Integrated voice and data communications for applications to air traffic control

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Abstract. In this work a possible setup of a data link, compatible with voice transmissions, between aircraft and ground stations is proposed. This method utilizes a hybrid amplitude-phase modulation of the same carrier: the amplitude modulation is used for voice transmission, while the phase modulation is for data transmission. This method is particularly simple to implement and requires only slight modifications to the actual on-board equipment for voice transmission. The interferences between the voice and data signals are evaluated through a computer simulation. Some different phase or frequency modulations for data transmissions, such as PSK, FSK and MSK, are considered.

1. INTRODUCTION

The present organization of air traffic control (ATC) is based almost completely on the voice communications between the pilot and the ground station. The control station keeps the status of the airways updated and regulates the whole system, communicating with all the aircraft in its control area [1], [2].

Communications with transoceanic or transcontinental flights are generally performed using HF bands; nevertheless such bands often present poor propagation.

In metropolitan areas, VHF and UHF bands are generally utilized. These bands allow a good communication quality, even though they can only be used over limited distances. Moreover, the channels available in these bands are often saturated due to the high density of air traffic, as in terminal areas, especially at some peak hours. This fact often determines delays in departure and arrival of flights and also consequences on the safety of flights.

A solution to this problem, which will probably be adopted in the near future, is the introduction of a digital channel for the automatic transmission of part of the data and information that are currently transmitted by voice to and from the aircraft. In this way it is possible to reduce the load and the duration of conversations between ground station and aircraft. At the same time, an automatic process of the control operations which today are performed exclusively by the pilot is conceivable.

Small or medium size aircraft represent an important part of the whole air traffic in many countries, as for example in Italy. Therefore, it is convenient to create a data link which can be extended to these aircraft as well. This makes it necessary to find solutions having a simple and economical implementation and, if possible, without great modifications to the present apparatus for voice transmission. Almost all the solutions proposed in the literature fail to meet these conditions.

In this paper a possible setup of a data link between station and aircraft, which satisfies the above requirements, is presented. In such a system the data signal modulates the phase of the carrier utilized for voice transmission. Therefore, the data link can be created by adding a phase modulator to the present apparatus for voice transmission. Of course, this communication system does not perform as well as other solutions using two separate channels, the former for voice and the latter for data transmission. Nevertheless, in this paper, it is shown that the proposed communication system achieves an overall performance which can be considered satisfactory for the particular application examined here, where very high data rates are not required.

The mutual interferences between the two modulations, amplitude and phase, are investigated using a computer simulation.

2. A DATA LINK USING A HYBRID AMPLITUDE-PHASE MODULATION

The possible solutions for creating a data link

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between a ground station and aircraft can be subdivided into two categories [3], [4], [5]:

i) specialized data link for air traffic control, integrated into secondary radar;

ii) VHF data link of universal type, compatible with the voice transmission and not specialized for air traffic control functions only.

The first solution, adopted for example in the Discrete Address Beacon System (DABS), permits a data link of high capacity to be achieved [1], but presents some important drawbacks. Indeed, this solution is very expensive and not easily extendible to small or medium-size airports for many years. At the same time, the possibility of a direct link between aircraft, without passing through the ground station, is excluded. In this solution, all the aircraft not equipped with a Secondary Surveillance Radar (SSR) transponder are excluded from the data link facility.

In many countries, such as Italy, small and medium-size aircraft represent an important part of the air traffic and therefore it is convenient to develop solutions which can be extended to all air traffic.

In the second category, on the other hand, economical, universal-type systems can be found. The solutions in this category can in turn be divided into two subcategories:

1) systems with separate channel, in which data are transmitted on a frequency different from that used for voice transmission;

2) systems with a common channel, in which data and voice utilize the same channel.

A separate-channel solution requires the availability of a certain number of channels to be destined solely for numerical transmissions and would hence bring about a further increase in the saturation of the bands presently available. Furthermore, it would require doubling the communication apparatus aboard the aircraft and hence a cost that may not be negligible for small aircraft.

