau_{low} = \tau - 0.25$ µs and $\tau_{high} = \tau + 0.25$ µs. Note that we are dealing with a worst case scenario in such a configuration and these conditions would be a lot less severe for shorter aircraft.

The AMU 200 channel simulator does not allow to model dynamic variations of the delay τ. So we propose to actually determine the two sets (α, τ_{low}) and (α, τ_{high}) achieving the three conditions mentioned in paragraph IV.A. First we introduce a very simple configuration where the transmission is made with both antennas and without multipath effect or noise.

In order to significantly improve the link budget compared to the *classical solution*, we choose to set the power attenuation α to 2 dB. The frequency response of the channel seen by the ground station is:

$$H(f) = 1 + |\alpha| e^{-j(2\pi f \tau + \varphi_0)} \tag{4}$$

It can be seen that φ_0 determines the position of the frequency selective fading in the signal bandwidth. However, its exact value cannot be predicted, as it fully depends on the variations of τ in the time interval $[\tau_{low}; \tau_{high}]$. Consequently, a way to cope with this is to proceed as follows: whenever a value of τ leading to a BER equal to zero is found, it must also be the case whatever the value of the phase φ_0.

C. Results in a distorsion-less scenario

As first lab tests, we suppose that both transmitting antennas are motionless and that no Doppler effect is considered: the channel is (quasi-)static. So we configured the path table in the AMU 200 as displayed in Table 1. Moreover, no Gaussian noise is added to the analyzed signal. Then each signal from a given transmitting antenna propagates into a perfect channel.

Table 1: configuration of the AMU 200

Parameter	Profile	Path loss (dB)	Delay (µs)	Const. Phase / Deg
Path 1	Static Path	0	0	0
Path 2	Const. Phase	2	variable	variable

We must find two values of τ corresponding to τ_{low} and τ_{high} so that the BER is equal to zero for all phases differences φ_0 (depicted by the parameter Const. Phase / Deg in the AMU 200). The experiments are done for bit rates between 1Mbps and 5Mbps. The global results are summed up in Table 2, considering the bit shifting between both antennas is calculated by multiplying the obtained delay with the considered bit rate.

Table 2: results of the experiments on a basic configuration

Data rate	1Mbps	2Mbps	3Mbps	4Mbps	5Mbps
α (in dB)	2	2	2	2	2.5
τ_{low}	3.5 µs 3.5 bits	1.7 µs 3.4 bits	1.2 µs 3.6 bits	0.8 µs 3.2 bits	0.7 µs 3.5 bits
τ_{high}	4 µs 4 bits	2.2 µs 4.4 bits	1.7 µs 5.1 bits	1.3 µs 5.2 bits	1.2 µs 6 bits

From these set of experiments, we may conclude that it is possible to find configurations for the considered bit rates having with the following characteristics:

- The attenuation α is greater or equal to 2.5 dB. Consequently, the link budget is considerably improved on the attenuated antenna when compared to the *classical solution*.

- The values of τ_{low} and τ_{high} are greater than 2.5 bits, which guarantees that the two-antenna problem is solved as seen on Fig. 5.
- The values of τ_{low} and τ_{high} fully match the requirement of a distance between antennas equal to 75 meters (worst case scenario).

Note also that, in practice, the delay τ seen by the ground station dynamically varies in the range $[\tau_{low};\tau_{high}]$ because of the aircraft maneuvers. Since AMU 200 does not permit to model such variations, this particular aspect is not taken into account and we only focus on a static but worst case scenario. The delay variations will be studied in real conditions and will be the object of a future publication.

D. Influence of multipath

This section aims at showing that the RTR (Radio Telemetry Receiver) is still capable to correct the distortions caused by the multipath channels even in the presence of a second LOS (Line of Sight), due to the signal propagation from the second antenna. To do so, we model this by supposing that one reflection affects the signal propagation from antenna 1, and one reflection affects the one from antenna 2, as illustrated on Fig. 8.