In the other subcategory of solutions, on the other hand, the numerical information must coexist in some way with the voice signal. This limits the performance to be expected from such solutions, in contrast to the solutions in the first subcategory, which do not present this type of problem.

The coexistence of voice and data in a single channel may be achieved in various ways: for example, by means of multiplex with frequency division or time division, or by orthogonal modulations.

The data link proposed in this paper lies in the second subcategory and therefore utilizes the same channel for voice and data transmission [6]. In this solution voice signal and data modulate the same carrier: the voice modulates the amplitude of the carrier, while data modulate the phase or the frequency of the same carrier. The general block diagram of this system is depicted in Fig. 1. The carrier $A\cos(\omega_o t+\theta)$, generated by a local oscillator, is first modulated in phase by the data sequence and therefore is of the form:

(1) $$s_1(t) = A\cos[\omega_o t + \phi(t) + \theta]$$

where

(2) $$\phi(t) = \sum_{K=-\infty}^{+\infty} d_k\, g(t-kT)$$

d_k being the k-th information symbol and $g(t)$ is the phase pulse depending on the particular modulation considered.

The signal is then sent to an amplitude modulator, which modulates the amplitude of the carrier by the voice signal $f(t)$. At the output of the AM modulator the signal is

(3) $$s(t) = A[1 + m\,f(t)]\cos[\omega_o t+\phi(t)+\theta]$$

where m is the amplitude modulation index.

A signal modulated in phase by means of a PSK modulation has a constant envelope. Nevertheless, because of the abrupt discontinuities present in a PSK signal, and hence the considerable extent of its spectrum, when that signal passes through a finite-band system, the envelope of the modulated wave is no longer constant [7], [8].

These envelope variations are particularly damaging in the communication system proposed, because they introduce a distortion which interferes with the voice signal. Such a distortion of course depends on both transmission rate and the modulation method utilized.

As is shown in the next section, these envelope fluctuations determine a poor performance of an amplitude-phase modulation, when the phase modulation is PSK. It is, then, convenient to utilize phase or frequency modulations which require less bandwidth. Therefore, in this paper, FSK and MSK modulations are considered, together with PSK, for data transmission.

3. PHASE MODULATIONS AND FILTERING

A binary phase-shift-keying (BPSK) signal has the form:

(4) $$\begin{cases} s(t) = \sqrt{2E}\;\cos(\omega_c t+\psi_k) \\ kT \leqslant t \leqslant (k+1)T,\ k \text{ integer} \end{cases}$$

where ω_c is the carrier angular frequency, T the bit time interval and E the signal mean power. If a_k is the binary data sequence to be transmitted, $a_k = \pm 1$, we have

(5) $$\begin{cases} \psi_k = 0 \text{ if } a_k = -1 \\ \psi_k = \pi \text{ if } a_k = 1 \end{cases}$$

If the spectral power density of a PSK baseband signal is given by [4]

(6) $$G(\omega) = T\left[\frac{\sin(\omega T/2)}{(\omega T/2)}\right]^2$$

and this expression is plotted in Fig. 2, normalized to the maximum value, corresponding to the carrier frequency. Spectral occupancy is considerable in comparison with other digital modulations, due to the signal sharp phase changes. For this reason, modified PSK modulations with narrower bandwidths are often to be preferred.

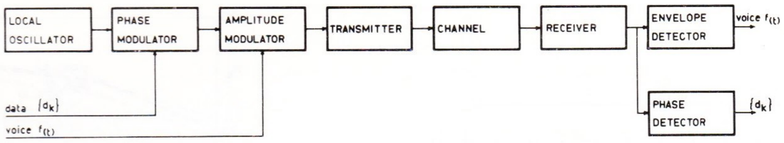

Fig. 1 - General block-diagram of a communication system using a compound amplitude-phase modulation for the simultaneous transmission of voice and data.

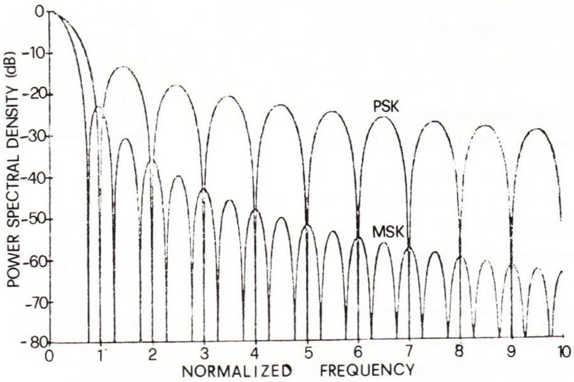

Fig. 2 - Spectral power density of BPSK and MSK.

A similar behaviour is presented by a four-level PSK (QPSK). Nevertheless such a modulation can be more interesting with respect to BPSK, because it permits a higher data rate.

Another interesting modulation for the communication system described in this section is the Minimum Shift Keying (MSK) [8], [9]. MSK is a particular frequency-shift-keying and the signal has the following properties: 1) the envelope of the modulated signal is constant (as for PSK); 2) the instantaneous frequency deviation is $\pm 1/4$ of the bit rate; 3) the instantaneous phase is continuous and varies linearly by $\pm\pi/2$ during every bit interval; 4) spectral occupancy is very little, if compared with other digital modulations with the same transmission rate. Therefore the signal tolerate severe bandpass filtering without great degradation in performance. The MSK signal can be expressed as [7]:

$$(7) \quad \begin{cases} s(t) = \sqrt{2E}\cos(\omega_c t + \frac{\pi}{2T} a_k t + x_k) \\ kT \leqslant t \leqslant (k+1)T, \ k \text{ integer} \end{cases}$$

where a_k are the binary data to be transmitted, and the constants x_k are determined for phase continuity as:

$$(8) \quad x_k = x_{k-1} + (a_{k-1} - a_k)\, k \frac{\pi}{2}$$

with $x_o = 0$ and therefore $x_k = 0$ or π (module 2π).

The spectral power density of an MSK baseband signal is given by:

$$(9) \quad G(\omega) = \frac{4\pi^2 T[1+\cos(\omega T)]}{(\omega^2 T^2 - \pi^2)}$$

and is represented in Fig. 2.

The envelope of a PSK or MSK modulated signal is constant, if the communication chain has an infinite bandwidth. Nevertheless if the modulated signal is passed through a bandpass filter, the signal at the filter output has en envelope no longer constant. Fig. 3 shows a typical behaviour of the envelope of a filtered PSK waveform, supposing that the modulated signal is filtered by a Butterworth bandpass filter of the fourth order and FT = 2.5, F being the single-side -3dB bandwidth of the filter.

Obviously, the envelope fluctuations are more evident in PSK than MSK, because the MSK waveform presents lower discontinuities and therefore the spectrum is more compact (Fig. 2).

4. SIMULATION OF THE DATA LINK AND RESULTS

The performance of the communication system described in the previous sections was derived through a computer simulation. The equivalent baseband model of the system was utilized to reduce the computation time.

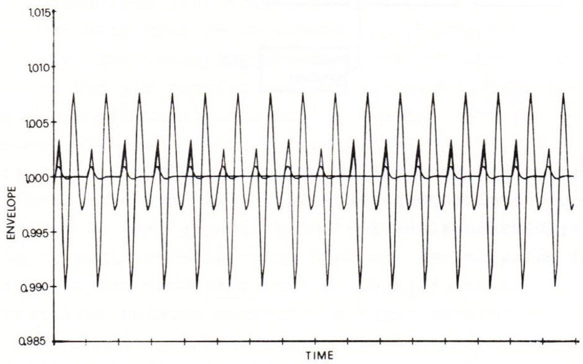

Fig. 3 - A typical envelope behaviour of filtered MSK waveform.

The bandpass filters in the communication chain were modeled as Butterworth filters with the following characteristics:
- transmitter filter: fourth order, with -3dB single-side bandwidth 7.5 kHz;
- receiver filter: eight order, with -3dB single-side bandwidth 5 kHz.