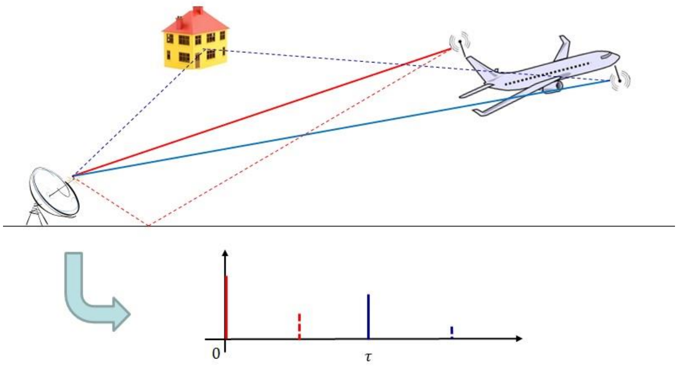

Figure 8: Channel study for the influence of multipath channels

For experimentation purposes, we introduce some time variability in the propagation channel. Each reflection is then simulated by a Rayleigh fading model with a Doppler frequency equal to 30Hz. The path table in the AMU 200 is then configured as follows:

Table 3: configuration of the AMU 200

Parameter	Profile	Path loss (dB)	Delay (µs)	Const. Phase / Deg	Res. Doppler Shift / Hz
Path 1	Static Path	0	0	0	0
Path 2	Const. Phase	2	τ	0	0
Path 3	Rayleigh	20	0.7 µs	0	30
Path 4	Rayleigh	20	τ + 0.5 µs	0	30

The resulting signal is now processed with our RTR in which an EQZ is inserted in the reception chain. The demodulation performance is displayed on Table 4.

Table 4: Bit error rate results of the Zodiac Data Systems solution in presence of time-varying multipath

Bitrate (Mbps)	Atten. (dB)	Delay τ (µs)	EQZ off	EQZ only
1	2	4	demod unlock	1.6e-4
2	2	2	demod unlock	3.2e-5
3	2	1.5	demod unlock	1.2e-5
4	2	1	demod unlock	1.3e-5
5	2	1	demod unlock	1.5e-5

From these experimentations, we observe that even in the presence of multipath effects, the transmission remains at an interesting level of BER (while the demodulator stays in an unlocked status if the EQZ is switched off). We then clearly observe that the blind and adaptive equalizer is able to correct at the same time the 2-antenna problem and also a certain amount of multipath effects caused by signal propagation. One may then conclude that the solution is well-adapted for telemetry in real environments.

However, in the case of the take-off of an aircraft (where the transmitting antennas are consequently moving quickly), the propagation channel may become quickly time-varying. In such a case, the EQZ may have some difficulties to track the quick channel variations and the demodulation could return some residual errors.

Nevertheless, since LDPC codes are now standardized in the IRIG 106 recommendation [5], they will most likely be very relevant in such a context. Actually, although LDPC codes are initially designed for error correction caused by thermal noise, they are very helpful after an equalizer to mitigate the multipath effect:

- The equalizer inverts the channel. This generally helps the demodulator and bit-synchronizer to lock, resulting in drastic reduction of the number of error.
- The LDPC helps to further reduce the number error.

Preliminary tests have showed that the combination of our equalizer with an LDPC code is able to maintain a quasi-error free transmission in presence of a certain amount of time varying multipath, while solving the two antenna problem at the same time. We shall focus our future studies on this very promising aspect.

E. Practical set-up

In our lab tests, the delay introduced between both antennas was managed by the AMU 200. In practice, the on-board setup consists of a standard SOQPSK transmitter, plus a device able to attenuate and delay the RF signal before feeding the second antenna. This device can be produced at a modest cost by using an RF-to-baseband transposer, a small FPGA designed to insert a programmable delay to the signal, and a baseband-to-RF transposer.

One may also manufacture dual output transmitters, as programmable digital delay lines are very easy to implement in FPGAs of modulators. This solution was selected by our customer Airbus for OFDM telemetry as it is the most flexible one.

V. CONCLUSIONS

We proved that a SOQPSK signal delayed by two and a half bits or more is orthogonal to its non-delayed version. Tests conducted in laboratory showed the ability of an equalizer designed for SOQPSK modulation to cancel the impact of the daisy patterns caused by two antennas when the delayed signal feeds one antenna. This solution is easy and cost-effective because:

- There is no need to modify the transmitter or the modulation scheme,
- The equalizer may be just a software option in a regular receiver (like our RTR),
- There is no need to insert any additional pilot or unique word in the data stream,
- The system also natively mitigates multipath channels,
- Slight modification of the on-board set-up by adding a delay line.

The next step is to evaluate the solution in an operational context and perform test range measurements.

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