Filtering was performed in the frequency domain, while non-linear operations, such as modulation and demodulation, were simulated in the time domain. The transformations from one domain to the other were done using the Fast Fourier Transform (FFT) algorithm.

In order to estimate the distortion introduced by data signal and phase modulation, the signal at the output of the AM detector $f_1(t)$ is compared with the original signal f(t), which modulates the carrier amplitude. An error signal e(t) = $f_1(t) - f(t)$ is therefore obtained. The simulation program gives some parameters relative to this error signal. First, the mean noise power N_o of this error signal is computed and expressed in dBm, taking as reference a disturbance of 1 mW. Denoting with S the power of the signal f(t), the signal-to-noise ratio S/N_o is also computed. Another interesting parameter is the maximum value e_p of the error signal, i.e. the peak error, which indicates the maximum error which can be encountered in this transmission system. In the following, the peak error is always expressed as a percentage of the maximum value of the modulating signal f(t). All these parameters are obtained by supposing the communication channel as a noiseless channel and having a transfer function C(ω) equal to 1 for any ω; in this way the error signal is due only to the interferences of the data with the amplitude modulation.

Four different signals, modulating in the voice channel, were utilized in the simulation:
- 1) a tone at 937.5 Hz frequency
- 2) a tone at 1875 Hz frequency
- 3) a sum of five tones, given by

$$(10) \quad f(t) = \sum_{i=1}^{5} Q_i \cos[2\pi i(468.75)t]$$

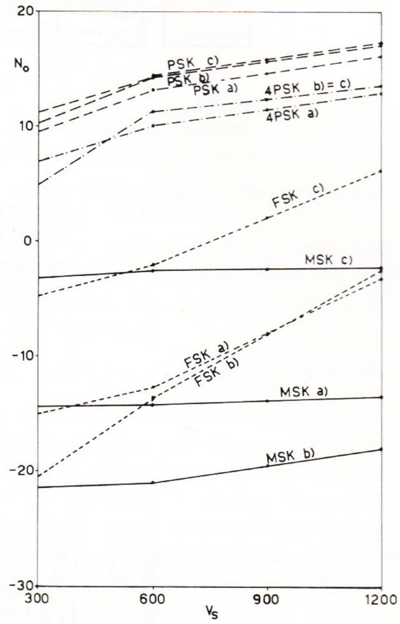

Fig. 4 - Noise power N_o in dBm versus the data rate v_s: a) tone at 937.5 Hz; b) tone at 1875 Hz; c) sum of five tones.

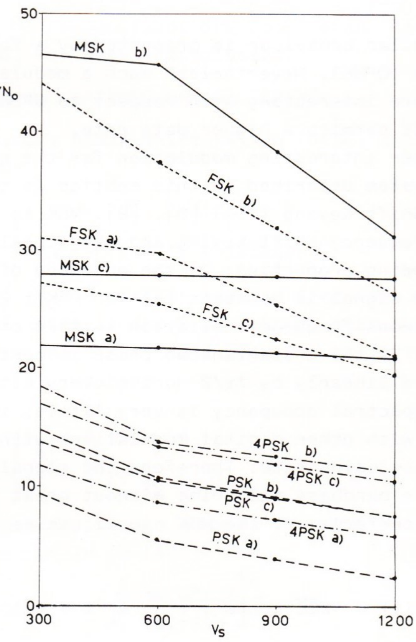

Fig. 5 - Signal-to-Noise ratio S/N_o versus the data rate v_s: a) tone at 937.5 Hz; b) tone at 1875 Hz; c) sum of five tones.

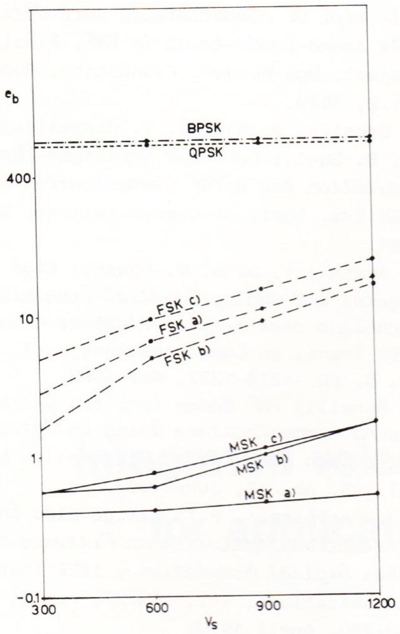

Fig. 6 - Peak error e_p versus the data rate v_S: a) tone at 937.5 Hz; b) tone at 1875 Hz; c) sum of five tones.

and the coefficients Q_i are: $Q_1 = Q_3 = 2/9$; $Q_2 = 1/3$; $Q_4 = Q_5 = 1/9$

- 4) a real voice signal having a time duration of 4 seconds.

The simulation with the previous signals was carried out for several values of the AM modulation index k_v.

The noise power N_o, the signal-to-noise ratio S/N and the peak error e_p are reported in Figs. 4, 5 and 6 respectively for the first three modulating signals as a function of the data transmission rate v_S. In these figures a, b and c refer to amplitude modulating signal formed by a tone at 937.5 Hz, a tone at 1875 Hz and the sum (10) of five tones respectively. The amplitude modulation index m is assumed equal to 0.8. In Fig. 7 the signal-to-noise ratio S/N_o is shown, when the amplitude modulating signal is the real voice signal. In this case the amplitude modulation index is m = 0.9.

From these results it is clear that BPSK systems often present poor performance; the signal-to-noise ratio can be lower than 15 dB, which is the minimum acceptable level for this type of application. Peak errors, which are often many times greater than the maximum value of the amplitude modulating signal, can arise.

QPSK systems often show a slight improvement in the signal-to-noise ratio and noise power with respect to BPSK. Nevertheless such an improvement is not sufficient to guarantee the required performance and is obtained at the expense of the error probability in the data.

On the contrary, FSK and particularly MSK modulations permit a greater improvement to be

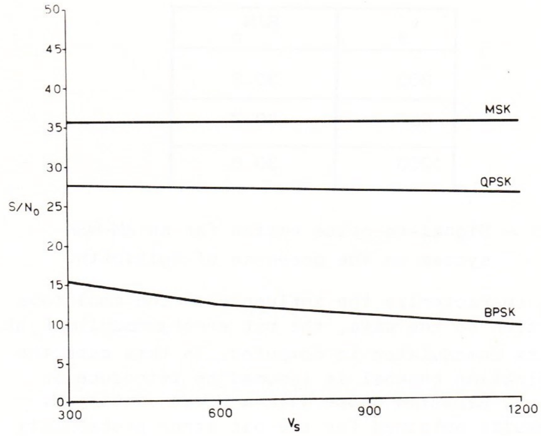

Fig. 7 - Signal-to-Noise ratio S/N_o versus the data rate v_S when the amplitude modulating signal is the real voice signal.

achieved with respect to BPSK. For example, AM-MSK systems give signal-to-noise ratios greater than 30 dB and peak errors lower than 1% in almost all cases.

These differences are essentially determined by the spectral spread of PSK; when an AM-MSK system is utilized, the channel bandwidth is sufficient to pass the phase modulated signal without considerable envelope fluctuations, for the considered data rates.

AM-FSK systems present an intermediate performance between AM-PSK and AM-MSK systems, which can be considered acceptable for a good reproduction of the voice signal in this case. Such a system also has the advantage that the data can be demodulated in a non-coherent way.

Moreover the AM-PSK system may be influenced by the Doppler effect due to the aircraft motion, which may not be negligible. Of course a differential PSK modulation could be considered to reduce the influence of the Doppler effect. However this solution has not been analyzed because of the generally poor performance of the AM-PSK system even in the absence of the Doppler effect.

Multipath phenomena are quite important in an aircraft communication system. In order to simulate a multipath situation, the transfer function of the communication channel was assumed as:

$$(11)\quad C(\omega) = [1 + a_r \cos \omega t_o] \exp [j\, b_r \sin \omega t_o]$$

where a_r, b_r and t_o characterize the multipath. In this way, both the amplitude and phase of the channel transfer function $C(\omega)$ present a sinusoidal ripple with amplitude a_r and b_r respectively; the parameter t_o is related to the frequency f_r of the ripple in the considered band, i.e. $t_o = 1/2\pi f_r$.

In Table 1 some results for the AM-MSK system, which is the most interesting system fot this type of applications, are reported for $a_r = b_r = 0.01$ and $f_r = 1600$ Hz. The loss in the performance is not important if the multipath amplitude is not too high.

v_s	S/N_o
300	30.8
600	30.7
1200	30.5

Table 1 - Signal-to-noise ratios for an AM-MSK system in the presence of multipath.

To characterize the influence of the amplitude modulation on the data, the bit error probability P_e at the data demodulator is computed. In this case the communication channel is assumed to introduce an additive, Gaussian noise with a power density N. The results obtained for the bit error probability are reported in [6].

Nevertheless, as is shown in [6], [10], the increasing P_e, due to the presence of the amplitude modulation, is not too high. Moreover such performance degradation is not as important as that on the voice channel and can be easily compensated with a channel coding operation.

5. CONCLUSIONS

In this paper a possible setup of a data link between aircraft and ground stations is presented, which is compatible with the voice transmission and is particularly simple to implement. The solution described in this paper requires only slight modifications to the actual on-board transmitter equipment on the aircraft and therefore can be extended also to small aircraft, which represent, in many countries, such as Italy, an important part of the air traffic. On the contrary, other more complex solutions, even though having higher efficiency, often cannot be extended to all air traffic and require replacement of the present equipment.

The simulation results presented in this work show that the performance of this system is satisfactory, even though not optimum. The performance depends strictly on the type of modulation utilized for data transmission. In particular FSK and MSK modulations give good performance in all the cases analyzed.

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REFERENCES

[1] W.L. Ashby: *Future Demand for Air Traffic Services*, Proc. IEEE, vol. 50, no. 3, March 1970.

[2] P.R. Drouilhet: *DABS: A System Description*, Lincoln Laboratory, ATC 42, FAA-RD-74-189, November 1974.

[3] M. Pent, M. Aimone Marsan: *Analisi sistemistica preliminare e individuazione di possibili tipi di compatibilità voce-dati sul canale terra-bordo-terra in VHF*, Finalized Project, Ugo Bordoni Foundation, Report II/B/1.2, 1979.

[4] G. Benelli, G. Borghi, V. Cappellini, E. Del Re, S. Gueli: *Combined Amplitude-Phase Modulation for a VHF Communication Link*, IEEE Int. Conf. on Communications, Denver 1981.

[5] F. Akashi, Y. Sato, M. Eguchi: *High Speed Digital and Analog Parallel Transmission Technique over Single Telephone Channel*, IEEE Trans. on Communications, vol. COM-30, no. 5, pp. 1213-1223, May 1982.

[6] G. Benelli: *VHF Radio Link for Ground-Air-Ground Communications Using an Integrated Voice-Data Modulation*, Electronics Letters, vol. 18, no. 13, June 1982.

[7] L.J. Greenstein, P.T. Fitzgerald: *Envelope Fluctuation Statistics on Filtered PSK and Other Digital Modulations*, IEEE Trans. on Communications, vol. COM-27, no. 4, pp. 750-760, April 1979.

[8] D.H. Morais, K. Feher: *The Effects of Filtering and Limiting on the Performance of QPSK, Offset QPSK, and MSK Systems*, IEEE Trans. on Communications, vol. COM-24, no. 8, pp. 809-820, August 1976.

[9] S.A. Gronemeyer, A.L. McBride: *MSK and Offset QPSK Modulation*, IEEE Trans. on Communications, vol. COM-24, no. 8, pp. 809-820, August 1976.

[10] G. Benelli, R. Fantacci: *An Integrated Voice-Data Communication System for VHF Links*, Accepted for Publication on IEEE Trans. Communications.